HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

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SPATIOTEMPORAL EVOLUTION AND SUSTAINABLE LANDSCAPE PLANNING OF PERI-URBAN AREAS IN POLYCENTRIC CITIES

THE PH.D. DISSERTATION

DOI: 10.54598/007450

SHI ZHEN

BUDAPEST

2025

The PhD School

Name:	**Hungarian University of Agriculture and Life Sciences**
	Landscape Architecture and Landscape Ecology
Discipline:	Agricultural Technology
Head:	**Dr. László Bozó**
	University professor, DSc, MHAS
	MATE Institute of Horticultural Science
	Department of Soil Science and Water Management
Supervisor(s):	**Dr. Krisztina Filepné Kovács**
	Associate professor, PhD
	MATE Institute of Landscape Architecture, Urban Planning and Garden Art
	Department of Landscape Planning and Regional Development

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Approval of the Head of Doctoral School **Approval of the Supervisor**

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LIST OF ABBREVIATIONS

ANOVA - analysis of variance

AREA_MN - Mean Patch Area

CONTAG - Contagion

CUA - Central Urban Area

GIS - Geographic Information System

ID - Imperviousness Density

LLR - Log-Likelihood Ratio

MSPA - Morphological Spatial Pattern Analysis

NDEI - Normalized Difference Expansion Index

NLI - Nighttime Light Intensity

PARA_MN - Mean Perimeter-Area Ratio

PCLA - Per Capita Land Area

PD - Patch Density

PNL - Proportion of (semi-)natural land

PLAND - Percentage of Landscape

POI - Point of Interest

PR breakpoints - Peri-urban to Rural breakpoints

PRISMA-P - Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols

PROX_MN - Mean Proximity Index

PUAs - Peri-urban areas

PU breakpoints - Peri-urban to Urban breakpoints

PULs - Peri-urban landscapes

RP breakpoints - Rural to Peri-urban breakpoints

SDG - Sustainable Development Goal

SHDI - Shannon's Diversity Index

TECI - Total Edge Contrast Index

TOD - Transit-Oriented Development

TVEs - Township and Village Enterprises

UGMPs - Urban Growth Management Policies

UK - United Kingdom

UP breakpoints - Urban to Peri-urban breakpoints

USA - United States of America

WOS - Web of Science

1.INTRODUCTION

1.1 Background

1.1.1 Global peri-urbanization phenomena

Global urbanization has led to the accelerated expansion of urban development in many regions. A key feature of urbanization was the global shift from a predominantly rural population to a predominantly urban population. In 1950, only 30% of the world's population lived in urban areas, but by 2021, this proportion had risen to 56%, and it is projected to increase further to 68% by 2050 (United Nations, 2014). A considerable portion of the urban population and territorial growth occurs at the urban periphery (Friedmann, 2011, Leaf, 2016, Tan et al., 2024, Webster, 2002). For instance, from suburban expansion in large cities to the agglomeration of peri-urban and rural areas due to the growth of peripheral villages and towns near large cities (Qadeer, 2004, Singh and Narain, 2020). As a result, an increasing number of spaces worldwide blur the boundaries between urban and rural areas (Chelcea and Moss, 2022, Leaf, 2016, Petrovici and Poenaru, 2025, Wandl et al., 2014a). This process is referred to as peri-urbanization.

This peri-urbanization process is primarily driven by urban characteristics, such as the spillover of urban population and economic activity. Therefore, most people consider the phenomenon of peri-urbanization as a key analytical point for observing urbanization. It is widely acknowledged that urban growth rates are the highest in developing countries (Akaateba, 2023, Ayambire et al., 2019, Dhanaraj and Angadi, 2021, Paul et al., 2021). Driven by industrialization and development policies, the peri-urban areas (PUAs) around Asian metropolises, in particular, represent interfaces of rapid urbanization. PUAs in developing countries undergoing urban transformation have attracted significant research interest, especially since the 1980s (Dadashpoor and Ahani, 2019). Cohen (2006) reported that in developing countries like India, the development of PUAs around urban centers had occurred widely (Singh et al., 2024).

In most literature, PUAs are defined through multiple characteristics. Geographically, they are situated at the intersection of urban and rural areas, often where key infrastructure such as roads and economic centers are present (Davis et al., 1994). Demographically, PUAs typically host a mix of urban residents, migrants from other rural areas, and local rural populations, resulting in a blend of lifestyles and livelihoods. In terms of land use, PUAs are generally characterized as a hybrid of urban and rural land uses. Functionally, they are increasingly recognized as multifunctional and mixed-use spaces (Butt, 2024, Holmes, 2008, Hugo, 2017). Ford (1997) described these areas as urban-rural continua, where these regions shift from urban to rural, with urban characteristics becoming less prominent and rural characteristics becoming more dominant. The ongoing and uneven process of urbanization in PUAs has led to a struggle between urban and rural forces, resulting in the distinct characteristics of these areas—hybridity and dynamism.

It is precisely these characteristics of PUAs that grant them unique value in urban studies. On the one hand, the urban-rural dynamics within PUAs involve multiple pressing issues. For example, Adam (2020) explored PUA-related conflicts in Ethiopia from a political economy perspective, identifying the state, private sector, and local communities as the primary stakeholders in competition for interests. Seifollahi-Aghmiuni et al. (2022) reviewed land degradation in PUAs of Southern Europe, proposing that PUAs serve as a new *laboratory* for studying the intrinsic relationship between humans and nature, as well as a socio-environmental system adapting to rapid socio-economic transformations. Chettry (2022) analyzed the evolution of PUAs within the Thiruvananthapuram Urban Agglomeration in India, finding that discontinuous low-density development dominated the expansion of PUAs. Across these global studies, PUAs have been shown to play a crucial role in optimizing urban development, promoting rational land use, and improving ecological environments. These contributions are also the key reasons why PUAs have become a focal point in academic research.

