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Green Infrastructure Fluctuations in Urban Agglomeration of Shanxi Province, China: Implications for Controlling Ecological Crises

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Abstract: The rapid urbanization process means that even moderate-sized cities can quickly become part of larger urban agglomerations, creating new urban zones. Urban Green Infrastructure (UGI) plays a crucial role in these clusters, acting as precious green spaces essential for maintaining ecological safety. This study combines fluctuation analysis based on Morphological Spatial Pattern with traditional landscape pattern analysis, comprehensively addressing the evolution of UGI in terms of quantity, characteristics, and morphology. We selected the Taiyuan-Jinzhong agglomeration as our study area, which is currently in an agglomeration process. The results demonstrated the critical role of surrounding mountains as natural ecological barrier zones. During urban agglomeration, management strategies focused on large-scale afforestation to ensure the quantity of UGI. However, this approach also led to a more clustered landscape with reduced connectivity. Additionally, linear or small-scale UGI types such as branch and islet have seen reductions over the past decade. Changes in internal morphological and complex fluctuations within UGI can harm the formation of ecological networks and potentially negatively affect biodiversity and ecological safety. The research highlights how ecological protection and urban planning policies can influence UGI fluctuations. Therefore, urban managers should not just concentrate on maintaining the quantity of UGI, but also give consideration to changes in its internal features and morphology. Before cities further agglomerate into larger urban clusters, it is crucial to address deficiencies in UGI, continuously improving type configurations and functional structures at the landscape scale. Through strategic planning of UGI, cities can mitigate ecological risks and foster sustainable urban development.

Keywords: urban green infrastructure; moderate urban agglomeration; landscape patten; fluctuation; Morphological Spatial Pattern Analysis (MSPA)

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1. Introduction

Cities are complex systems that integrate socioeconomic aspects, human culture, ecology, and infrastructure [1]. With the global intensification of urbanization, there has been a notable increase in the population moving to urban areas. The United Nations forecasts that by 2050, 66% of the global population will reside in urban regions. Urban agglomerations, as an inevitable result of urbanization and a critical node in social development, consistently attract investments and populations. These areas become centers of land expansion, significantly altering landscape patterns and ecological processes [2–4]. When urban activities are concentrated intensely and landscape alterations occur rapidly, the challenges of public safety and ecological sustainability can compromise the urban development framework.

This degradation impacts the efficiency of urban functions and the living standards of residents, thereby posing substantial threats to human societal progress [5].

Green Infrastructure comprises various green spaces, creating ecological networks that act as effective tools for ensuring ecological safety and providing ecosystem services [6,7]. Urban Green Infrastructure (UGI) is essential for offering "life support services" to enhance urban ecological safety, encompassing green open spaces both within and surrounding cities [8]. It establishes a supply system that supports ecological security and promotes sustainable development. In densely populated urban clusters, UGI is a key strategy for combating climate change [9], halting biodiversity loss, and averting ecological crises [10,11].

Ecologists associate the concept of ecological networks with strategic planning for UGI, exploring the potential of urban planning centered on UGI to enhance urban resilience and ensure ecological safety [12]. In rapidly urbanizing areas, the scientific planning of UGI emerges as an urgent and important topic. The increasing population density in urban agglomerations boosts the demand for UGI to provide ecosystem services, making it crucial to meet these demands for sustainable urban development. Moreover, studies based on urban morphology have demonstrated the influence of UGI's distribution and pattern on various aspects, including thermal adaptation [13], transportation [14], energy [15], cultural services [16], and ecological networks [17]. Therefore, the processes of urban consolidation necessitate diverse spatial forms of UGI. For instance, as urban expansion forms urban clusters, the demand for UGI evolves from individual facilities to a landscape scale, requiring green infrastructure to be distributed between cities and closely connected in terms of space and function [18]. However, as urban agglomeration accelerates and urban sprawl becomes more widespread, cities encroach on internal parks and green spaces, and extend into forests, grasslands, wetlands, and other native green spaces beyond the urban perimeter. Therefore, quantifying the morphological changes in UGI during urbanization is essential for identifying urban challenges. This knowledge is vital for urban managers to determine the optimal configuration of UGI to address the requirements of urban sustainable development.

China ranks among the countries with the fastest urban expansion worldwide, with urban growth becoming more expansive than compact [19]. Since the 1980s, swift economic development has further accelerated urbanization [20,21]. This surge has led to the emergence of massive urban agglomerations, including the Jing-Jin-Ji, Yangtze River Delta, and Pearl River Delta regions, alongside the rapid expansion of numerous medium-sized cities [22]. These cities often develop tight spatial and functional connections with neighboring cities, creating cohesive groups. While large urban conglomerates like Jing-Jin-Ji exhibit a pronounced conflict between economic development and ecological security, making landscape-scale changes in urban planning practices is increasingly challenging. However, groups of moderate urban agglomeration present an unmissable opportunity for human societal progress by enabling the avoidance of ecological crises through sophisticated UGI planning. Despite this potential, studies on urban clusters seldom concentrate on these cities. The planning and development of small and moderate cities, in developing countries, offer a unique opportunity for more impactful human intervention during the urban agglomeration process. This situation necessitates a detailed investigation into the spatiotemporal distribution and evolution of UGI. Such analysis can promptly pinpoint ecological safety hazards within urban planning, enabling the formulation of ecological safety strategies that are aligned with the rapid urban agglomeration process.