On the other hand, PUAs, which emerge under the influence of urban, economic, and social processes of varying scales, have yet to receive a universally accepted definition. Moreover, these areas are often located between different administrative regions and may constitute part of a metropolitan area, a functional urban region, or a segment of a city (Spyra et al., 2025). Consequently, their boundaries remain ambiguous (Gonçalves et al., 2017). Amirinejad et al. (2018) examined PUAs in the context of Australia, highlighting the ambiguity in their definition, characteristics, typology, and policy formulation and implementation. These ambiguities indicate that further research on PUAs is still necessary.

1.1.2 The peri-urbanization in China

Since the reform and opening up in 1978, China has undergone rapid urbanization. By 2021, the urbanization rate in China reached 64.7%. The expansion of urban areas has led to an increasing number of transitional zones between urban and rural areas (Li, 2013). This peri-urbanization phenomenon is particularly prominent in economically developed cities, such as Beijing and Shanghai (Zhao et al., 2009, Tian et al., 2017a, Li et al., 2021).

In these cities, the significant urban-rural disparity has facilitated the development of PUAs, and this disparity can be traced back to China's dual urban-rural structure. The primary manifestations of this dual structure include the differentiated household registration system and land ownership system. Urban residents enjoy more comprehensive social welfare, including education, healthcare, and housing benefits, but they do not have individual land ownership. Rural residents, on the other hand, have the right to use collectively owned rural land but face long-standing disadvantages in accessing education, healthcare, and social security resources, while the market mobility of their land remains restricted.

These systems institutionalize the unequal distribution of resources between urban and rural residents and ensure that this distribution remains unaffected by population mobility (Li, 2013). As a result, rural-to-urban migration faces numerous obstacles, making urban peripheries particularly attractive to these migrants. Meanwhile, as urban areas continue to encroach upon rural regions, the extent of these peripheral zones is gradually expanding. With the influx of population and the expansion of space, PUAs have progressively grown and developed.

From an international perspective, peri-urbanization is not unique to China, but what distinguishes China is its large rural population base and strong institutional constraints. Other developing countries, such as India and those in Latin America, also experience similar forms of incomplete urbanization, though the expressions and driving factors may differ.

1.1.3 Sustainable planning of peri-urban landscapes (PULs)

The interaction between urban and rural landscapes within PUAs has shaped unique peri-urban landscapes (PULs), highlighting the coupled and coordinated relationship between human activities and natural habitats within limited space. At the same time, PULs are highly susceptible to the dual pressures of urban expansion and natural disasters, posing significant challenges (Aguilar et al., 2022, Chettry, 2022, Salem and Tsurusaki, 2024). According to *Sustainable Development Goal (SDG) 11: Sustainable Cities and Communities*, proposed by the United Nations in 2015, PULs, as an increasingly prevalent landscape type in cities, should undoubtedly incorporate sustainability as a fundamental objective in planning (Hopkins, 2012).

Moreover, many scientists believe that enhancing sustainability is the primary goal of landscape and regional planning, including planning for the conservation, protection, and rational use of land and natural resources (Forman, 1995). Sustainability is multidimensional, involving the maintenance of spatial patterns of land use and natural resources that are beneficial to ecological, social, and economic outcomes. Therefore, appropriate tools are needed to apply sustainability principles to planning and management (Leitao and Ahern, 2002).

In fact, PULs contribute to the sustainability of the entire urban area and provide regenerative potential for urban systems. Typically, PULs provide a range of resources, including natural resources, food production, and urban water supply, to contribute to urban sustainability and resilience (Butt, 2024). However, urbanization has had a significant impact on the sustainability of PULs. Potapov et al. (2022) analyzed global land cover changes and found that between 2000 and 2020, the built-up area increased by 50%. Urbanization demands an increasing supply of residential, commercial, and transportation infrastructure (Kudas et al., 2022). This often results in the occupation of natural areas such as farmland, open spaces, or reservoirs to meet these needs (Byomkesh et al., 2012, European Commission, 2012, Gardi et al., 2015), leading to the loss of natural PULs (Spyra et al., 2021) and a reduction in ecosystem services (Rozas-Vásquez et al., 2022). The expansion of transportation infrastructure further fragments ecosystems, creating challenges for landscape restoration and biodiversity conservation (Crossman et al., 2007). Moreover, new infrastructure facilitates the spread of low-density and dispersed building surfaces, which is a hallmark of urban sprawl.

According to the European Environment Agency’s report, these trends of reduced landscape sustainability will continue due to the high demand for developable areas in PUAs. This phenomenon is not limited to Europe; it is a global issue (Ronchi et al., 2021, Schneider and Woodcock, 2008, European Environment Agency, 2006, Spyra et al., 2025). This trend threatens the natural PULs, as they are increasingly transformed into artificial landscapes, contrasting sharply with sustainable urban forms (Jabareen, 2006).

1.2 Concepts of terminology

(1) Urbanization and urban sprawl

Over the past two hundred years, the global landscape has undergone significant transformations, most notably due to population growth and the essential infrastructure required to meet human needs, commonly referred to as urbanization. Urbanization is a complex socio-economic, political, and technological process, with no single universal model from which a definitive conclusion or definition can be derived. The dynamic development of cities worldwide is driven by factors such as population growth, economic development, migration, and shifts in resident preferences (Cegielska et al., 2018b, Paraschiv, 2012, Grabowska et al., 2024).

Urbanization often entails expansion beyond planned city limits and the transformation of rural land into urban land to accommodate population growth. In this process, cities extend further than initially anticipated (utilizing rural land that would otherwise remain undeveloped), leading to urban sprawl. Urban sprawl is a form of unplanned, incremental urban development characterized by low-density, mixed land use (European Environment Agency, 2006).