Furthermore, current ecological conservation and restoration policies focus on protecting core ecological sources, such as nature reserves, with all policies and funds inclined towards these critical areas. However, small patches and ecological corridors, crucial for constructing urban ecological networks, are often overlooked. Despite being valuable green resources in urban clusters where land resources are scarce [23], these small-scale UGI patches are easily altered by urban expansion.

This study focuses on a typical agglomeration of a moderate urban region in China, employing the Morphological Spatial Pattern Analysis (MSPA) method, a prevalent method in current urban morphology research [13,24,25], alongside landscape pattern analysis from landscape ecology [2]. Our objectives include (1) accessing the spatiotemporal distribution of UGI during the Taiyuan-Jinzhong agglomeration from 1985 to 2020; (2) identifying landscape-scale characteristics of UGI; and (3) investigating UGI's fluctuations. Our findings can reveal potential UGI deficiencies in medium-sized cities during the agglomeration process, serving as a scientific foundation for the design of cross-jurisdictional UGI projects aimed at enhancing ecological safety.

2. Materials and Methods

2.1. The Location of the Study Area

The central urban cluster of Shanxi is primarily centered around the provincial capital, Taiyuan, including parts of the cities and counties within Taiyuan, Jinzhong, Xinzhou, Lüliang, and Yangqu, totaling five cities [26]. As the province's heart, Taiyuan stands as a leading economically developed area in central China. Historically challenged by severe ecological crises from coal mining and large-scale heavy industries, Taiyuan was one of the most polluted cities globally [27]. To counteract this, the local government has implemented a series of sustainable development strategies aimed at balancing economic development and ecological safety. These measures include afforestation, cleaner production plans, and the construction of new districts [28–30]. And the Chinese government initiated a large-scale ecological restoration program, the Grain-to-Green Program (the GTGP), in 1999, designating the central of Shanxi as a key area [31,32]. The region, mainly situated in the eastern part of the Loess Plateau in the Fen River valley, faces significant natural geographical constraints on urban development. Jinzhong, located south of Taiyuan and featuring flat terrain, became one of the earliest areas to develop an agglomerated pattern alongside Taiyuan (Figure 1). Therefore, this study focuses on the typical medium-sized and rapidly agglomerating Taiyuan-Jinzhong agglomeration (TJA) as the research area (Figure 2).

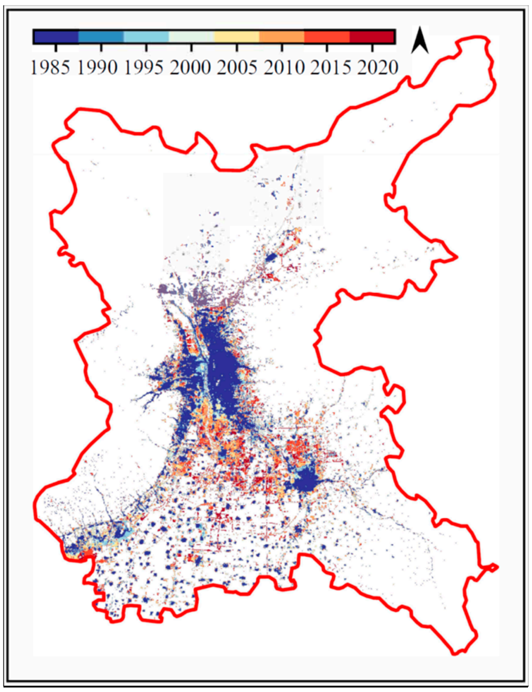

Figure 1. The spatial agglomeration process of Taiyuan City and Jinzhong City: different colors indicate the years of land transformed into impervious surface.

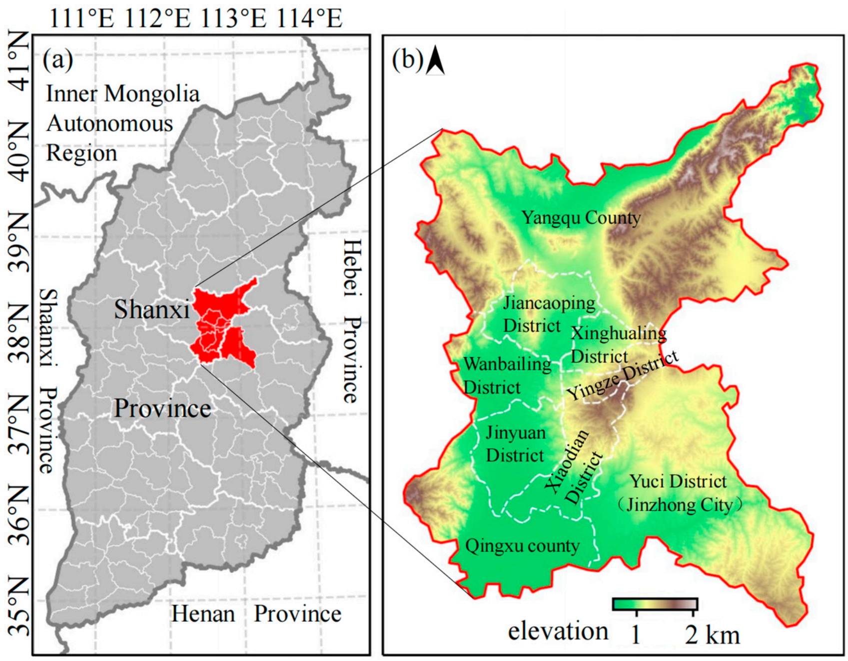

Figure 2. The Location map of the Taiyuan-Jinzhong agglomeration (TJA): the (**b**) study area is located in the central part of (**a**) Shanxi Province.