(2) Peri-urbanization and peri-urban areas (PUAs)

Research indicates that peri-urbanization is a byproduct of urbanization (Lebrasseur, 2024). Peri-urbanization is an ongoing dynamic process characterized by the artificialization of landscapes beyond the urban periphery (Zasada et al., 2011). This process involves the expansion of the urban fabric into non-urban areas rather than utilizing existing urban built-up areas (Spyra et al., 2025), as well as evolving patterns of land use and livelihoods within these transitional zones (Follmann, 2022, Nilsson et al., 2013, Salem and Tsurusaki, 2024). Under the unique institutional framework of China, the phenomenon of peri-urbanization is not only manifested in terms of landscape and spatial structure, but also in the large number of incompletely urbanized populations that exist during the urbanization process (He and Huang, 2012).

Typically, PUAs are described as *gray areas* (Iaquinta and Drescher, 2000) or as *transitional and temporary spaces* (Bartels et al., 2020). PUAs are generally defined as transitional zones that emerge at the periphery of large urban regions and in rural areas with significant non-agricultural industries (He and Huang, 2012). These areas are characterized by a complex interweaving of urban and rural landscapes, with a high degree of functional integration. In PUAs, the industrial structure is mainly dominated by manufacturing, with the status of agricultural economy significantly declining. Along with this, there has been a substantial increase in the number of migrant workers and an intensification of the fragmented spatial pattern (Tian and Ge, 2011).

(3) Peri-urban landscapes (PULs)

PULs are dynamic mixtures of natural and artificial land cover, as well as land use associated with green open spaces, farmland, and artificially developed areas with varying degrees of urbanization (Amirinejad et al., 2018, Spyra et al., 2021). Based on the land use data, the PUL in this study is classified into four categories: agricultural landscape (agricultural land), green landscape (forest and grassland), water landscape (water body), and artificial landscape (built-up land).

(4) Landscape morphology

Landscape morphology refers to the external spatial expression of a landscape, including its geometric shape, spatial distribution characteristics, and visual perception properties. The morphological approach is commonly used in landscape analysis (Denis and Marius-Gnanou, 2010, Lynch, 1960, Lebrasseur, 2024).

(5) Landscape structure

Landscape structure refers to the relationships and organizational forms between the components within a landscape, including spatial patterns and functional connections. Landscape Metrics can serve as useful concepts and analytical tools for understanding the structure of PULs (Leitao and Ahern, 2002).

(6) Sustainable planning

Determining appropriate management and governance strategies for the correct development of urban areas is a significant challenge in the Anthropocene era. In response to these challenges, the United Nations incorporated innovative management and governance strategies in the SDGs for 2030 (Colglazier, 2015). The 11th goal of the SDGs states: “Make cities and human settlements inclusive, safe, resilient, and sustainable,” and aims to promote sustainable urban planning and management by improving environmental infrastructure, developing a sustainable construction industry, and promoting sustainable energy and transportation systems (Marzialetti et al., 2023).

(7) Polycentric City

Based on the original urban center, new suburban centers continue to expand and develop, creating a unique urban form and pattern in the landscape, referred to as polycentric development (Sýkora et al., 2009). Unlike the monocentric urbanization model centered around a single urban core, polycentric urban regions are typically defined by their spatial structure, which includes various subcenters or multi-core structures (Finka and Kluvánková, 2015, Lebrasseur, 2024).

As a multi-scale spatial planning concept, polycentrism has become the preferred spatial form for adapting to urban growth in most regions (ESPON, 2017). However, like most urban expansions, non-urbanized landscapes are vulnerable to change. Moreover, polycentric urbanization often leads to land cover changes and landscape fragmentation (Barros et al., 2018, Grigonis, 2013, He et al., 2020, Lebrasseur, 2024).

(8) Compact city

A compact city is characterized by high population and building densities, as well as a mixed-use land layout. It promotes the redevelopment and intensification of existing urban areas to limit urban sprawl and protect surrounding agricultural and natural lands. A compact city offers numerous advantages, such as reducing commuting distances, enhancing social interaction, and improving the efficiency of infrastructure services, thereby contributing to the achievement of sustainable development goals. However, the compact city model also faces several challenges, including potential declines in quality of life, the exacerbation of social problems, and increased environmental pressures (Thomas and Cousins, 1996).

1.3 Objectives and questions

1.3.1 Research objectives

Space and time are fundamental dimensions of sustainable planning (Forman, 1995, Golley and Bellot, 2012). The overall objective of this study is to quantify the spatial extent of PUAs in polycentric cities, analyze their spatiotemporal evolution, and propose guidelines for sustainable PUL planning. Within this overarching objective, a series of sub-objectives are included:

(1) Summarize the research progress and gaps in PUAs through a literature review;

(2) Compare the accuracy and applicability of three quantitative methods (Threshold method, Breakpoint Clustering, and Multilayer Perceptron model) in identifying PUAs within the study region;

(3) Conduct a quantitative analysis of the spatiotemporal evolution of PUAs from 2000 to 2020, focusing on changes in spatial transitions, expansion patterns, land use, and location types;

(4) Examine the differences among PUAs, urban areas, and rural areas along the urban-rural gradient in terms of construction, economy, naturalness, and population;

(5) Analyze the morphology of PUAs and PULs using Morphological Spatial Pattern Analysis (MSPA);

(6) Determine the structural characteristics of PUAs and PULs in terms of composition and configuration based on Landscape Metrics;

(7) Explore the multifaceted driving factors behind the evolution of PUAs;

(8) Propose specific PUL planning guidelines based on the context of the study area.

1.3.2 Research questions

Corresponding to the research objectives, I proposed the following research questions:

(1) What are the global research trends and hotspots related to PUAs? What advancements and gaps exist in the identification of PUAs and the PUL planning?

(2) Given the same multi-source indicator system and study area, how do the accuracy and applicability of the three quantitative methods, Threshold method, Breakpoint Clustering, and Multilayer Perceptron model, compare in identifying PUAs?

(3) From a spatiotemporal perspective, what are the characteristics of PUAs in polycentric cities in terms of spatial transition, expansion patterns, land use changes, and locational types?

(4) How do PUAs differ from urban and rural areas in terms of construction, economy, naturalness, and population? Are there significant differences in these characteristics among PUAs of different locational types?

(5) How do the morphological evolutions of PUAs and PULs manifest?

(6) What structural characteristics do PUAs and PULs exhibit in terms of composition and configuration?

(7) What factors influence the evolution of PUAs and PULs in polycentric cities?

(8) Based on the existing peri-urbanization challenges, what PUL planning guidelines can be derived from global experiences?

1.4 Research significance

In this study, I provided theoretical and case-based references for the research on PUAs worldwide. Through a series of quantitative analyses, from the identification of PUAs to their characteristics, morphology, structure, and driving factors, I established a step-by-step theoretical foundation for in-depth studies on PUAs and PULs. These analyses help to distinguish the characteristics of PUAs from those of urban and rural areas, contributing to a rational planning of PULs.

As potential sites for urban expansion, the spatiotemporal evolution of PUAs reveals the dynamic process of urban encroachment into rural areas and indicates future development trajectories. This, in turn, elucidates the relationship between urban expansion and peri-urbanization. Given the global trend of dispersed urban development, this study offers insights into the evolution and planning of PUAs in polycentric cities, addressing a critical research gap in this domain.

For policymakers and planners, PUAs serve as strategic zones for mitigating urban sprawl and enhancing urban land use efficiency. Moreover, leveraging large-scale spatiotemporal geospatial data to assess PUA expansion and its impact on urban environmental sustainability and livability is a crucial consideration for developing effective PUA management policies (Sahana et al., 2023b). Therefore, delineating the spatial extent and spatiotemporal evolution of PUAs will aid policymakers and planners in planning, regulating, and monitoring these regions while predicting their future development trajectories. These efforts are essential for promoting sustainable PUL planning, optimizing land use distribution, and bridging the urban-rural divide.

The PUL planning guidelines I proposed offer valuable insights for policy formulation and urban planning concerning PUAs. As PUAs remain a blind spot in existing policies and planning frameworks, emphasizing their critical role in urban development will help elevate their importance in future policymaking and planning processes, ultimately contributing to their scientifically informed and sustainable development.

1.5 Research methodology

I primarily collected diverse data required for this study through literature review, case studies, remote sensing imagery, and field investigations. These data were employed at different stages of the research using various analytical methods. For instance, data obtained from the literature review were analyzed through bibliometric and text analysis, with the resulting insights informing both the initial and final stages of the study. Meanwhile, data gathered through case studies, imagery, and field surveys were utilized in Geographic Information System and statistical analyses, forming the core component of this research.

1.5.1 Data collection methods

(1) Literature review

In the initial phase of the study, a literature review was conducted to summarize global research trends and key themes related to PUAs. Through this review, the challenges in selecting identification methods for PUAs and the limitations in the quantitative study of PULs were identified, thereby highlighting the significance of this research.

In ***Section 4.7*** on sustainable PUL planning, a literature review was also conducted to compile global experiences in sustainable PUL planning, serving as a reference for guiding regional and local planning.

(2) Case study

At the regional level, I selected Zhengzhou as a case for comparing PUA identification methods and analyzing spatiotemporal evolution. Zhengzhou not only represents a typical city in developing countries that has undergone rapid urbanization with significant peri-urbanization, but its polycentric structure also provides more possibilities for studying the spatiotemporal evolution of PUAs, providing a reference for other polycentric cities.

At the local level, three representative towns were selected to explore the challenges faced in the peri-urbanization process and the corresponding planning objectives and tools.

(3) Remote sensing imagery and field investigation

The majority of the data in this study are derived from remote sensing imagery, such as Landsat series images and nighttime light imagery. These images are used to collect information on land use changes, nighttime light intensity, population distribution, and other relevant factors within the study area. To visually demonstrate the spatiotemporal evolution of PUAs in the case study, this research utilized historical imagery from Google Earth Pro and historical street views from Baidu Maps to understand past PULs. Additionally, field investigations were conducted to survey the current status of PUAs, providing a foundation for developing sustainable planning based on the existing conditions.

1.5.2 Data analysis methods

(1) Bibliometric analysis

This method is primarily applied in ***Chapter 2***, the literature review. The analysis is conducted using CiteSpace software. Bibliometric analysis enables the visualization of research trajectories and trends, providing a clearer understanding of the existing research hotspots and gaps.

(2) Text analysis

Through a literature review, relevant studies on specific topics were selected, including research on PUA identification and PULs. These studies were then subjected to text analysis. By analyzing the literature on PUA identification, I summarized widely applied or innovative identification methods, providing a reference for selecting the identification approach. Furthermore, an analysis of PUL research helped identify commonly used research methods and summarize planning and management experiences from case studies, which serve as the foundation for further analysis and discussion in this study.

(3) Geographic Information System (GIS)

In the 1970s, Geographic Information Systems (GIS) emerged as a crucial planning tool (Leitao and Ahern, 2002). In this study, GIS analysis is the primary analytical method. I spatialized various indicators of PUAs through GIS and visualized the identification results. Subsequent analyses of PUA characteristics, morphology, and structure are also conducted using GIS to achieve spatialization and visualization.

(4) Statistical analysis

Statistical analysis is the most commonly used method for analyzing the spatiotemporal evolution of PUAs. By statistically examining the spatial and land transitions of PUAs, the evolving trends of PUAs can be clearly understood. Additionally, when analyzing the characteristic differences of PUAs, I employed the one-way analysis of variance (ANOVA) and post hoc analysis.

1.6 Framework of the dissertation

This dissertation consists of six chapters (***Figure 1.1***):

Chapter 1 provides the basic background of the study and offers definitions for key terms. Based on the research objectives, the research questions are presented, highlighting both the theoretical and practical significance of the study. The chapter then outlines the research methods. Finally, an overall framework for the dissertation is established to facilitate understanding.

Chapter 2 reviews the literature on PUAs, summarizing global and China-specific research trends and key topics. The literature review provides the theoretical foundation for this study and identifies gaps in current PUA research, further emphasizing the research's significance.