The TJA has a temperate continental monsoon climate, characterized by clear seasonal changes and concentrated precipitation. According to the Shanxi Statistical Yearbook and other sources, in 2021, Taiyuan experienced a highest temperature of 38 °C (7 July) and a lowest temperature of −17 °C (19 February); the annual rainfall was 243.9 mm, primarily concentrated in summer; and the total annual sunshine hours were about 2808 h [33,34]. The climatic features of simultaneous heat and rain, limited total precipitation, and long sunlight hours exacerbate soil erosion, a common issue on the Loess Plateau, and make the region prone to natural disasters such as sandstorms, torrential rains, and droughts [35–37]. Additionally, with over 2500 years of urban history, the area experiences frequent human activities. As a modern urban area, it hosts a large population and socioeconomic activities [38], leading to ecological safety risks like exacerbated urban heat islands [36].

2.2. Data and Pre-Processing

Land cover data (CLCD) from 1985 to 2020, collected at five-year intervals, were utilized for this study, sourced from remote sensing monitoring data [39]. This dataset, based on Landsat series satellite imagery, has a spatial resolution of 30 m and has been widely applied and validated in scientific research [20,40,41]. To extract the boundaries of the central urban agglomeration area, a 5 km buffer zone was established around the built-up areas of the five cities within the central urban cluster. The largest patch, primarily overlapping with Taiyuan and Jinzhong cities, indicated the formation of a grouped development pattern. Further overlaying these data with administrative boundaries provided the analysis boundaries of the TJA development (Figure 1) and its land use data. All data pre-processing was performed using Python and the ArcGIS platform.

2.3. Landscape Patterns Analysis

Landscape patterns reveal characteristics such as the existence, diversity, and frequency of patches of various land use types, such as urban areas and agricultural lands. Landscape metrics, tools that have been widely used to assess land use/land cover changes and landscape patterns [42], were used in this analysis. Combining extensive published research and our existing knowledge of the study area, we selected three indices to capture the overarching traits of UGI within the TJA: Number of Patches (NP), Contagion Index (CON), and Shannon's Diversity Index (SHDI). To discern the specific features of different UGIs at the class level, four additional indices were selected: Proportion of Landscape (PL), Patch Density (PD), Largest Patch Index (LPI), and Total Edge (TE). Detailed formulas and ecological significances of the landscape metrics can be found in the references [42,43]. The calculations of these landscape metrics were calculated using the 'pylandstats' library [44] in Python.

2.4. MSPA and UGI Mapping

MSPA enables the quantitative analysis of digital images and has demonstrated its efficacy in accurately identifying and precisely reclassifying UGI [45]. By analyzing land use maps from various periods within the study zone, areas functioning as UGI, such as forests, shrubs, grasslands, and water bodies, are categorized as the foreground. In contrast, impervious surfaces and other land use types are considered the background, resulting in binary raster datasets. These raster data are subsequently imported into the Guidos Toolbox for quantitative computation and visualization [46,47]. The methodology employed an eight-neighbor rule with an edge width at 3, equating to a real distance of 90 m. Ultimately, UGI categories are refined into seven distinct, non-overlapping types based on landscape morphology [17,45,48], namely core, islet, perforation, edge, loop, bridge, and branch. For more detailed information, refer to the supporting information in Appendix A (Table A1).

2.5. UGI's Pattern Short-Term Fluctuation Analysis

To characterize the short-term fluctuations of UGI, this study was based on published research methods to propose the Fluctuation Index (FI) to represent each UGI's pattern fluctuation [49]. The FIs of landscape morphology are calculated by measuring the overlap between adjacent years. The specific formula is as follows:

$$FI_i = 1 - \frac{S_i}{S}$$

FI_i represents the Fluctuation Index of landscape morphology from year i to i -5 from 1985 to 2020, respectively. The value range for both indices is 0 to 1. Si represents the area where a certain landscape morphology is present both in year i and year i $-$ 5.