Chapter 3 outlines the materials and methods used in this study. It begins by detailing the process of acquiring and processing data related to Zhengzhou. The chapter then provides a comprehensive explanation of the methods for identifying PUAs, spatiotemporal analysis of PUAs, gradient zone analysis, morphological spatial pattern analysis, and Landscape Metrics. Finally, the chapter presents the planning framework for PULs.

Chapter 4 presents detailed research results and discussions, organized into seven sections. The first section compares different PUA identification methods, from which multi-year PUA identification results for Zhengzhou were derived, along with insights into spatial transitions, expansion patterns, location types, and land use changes. Next, the study visualizes the evolution of PUA's multidimensional characteristics along urban-rural gradient zones and quantifies the characteristic differences between PUAs using statistical methods. The chapter then defines the morphology and structure of PUAs and PULs, as well as their driving factors. Finally, based on existing experiences and the specific conditions of the study area, planning guidelines are proposed at both the regional and local levels.

Chapter 5 introduces eight new scientific findings. These findings are derived from the literature review in **Chapter 2** and the research results in **Chapter 4**. These contributions address some of the existing gaps in PUA research.

Chapter 6 summarizes the main findings of the study and provides answers to the research questions. Additionally, it provides limitations and recommendations for future research, aiming to advance PUA studies in a more scientific and efficient manner.

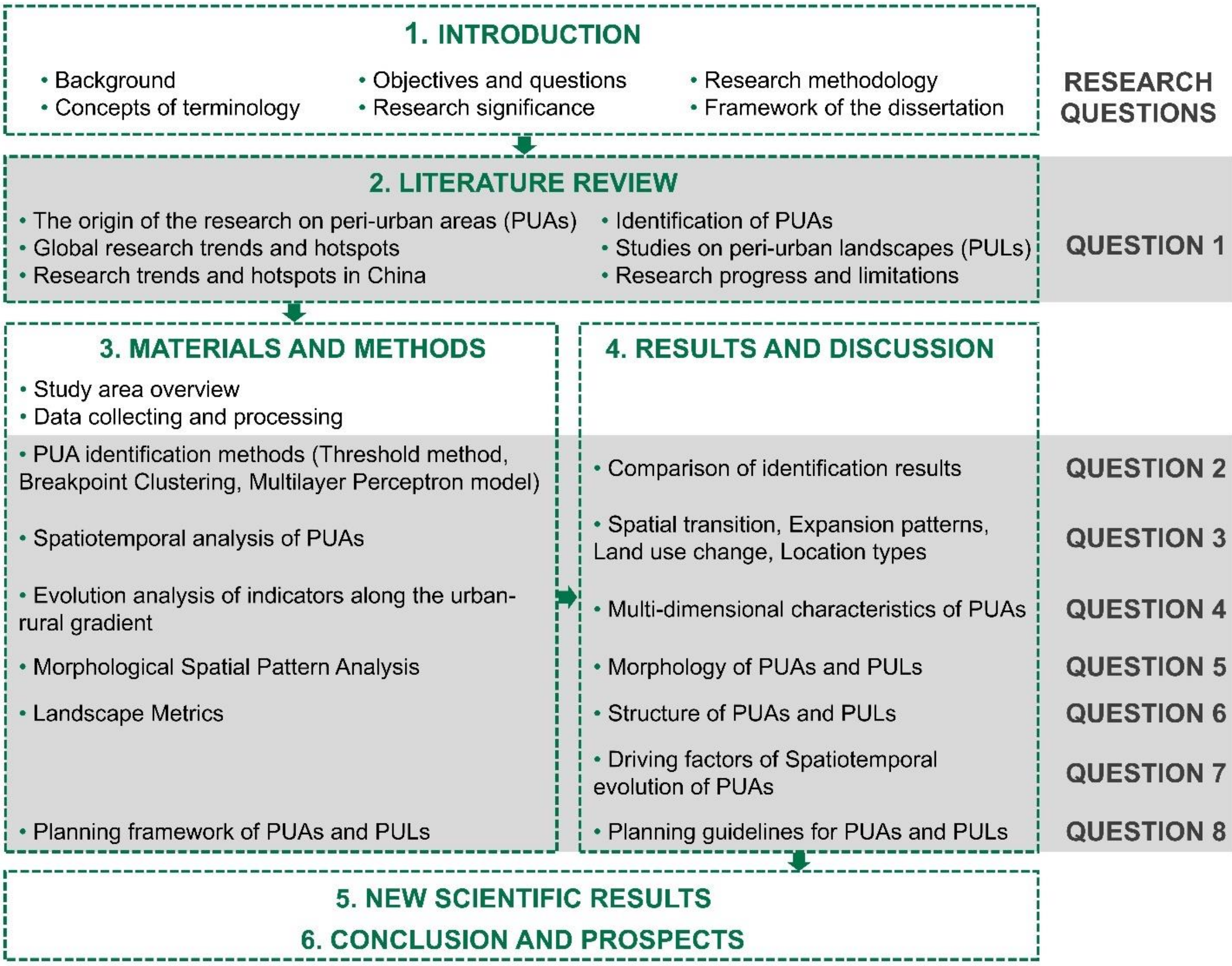

Figure 1.1: Framework of the dissertation.

2. LITERATURE REVIEW

In global literature, terms such as urban fringe, rural-urban fringe, suburban, and urban outskirts are also widely used as synonyms for peri-urban area (PUA) (Petrovici and Poenaru, 2025, Dadashpoor and Ahani, 2019). These concepts are linked to the theoretical context of their emergence, which has led to a fragmentation in the understanding of PUAs (Petrovici and Poenaru, 2025). The diversity of names and development for PUAs reflects the diversity of global PUAs. However, this does not necessarily indicate a lack of transferability in the concept and methods of PUAs (Tan et al., 2024). Follmann (2022) suggests developing peri-urbanization into an overarching concept to encompass the various concepts derived from different urbanization processes worldwide. Therefore, I use PUA as a general term for the aforementioned concepts and include all literature containing any of these terms in the scope of discussion.