3. Results

3.1. Changes in the Amount of UGI Based on Land Use

During the agglomeration process of the TJA, non-UGI areas consistently occupied about half of the total study area and did not expand in tandem with urban cluster development (Figure 3). In 1985, non-UGI accounted for 52.2% of the total area and remained relatively stable over the next decade. However, it gradually decreased to 47.8% of the total area between 2000 and 2010. By 2020, the non-UGI area rose again to 51.8%, yet remained slightly lower than its 1985 proportion. This indicates that UGI was not excessively compromised during the urban expansion and agglomeration process. Within UGI areas, grasslands formed the largest segment (approximately 29% of the total study area), followed by forests (18%), shrubs (2%), and water bodies (under 1%). Throughout the study period, UGI first expanded and then contracted (Figure 3). In the initial decade, UGI diminished marginally by 26.46 ha, then grew consistently for the next 15 years, peaking in 2010, before experiencing a sharp decline. In the last decade, UGI shrank by 212.71 ha, returning almost to its original size from 30 years prior by 2020.

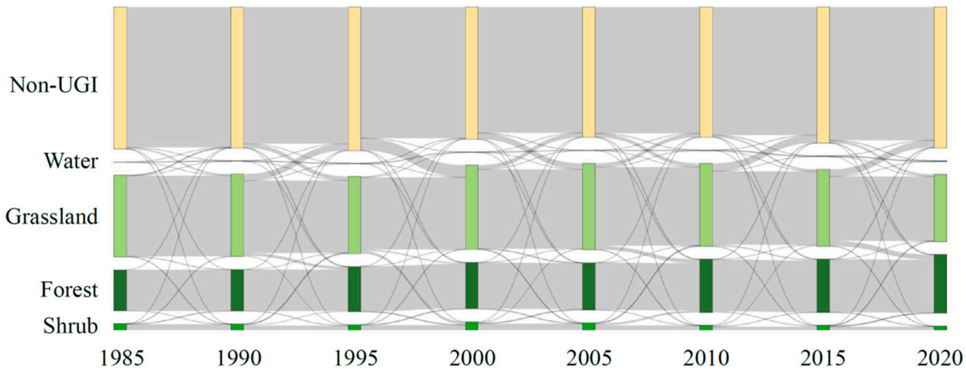

Figure 3. Changes in UGI's area in the TJA from 1985 to 2020.

3.2. The Characteristic Variations of UGI at Landscape Scale

During the urban agglomeration process, UGI exhibited rich variations in SHDI and the CON (Figure 4a,c), while NP consistently demonstrated a downward trend over time (Figure 4b). SHDI remained relatively stable in the initial decade, then surged from 1995 to 2000, and has been continuously declining since 2000, indicating a negative correlation with time. These landscape metrics indicate a trend towards reduced heterogeneity and decreasing diversity of UGI at the landscape scale.

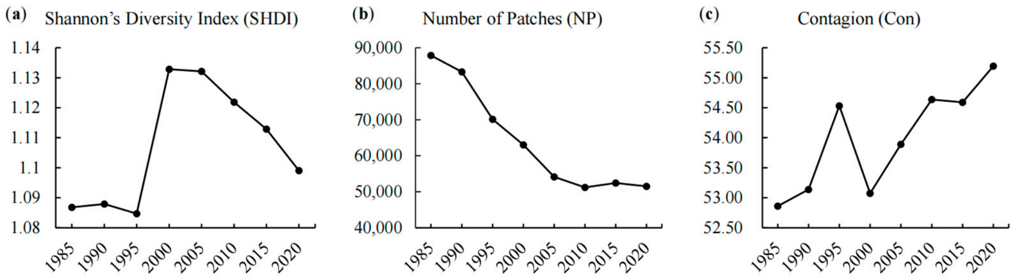

Figure 4. Changes in UGI landscape pattern in the TJA.

The analysis of landscape pattern indices at the class scale shows that, during the development of the TJA, the predominant characteristic of non-UGI is a decrease in PD, dropping from 5.52 to 1.93. The PD of non-UGI negatively correlates with time ($y = -0.57x + 6.10$, $R^2 = 0.94$), indicating that urban agglomeration and sprawl have reduced the fragmentation of non-UGI.

Within UGI areas, we observed the following:

Forest areas have steadily increased from 15.13% to 21.69% over the past 35 years. Both the PD ($y = 0.91x + 13.73$, $R^2 = 0.95$) and LPI ($y = 0.18x + 2.19$, $R^2 = 0.94$) of forested areas show a positive correlation with time, indicating an expansion in area and a strengthening in dominance.

The PD for shrublands continuously decreased ($y = -0.22x + 3.36$, $R^2 = 0.79$), but its LPI initially increased before decreasing. Compared to forests and grasslands, shrublands have significantly lower PI and LPI each year, suggesting that shrublands may not have received sufficient attention in long-term UGI construction and are highly susceptible to the impacts of urban agglomeration.

Grasslands show rich variations in PI and PD, but LPI negatively correlates with time ($y = -1.23x + 15.53$, $R^2 = 0.71$), indicating significant changes and a trend of decreasing dominance during the urban agglomeration process.

Water bodies have continuously increased in area ($y = 0.02x + 0.12$, $R^2 = 0.81$), while their PD has consistently decreased over time ($y = -0.01x + 0.06$, $R^2 = 0.69$), suggesting an increase in water body areas and a reduction in their fragmentation trend.