2.1 The origin of the research on PUAs

The study of PUAs can be traced back to early 20th-century European urban morphology research. German geographer Louis (1936), while analyzing the urban structure of Berlin, observed that certain lands initially located on the periphery of the city were gradually absorbed by the expansion of built-up areas. Louis termed these areas *Stadtrandzonen*, providing one of the earliest designations for such zones. Later, Smith (1937) introduced the term *urban fringe* to describe built-up areas on the outskirts of cities. Andrews (1942) proposed the concept of the *rural-urban fringe* as a comprehensive term for the entire transition zone between urban and rural areas. This strong research trend initially concentrated in the United Kingdom (UK) (Conzen, 1960, Whitehand and Morton, 2003, Whitehand and Morton, 2004, Whitehand and Morton, 2006). Over the following decades, studies on this topic increased exponentially, and these concepts were further developed and refined. In general, these studies mainly focused on the transitional zones formed by the encroachment of urban areas into rural land during urban development.

The *French National Institute of Statistics and Economic Studies (INSEE)* later introduced the term *périurbanisation* to describe such transitional zones in France, which became the origin of the term PUA (Mbiba and Huchzermeyer, 2002). In 1998, a research report by the *University of Nottingham and the University of Liverpool* defined the *peri-urban interface* as a zone at the urban periphery where urban and rural elements intersect, mix, and interact (Phillips and Williams, 1999). In 2002, Douglas Webster's study on *peri-urbanization* in East Asia characterized it as a highly dynamic process and identified three key dimensions: changes in economic activities and employment, population growth, and spatial patterns (Webster, 2002). In 2007, the *Organization for Economic Co-operation and Development (OECD)* used the term *peri-urban* to describe urban expansion in Europe during the 1980s, referring to it as a *gray area* that is neither entirely urban nor rural (Piorr et al., 2011, Sahana et al., 2023a).

Gu and Xiong (1989) first introduced the concept of the *urban fringe* in China. Gu et al. (1993) conducted a preliminary study on urban fringe areas based on field investigations in major cities such as Beijing, Shanghai, Guangzhou, and Nanjing. With the acceleration of China's urbanization process, subsequent research on this topic increased, and the scope of the study expanded accordingly. Jia and Liu (2002) introduced the concept of *peri-urbanization* to China for the first time. They argued that China's peri-urbanization was primarily driven by investments in non-agricultural industries in suburban and rural areas. Since then, extensive research on PUAs has emerged in Chinese academia, focusing on key aspects such as economic transformation and the labor market, urban-rural integration and social security, social governance and public services, as well as cultural identity and social integration.

2.2 Overview of existing literature reviews

Based on the extensive research on PUAs, scholars have conducted several literature reviews: Ren and Zhang (2008) compiled a literature review on the definition of PUAs, aiming to establish a universally applicable delineation method from both qualitative and quantitative perspectives. Conzen (2009) compared studies on urban fringes across European countries, the United States, and Russia, highlighting significant differences in the number and morphology of urban fringe areas due to varying cultural contexts. Rong et al. (2011) summarized the development process and research trends of PUAs in China, emphasizing concerns in the early 21st century regarding spatial expansion, land use, and industrial development. Zhou and Xie (2014) concluded that research on PUAs in China started later than in Western countries but is evolving into an interdisciplinary field with a growing emphasis on ecology. Mortoja et al. (2020) systematically reviewed descriptions of PUAs and ultimately concluded that no universally accepted definition exists. Sahana et al. (2023a) compared characteristics of PUAs in the Northern and Southern Hemispheres, finding that PUA expansion in the Northern Hemisphere began earlier and is associated with social welfare and the pursuit of a better lifestyle, with residential purposes being the primary driver. In contrast, peri-urbanization in the Southern Hemisphere emerged later but has progressed more rapidly and unpredictably, mainly driven by industrial and corporate developments, with inadequate infrastructure and, in some cases, residential purposes. Tiwari and Vajpeyi (2023) conducted a bibliometric analysis of global PUA literature, identifying key research focuses on land use and land cover change, urbanization processes, and their environmental impacts. However, the study also pointed out a shortage of empirical analyses using GIS and remote sensing, as well as a lack of research from social perspectives.

The aforementioned literature reviews have summarized the research progress on PUAs. However, as the volume of related studies has multiplied, the timeliness of these reviews has diminished, making them less reflective of the current state of research. In recent years, there has also been a lack of systematic literature reviews utilizing bibliometric methods, which has limited a deeper understanding of the internal knowledge structure and the evolutionary relationships within this field. Moreover, with the increasing prevalence of peri-urbanization, PUAs have become a potentially important consideration in urban planning (Hopkins, 2012). Given these theoretical and applied contexts, it is necessary to employ new analytical techniques to conduct a more refined review of the PUA literature.

2.3 Literature review methodology

In this chapter, I used bibliometric analysis and text analysis to synthesize research on PUAs from both global and Chinese perspectives. In the bibliometric analysis, a systematic literature review technique is employed to ensure data transparency and the scientific rigor of the results. The literature search procedure is designed based on the guidelines of Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P). PRISMA-P provides a set of minimum items for inclusion in systematic reviews, ensuring a well-planned and transparent review process (Shamseer et al., 2015). The literature search procedure includes database retrieval, search strategy, inclusion criteria, and exclusion criteria.

The data I used were sourced from the Web of Science (WOS). WOS is one of the most commonly used and authoritative research literature search engines, covering the most important and influential academic research outcomes from around the world, making it an ideal database for literature reviews (Hosseini et al., 2018).

In terms of eligibility criteria, I considered several factors, including search terms, document types, language, and publication date. The search terms used in WOS were *peri-urban area*, *urban-rural fringe*, *rural-urban fringe*, *urban fringe*, *city fringe*, *rural-urban interface*, and *urban-rural interface*. Articles with any of these terms in their titles were selected. For inclusion criteria, only *articles* and *Proceedings Papers* available in full-text online were considered, with English as the language, and publications selected up until December 31, 2024. The exclusion criteria included *book chapters* and *data papers*.