3.3. Spatiotemporal Distribution Variations of UGI

Influenced by natural geographical conditions and urban expansion patterns, UGI in the TJA is primarily distributed to the east, north, and west, with less presence in the central and southern areas (Figure 5). According to MSPA, UGI is classified into 7 landscape types (Table 1). Over the past 35 years, the core type has averaged 63.4% of the total UGI, followed by bridge (18.8%), loop (8.3%), perforation (4.1%), edge (3.8%), islet (2.8%), and branch (1.9%). The core dominate, mainly distributed in the mountainous regions of the east and west. During the urban agglomeration process, over 60% of UGI is located in Yangqu County (38.4%) and Yuci District (24.3%); the rest have an average UGI proportion ranging between 2% and 11.2%. In addition to the landscape base determined by natural geographical conditions, the size of administrative districts also affects the scale of UGI in different districts and counties.

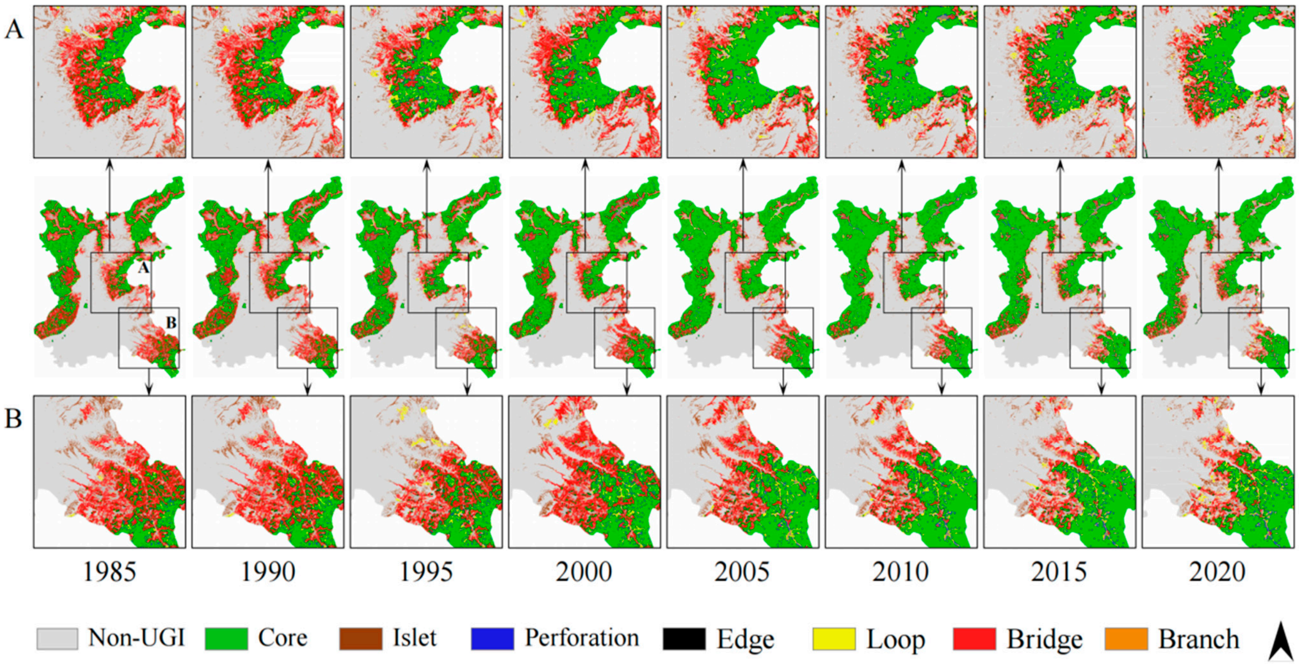

Figure 5. Spatiotemporal distribution variations of UGI in the Taiyuan–Jinzhong agglomeration. The UGI changes significantly in areas (**A**) (close to the center of Taiyuan city) and (**B**) (where Taiyuan borders Jinzhong in the south).

Table 1. The average Fluctuation Index of different types of UGI on the TJA.

Year	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	1985–2020
Branch	0.29	0.69	0.76	0.72	0.63	0.69	0.71	0.64
Bridge	0.06	0.16	0.44	0.28	0.28	0.47	0.44	0.31
Core	0.03	0.13	0.16	0.14	0.09	0.03	0.03	0.09
Edge	0.09	0.30	0.51	0.46	0.38	0.50	0.56	0.40
Islet	0.14	0.49	0.64	0.48	0.45	0.59	0.52	0.47
Loop	0.20	0.61	0.62	0.66	0.53	0.63	0.59	0.55
Perforation	0.14	0.45	0.54	0.51	0.53	0.53	0.49	0.46

Over time, core expanded continuously for 25 years from 1985, increasing from 50% to 73% of the total UGI. In the last decade, there has been a slight reduction, but it still accounts for 70% of UGI, indicating that core has an increasing dominance within UGI. Bridge, not only the second largest type of UGI but also the most significantly reduced, are primarily located near non-UGI. Bridge accounted for 31% of UGI in 1985 but reduced to only 11% in the subsequent 25 years. The proportions of the other six types in UGI are all below 10%, mostly located at the interface between non-UGI and UGI or around core. Except for minimal changes in branch, the other five categories have shown rich variations since 1990. For example, islet expanded significantly between 1990 and 1995 but has been continuously reducing over the last 20 years; edge have undergone complex changes since 1995, rapidly expanding in the last five years to 1.3 times their size 35 years ago. These findings indicate that changes within UGI mainly involve transformations between loop, perforation, edge, and islet.