In total, 2,014 articles were selected for the Global Database, covering the years from 1995 to 2024. Subsequently, literature from China was extracted from the Global Database based on the research region, forming the Chinese Database, which consists of 283 articles.

The Global and Chinese Databases were then imported into CiteSpace software for bibliometric analysis. CiteSpace is a visualization-based citation analysis software that provides researchers with a scientific and efficient method to replace traditional literature reviews, allowing them to avoid spending excessive time reading and conducting statistical analysis (Chen, 2006, Kim et al., 2016). I selected the Node Types of *Country* and *Keyword* for co-occurrence analysis. The Log-Likelihood Ratio (LLR) algorithm was then applied to perform keyword clustering analysis, evaluating the co-occurrence significance of keywords across different clusters. This approach helps identify the evolution of research topics over specific time periods (Kim et al., 2016).

Finally, I conducted a text analysis on articles related to PUA identification and peri-urban landscapes (PULs). The commonly used PUA identification methods and emerging technological approaches from past research were summarized, along with the frequently employed research methods for PULs, highlighting their commonalities and regional characteristics.

2.4 Global research trends and hotspots

2.4.1 Publication trends

After conducting a visual analysis of the countries in the Global Database, it was found that China has the highest number of publications. The USA, India, Australia, Italy, the UK, and Germany follow, with each of these countries having more than 100 publications. These countries are primarily located in Asia, North America, and Europe, with Europe and Asia having the highest total publication counts, far surpassing other continents. Sahana et al. (2023a) also found that the UK has the most PUA publications in Europe, which is consistent with the findings of this study. In contrast, Africa, South America, and Oceania have relatively fewer publications (***Figure 2.1***).

In terms of publication timeline, the USA was the first to publish a PUA article in 1995. Countries such as Australia, North Africa, Japan, Canada, Sweden, Mexico, Greece, Denmark, and Guinea-Bissau also had PUA articles published before 2000. Countries such as China, India, the UK, Germany, and France began publishing articles in the early 21st century. Countries such as Ecuador, South Korea, Tunisia, Morocco, and Cambodia started publishing relevant articles only after 2020 (***Figure 2.1***).

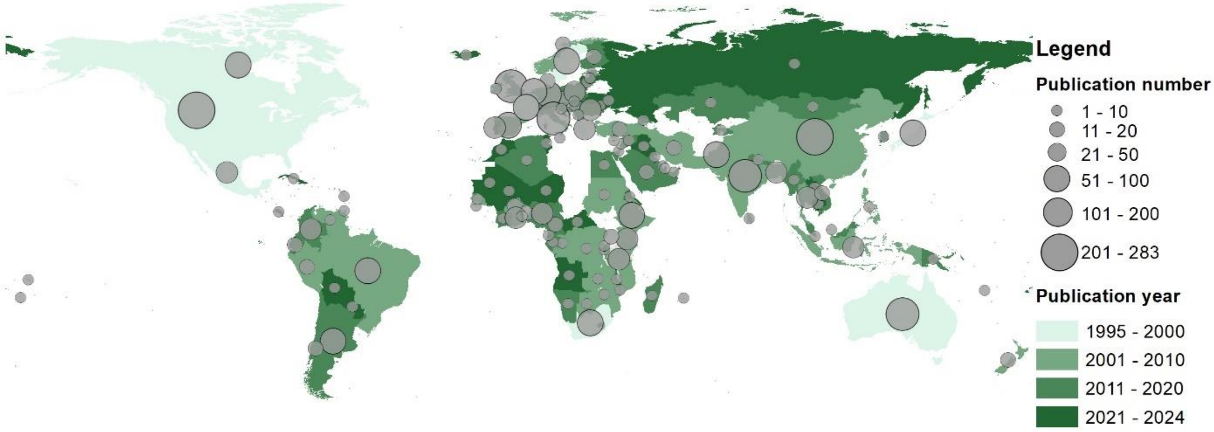

Figure 2.1: Map of the number and starting years of publications in the Global Database.

2.4.2 Keyword clustering

Keywords are a core summary of the themes in the literature, and analyzing them helps to uncover research hotspots in a specific field. After performing a co-occurrence analysis of keywords in these articles, it was found that *urbanization* appeared most frequently as a keyword, indicating the close relationship between peri-urbanization and urbanization. High-frequency keywords such as *city*, *land use*, and *landscape* also reflect various hotspots in PUA research (***Table 2.1***).

Betweenness centrality is a key metric for measuring the importance of nodes in a network. Among the high-frequency keywords in the global database, *management*, *land use*, and *urban fringe* exhibited the highest betweenness centrality, indicating that these terms have a higher degree of connection with other keywords in the keyword contribution network (***Table 2.1***).

Table 2.1: High-frequency keywords in the Global Database.

No.	Keywords	Centrality	Count	Year
1	urbanization	0.09	107	1997
2	city	0.06	87	2004
3	land use	0.11	70	2001
4	landscape	0.08	59	1998
5	impact	0.05	59	2001
6	growth	0.08	52	2001
7	urban fringe	0.10	47	1997
8	management	0.13	46	2000
9	pattern	0.04	44	2014
10	dynamics	0.04	39	2013

Through LLR clustering analysis, nine main clusters of keywords were identified (***Table 2.2, Appendix 1***). The automatically extracted cluster titles tend to be overly specific. Therefore, it is necessary to explore the connections between these clusters by considering the multiple keywords included within each cluster (Liu et al., 2022). Further synthesis of these clusters led to the identification of the following four themes:

(1) **Ecology and environmental research**

This section is composed of clusters #0, #1, and #2. As urban areas expand, the focus on environmental issues has spread from urban areas to PUAs, with the ecological and environmental problems of PUAs becoming a global research hotspot. The main driving factor behind environmental conflicts in PUAs is the incompatibility between economic development and environmental conservation (Kennedy, 2017). According to the study by Včeláková et al. (2023), the ecosystem service levels of PUAs are even higher than those of rural areas. Particularly in PUAs, natural landscapes such as forests and grasslands exhibit high biodiversity and environmental value, contributing to a higher level of ecosystem services (Huera-Lucero et al., 2020, Sambieni et al., 2018). These areas can, to some extent, mitigate a range of environmental issues that arise during urbanization, such as the urban heat island effect and air pollution (Colaninno and Morello, 2019, Hanna et al., 2024, Tan et al., 2025). However, these areas are often more vulnerable to ecological degradation due to the lack of policy protection (Lu et al., 2023a).