Spatially, UGI changes significantly in areas close to the center of Taiyuan (the area A in Figure 5) and where Taiyuan borders Jinzhong in the south (the area B in Figure 5). Before 1990, various types were widely distributed in the mountains to the east and west of Taiyuan. From 1995, bridge and branch in the mountains regions significantly reduced, partially transforming into edge and perforated. In 2000, the southern part of the west mountain saw a significant reduction in bridge and branch, largely transforming into core, with many scattered perforation and edge appearing. Between 2005 and 2010, core located in mountainous regions continued to expand. However, by 2015, bridge, branch, loop, and edge all increased near core areas in mountains of the east and west. This trend continued until 2022, with most areas in the central and southern parts of west mountain transforming from core areas to bridge, branch, and other types. This suggests that the mountains to the east and west, while providing natural ecological barriers for the city, are also the closest large-scale UGI to the city center and thus may be more disturbed during the urban agglomeration process.

Additionally, the Yuci District to the southeast, located between Taiyuan and Jinzhong, had a fragmented UGI composed mainly of bridge, branch, islet, and edge before 1990 (Figure 5, area B). In 1995, the expansion of non-UGI areas significantly reduced bridge and branch or transformed them into edge. By 2000, the northern part of Yuci and the southeastern part of the east mountain in Taiyuan formed a clear connection, with many branch areas appearing and some aggregation. However, five years later, the expansion of non-UGI caused them to continuously reduce towards the southeast.

3.4. The Fluctuations of UGI Based on Morphological Spatial Pattern

By quantifying the fluctuations of UGI at five-year intervals, we observe significant short-term fluctuations across different types of UGI (Figure 6). Spatially (Figure 6a), the core type have maintained the most stability over the past 35 years, exhibiting low spatial heterogeneity in their fluctuations. Remarkably, 55.08% of core areas remained unchanged for more than 30 years, predominantly located in the center of UGI, far from the city center. The bridge and edge exhibited weaker fluctuations, particularly in regions adjacent to non-UGI regions. This suggests that urban expansion might have a lesser impact on them compared to changes within the internal structure of UGI.

Temporally (Figure 6b), the three types experiencing the strongest fluctuation over the past 35 years are branch (FI = 0.64), loop (FI = 0.55), and islet (FI = 0.47), indicating that they struggle to maintain a stable ecological function throughout the long process of urban agglomeration. Additionally, we used FI measured every five years, which quantifies the fluctuations of each UGI type at different stages. The study revealed that fluctuations across all UGI types were least pronounced before 1990. Between 1995 and 2000, the study area's UGI underwent the most intense fluctuations. During these five years, three types of UGI (branch, islet, core) reached their highest FI. Additionally, five UGI types (branch, islet, loop, perforation, edge) had an FI exceeding 0.5. It was also observable that each UGI type fluctuated at different stages. For example, fluctuations in core were very weak after 2010. A possible reason is the large-scale afforestation initiated in 1999, which formed stable patches after ten years. Conversely, fluctuations in branch and edge areas became increasingly strong, indicating that each morphological type of UGI does not fluctuate simultaneously.

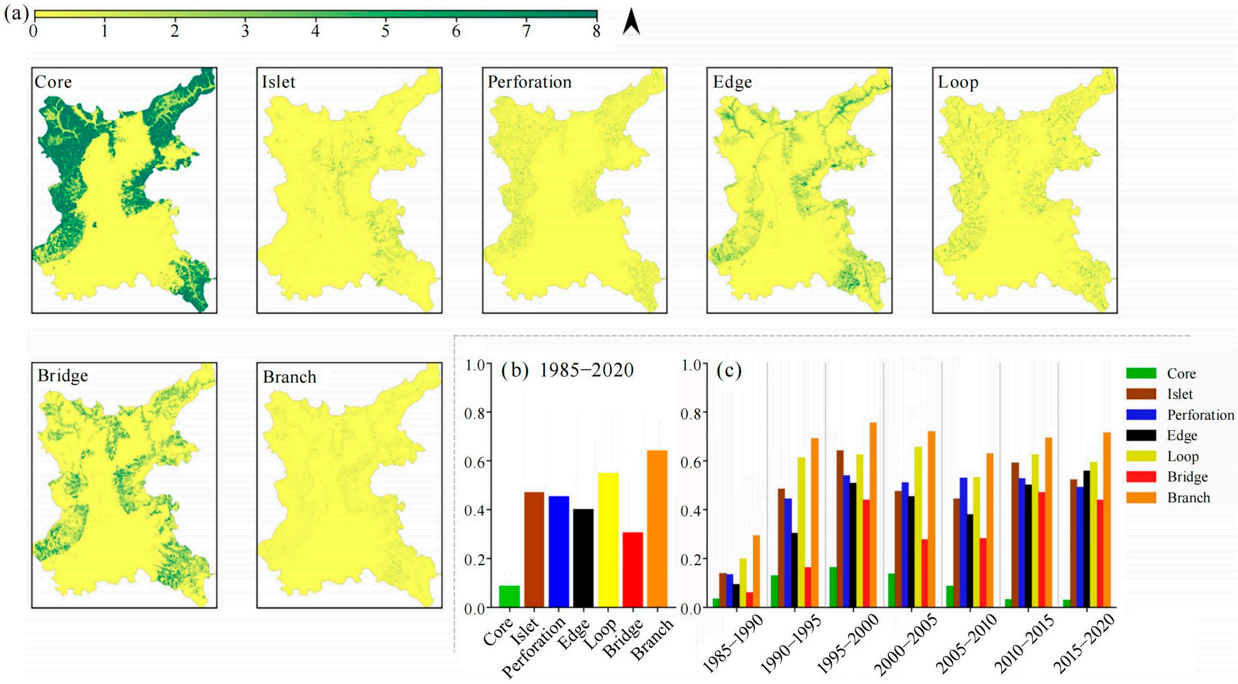

Figure 6. The fluctuations of UGI pattern in the TJA: the colors in (**a**) represent the frequency at which a specific type of UGI has appeared between 1985 and 2020. Yellow indicates areas that have never been classified as that particular type of UGI. Green, on the other hand, denotes areas that have consistently been identified as the same type of UGI throughout the study period. Bar charts reflect each type of UGI's Fluctuations Index (FI) between (**b**) the past 35 years and (**c**) every five years.

4. Discussion

This study, focusing on the rapidly agglomerating TJA (Figure 1), quantifies the progression of UGI regarding its quantity, pattern, and morphology. Findings indicate that while UGI has not diminished due to urban expansion, there is a trend towards a reduction in the number of patches and an increase in aggregation at the landscape scale. The internal composition of UGI has undergone complex spatiotemporal changes during urban agglomeration.

This study revealed that the land use of UGI is characterized by the expansion of forests within the TJA (Figure 3). Landscape diversity (SHDI) significantly increased between 1995 and 2000 (Figure 4a), likely due to the extensive implementation of the Grain-to-Green Program (GTGP) [50]. The study area is located in the eastern part of the Loess Plateau, which is one of the most serious regions of soil erosion in the world. To reduce erosion and enhance ecological safety, the Chinese government initiated the GTGP in 1999 [51]. Changes in landscape characteristics reflect the profound impact of this policy on urban land use around 2000. The GTGP has promoted the conversion of degradation lands (i.e., cropland and bare land) to vegetation-restored land [52]. So, more than 20 years of GTGP implementation have ensured that UGI has not been overrun by rapidly expanding urban areas since 2000 [50]. However, the increase in forest caused by GTGP led to changes in shrubs and grasslands in UGI's areas, especially after 2005. Previous studies have indicated that large-scale afforestation in the Loess Plateau region might exacerbate evapotranspiration effects. This creates new threats of ecological safety, such as excessive groundwater consumption and land degradation [53]. The native and secondary shrub forests are more suitable for the study area [54]. Thus, we believe that the further expansion of artificial forests should be controlled. We recommend emphasizing the protection of existing shrubs and grasslands in ecological restoration.

The MSPA result showed that 1995–2000 was the period with the highest overall fluctuation in UGI (Figure 6b) because it was the initial stage of the GTGP implementation. This indicates that large-scale changes in land use caused by urban planning and ecological restoration strategies are reflected in the fluctuations of UGI morphology. Furthermore, the core type has been continuously expanding over the past 35 years, with weak fluctuations (Figure 6). This result validates the urban managers' control over UGI construction during the process of urban agglomeration. In the decade following the implementation of GTGP, many newly planted forests formed stable patches. The local government has given strict protection to the newly created forest in this program, such as prohibiting private logging or reclamation, and prohibiting industrial occupation. These patches are relatively large and highly homogeneous. In 2006, the Taiyuan municipal government transformed 9.48 km^2 of restored forest land into a park in western mountainous regions, called "Urban EcoPark" [55]. Primarily composed of these patches, the park can ensure the stable provision of ecological functions as habitats and species pool in urban clusters with prominent human-land conflicts. Except for the core type, other types of UGI exhibit significant fluctuations. The bridges, branches, and loop areas were reduced in different periods, which verified the changes in landscape connectivity and heterogeneity. For example, the areas of bridge and branch have continuously reduced, accompanied by significant fluctuations in the past decade (Figure 6b). It means that the ecological corridor function of UGI has been weakened in the process of spatial agglomeration in the TJA. This would have some negative impact on biological migration and energy flow in urban clusters, which is detrimental to the formation of a safe and stable ecological network [23,56]. It also indicates a decline in accessibility of UGI, suggesting that residents residing in urban centers may face increasing challenges in experiencing the benefits and amenities provided by UGI [57].

To avoid ecological crises and unsustainable expansion [58,59], the UGI in urban clusters has received significant attention from managers and landscape designers [60–62]. Based on our findings, we strongly recommend that future planning not only focuses on preventing the loss of UGI area but also emphasizes the internal structure and characteristics of UGI. By examining the spatial fluctuations of UGI (Figure 6a), we observed that some types of UGI are more susceptible to internal changes within UGI (rather than urban expansion). For the TJA, we suggested: (1) Maintaining the role of the eastern and western mountainous regions as the ecological barrier zones. The impact of potential land use change on ecological security pattern (ESP) was considered [43]. It is advisable to improve vegetation structure and enhance landscape heterogeneity by supplementing diverse local plants and shrubs. This approach will enhance the habitat quality within the core and facilitate its function of species pool for fostering greater biodiversity. Additionally, we believe that prioritizing the establishment of linear landscapes within UGI is essential; for instance, constructing buffer zones along road edges with the objective of creating semi-natural habitats. Similar approaches, such as forming loops, can be employed to enhance ecological processes and energy flow in core patches. (2) Planning riverside parks and greenbelts strategically. It is crucial for Yangqu County in the northern region and Yuci District in the southern region. The fluctuations of bridge and branch types reflect the inability of ecological corridors to sustain its function. Currently, the ecological corridor between the northern core area and non-UGI areas is notably insufficient. Yuci District, a new urban area formed during the agglomeration process of two cities, requires the timely integration of ecological corridors into urban planning. This approach can prevent the disruption of ecological functional connections between the two cities due to excessive land development. (3) Adding small parks and gardens in non-UGI areas and focusing on the construction of small patches in UGI areas. This study has identified a continuous reduction and high levels of fluctuation in islet and perforation patches over the past decade. Increasing such small patches can enhance "steppingstones" and transitional zones, promoting biodiversity while also improving the equitable access of UGI's benefits for urban residents. These measures can help in creating a more connected and biodiverse urban ecosystem. Urban managers can reduce ecological risks and enhance ecosystem services by planning and constructing green spaces carefully. All of these efforts will help strike a balance between rapid urban development and ecological security.

This study can provide valuable insights into how to plan UGI for more cities experiencing ongoing processes of urbanization and agglomeration. It represents a crucial strategy for urban clusters to address ecological crises. We strongly recommend that cities in rapid expansion and agglomeration not only focus on maintaining the UGI's area but also place a high emphasis on the landscape characteristics and morphological changes in UGI. Future planning of UGI should incorporate changes across spatial and temporal scales to foster practices aimed at enhancing ecological safety and sustainability. However, our study has limitations. We recognize that the morphological changes in UGI may lead to an increasing disconnection between urban residents and UGI. These changes can also potentially affect the quality and services of ecosystems. We will continue to explore these issues in the future. We also call for more scholars to focus on the characteristics, morphology, and evolution of UGI, seeking reliable methods to balance rapid urban economic development with ecological protection.

5. Conclusions

Taking the TJA as a case study, this study explored the spatiotemporal distribution and fluctuation of UGI amidst swift urban agglomeration. The results indicate that during the urban agglomeration process over the past 35 years, the TJA has maintained the extent and habitat function of UGI, with a significant presence of core. While urban expansion did not directly reduce the quantity of UGI, it led to complex changes in landscape pattern and morphology. The decrease in size or notable variation in smaller UGI patches, like branch, loop, and islet, impair the efficacy of ecological corridors and steppingstones, negatively impacting the cohesion of urban ecological networks. By quantifying the fluctuation across various morphological types of UGI at different periods, we verified that the implementation of the GTGP promoted the expansion of UGI and the stability of core. Although the newly planted artificial forests may encroach upon some native vegetation such as shrubs, introducing new ecological risks, the spatiotemporal characteristics and fluctuations of UGI confirmed that the implementation of GTGP at different stages influenced the morphology of UGI. This could alter the ecological network constituted by UGI. Therefore, urban managers should bolster UGI's role in ecological safety by implementing large-scale ecological management or urban planning strategies, to avoid the ecological crises of highly agglomerated cities.

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Appendix A

Table A1. MSPA types and the ecological meanings.

Landscape Class of UGI	Ecological Meaning	Typical Facility
Core	Large patches located at a certain distance from the boundary, providing contiguous habitats as source areas in ecological networks, crucial for constructing an ecological security pattern and protecting biodiversity.	Nature reserves, forest, wetlands, big parks, etc.

Table A1. *Cont.*

Landscape Class of UGI	Ecological Meaning	Typical Facility
Islet	Isolated, unconnected small patches where it is relatively challenging to initiate material and energy exchange or species migration, but often functioning as "steppingstones".	Garden, etc.
Perforation	Edges of interior patches, typically found in zones of the core area degraded due to disturbances, serving a transitional role to some extent.	Road boundaries within the core area, etc.
Edge	Transition zones between the core area and the primary non-green infrastructure areas, usually functioning as buffer zones.	Greenbelts around parks, etc.
Loop	Narrow strips connecting at least one core area, generally characterized as ecological corridors, enhancing ecological processes like species migration and energy flow within large patches.	Road boundaries within the protected areas, greenbelts, etc.
Bridge	Non-core UGI patches connecting at least two different core areas, exhibiting a narrow and elongated shape, and characterized as ecological corridors.	Urban riverbank parks, road greenbelts, etc.
Branch	Collections of non-core of UGI areas in UGI, with only one end connected to an edge, bridge, loop, or perforation, serving as a passage for species migration and energy flow between the core area and non-UGI patches.	Road greenbelts connecting parks and residential areas in the city.

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