(2) **Policy and conflict research**

This section is composed of clusters #4, #6, and #7. It primarily covers discussions on government policies for PUAs and the various conflicts within PUAs. Current urban conflict research mainly focuses on urban areas, where the concentration of factors such as population, infrastructure, and capital leads to more conflicts. In this context, PUAs seem to be overlooked. However, in reality, PUAs are hotspots for land-use conflicts (Cegielska et al., 2025). Conflicts arising from land use, particularly those related to land-use interests, have become the primary source of conflict in PUAs, which is common worldwide (Cegielska et al., 2025, Kleemann et al., 2023). The reduction of farmland in PUAs has raised concerns among many researchers regarding food supply (Muchelo et al., 2024). Kleemann et al. (2023) summarized that the major conflicts in European PUAs include land-use conflicts, socio-economic conflicts, ethnic conflicts, and human-environment conflicts, emphasizing that the primary issues in PUA conflicts are intensified development, socio-economic imbalance, and ethnic differences. In Ethiopia, the state, private enterprises, and local communities are the main competing stakeholders in PUA conflicts (Adam, 2020). Additionally, Mazur (2022) pointed out that the lack of appropriate spatial policies and uncontrolled housing expansion lead to spatial conflicts in PUAs. Generally, PUAs are located on the urban planning periphery or are not included within urban planning boundaries, which often results in a lack of direct policy guidance. However, many policies indirectly affect the development of PUAs, such as the demarcation of urban growth boundaries, the use of buffer zones, and green belts to limit urban sprawl (Salvati et al., 2016a, Kirby and Scott, 2023).

(3) **Spatial morphology research**

This section is composed of clusters #5 and #11. The outward expansion characteristic of de-densification patterns during the urbanization process leads to urban areas growing at a rate higher than population growth (Morris et al., 2024), which in turn triggers urban sprawl. In some Mediterranean cities in Southern Europe, local governments relaxed regulations on central city development, which caused high-income groups to concentrate in the city center again, prompting middle- and low-income households to migrate to surrounding areas, thereby promoting the development of informal settlements and the expansion of PUAs (Brenner et al., 2024). In cities like Athens and Rome, the multi-center urban structure gradually replaced the original monocentric urban development model. These phenomena have accelerated the rapid development of peri-urbanization, with PUAs often playing a significant role in urban spatial reconstruction. As a result, spatial demarcation and planning of PUAs have become important and widely discussed research topics in many countries.

(4) **Land use research**

This section is composed of cluster #3. The dynamic change in land use is an important criterion for analyzing the evolution of PUAs. The rental differences between agricultural uses and real estate development drive land use changes, thereby accelerating socio-economic transformation (Gonçalves et al., 2017, Petrovici and Poenaru, 2025). Shaw et al. (2020) pointed out when summarizing the existing literature on peri-urbanization in Europe that 55% of the cases described land cover changes and socio-economic processes as markers of peri-urban transformation. In PUAs, the increase in built-up land and the sharp decline in agricultural land are often the primary trends, as evidenced in case studies from India (Singh et al., 2024), Egypt (Salem and Tsurusaki, 2024), Sub-Saharan Africa (Muchelo et al., 2024), Krakow (Cegielska et al., 2025), Istanbul (Bayraktar et al., 2024), and Florida (Li et al., 2019). Filepne Kovacs et al. (2024) noted that in Pécs County and Bratislava, about 90% of land cover changes affected agricultural areas, while in the Krakow sub-region, nearly 99% of the converted land was agricultural.

Table 2.2: Keyword clusters in the Global Database.

No.	Cluster	Keywords
0	climate change	agriculture, ecosystem service, conservation, urban, challenge, health, quality, et al.
1	biodiversity	urbanization, pattern, dynamics, region, model, ecology, et al.
2	heavy metals	Impact, soil, contamination, pollution, state, et al.
3	land use	land use, area, evolution, transition, rural-urban fringe, index, et al.
4	policy	city, landscape, policy, peri-urban agriculture, food, et al.
5	urban fringe	urban fringe, China, sprawl, system, urban expansion, et al.
6	peri-urban areas	management, peri-urban areas, community, conflict, et al.
7	Africa	Africa, productivity, et al.
11	spatial models	rural-urban interface, land economics, et al.

2.5 Research trends and hotspots in China

2.5.1 Publication trends

For the China Database, the number of PUA articles from different provinces and municipalities was statistically analyzed. From ***Figure 2.2***, it is clear that Beijing has the highest number of PUA articles, followed by Jiangsu Province, Guangdong Province, and Zhejiang Province. The provinces and municipalities with more research are mostly located in the developed coastal areas of eastern China, where the phenomenon of peri-urbanization first appeared. Under the policy guidance of decentralized rural industrialization and urbanization, these areas were the first to form PUAs (Zheng et al., 2003). Some provinces in the northwest still lack research on PUA, which is partly related to their slower pace of urbanization (Li, 2013). In addition to these individual cases, in recent years, there has been research on larger areas, such as the Pearl River Delta (Liu et al., 2023), the Yangtze River Delta (Liu et al., 2024), the Guangdong-Hong Kong-Macau Greater Bay Area (Pan et al., 2023), the Qinhuai River Basin (Jin et al., 2023), and even the entire country (Xu et al., 2024).

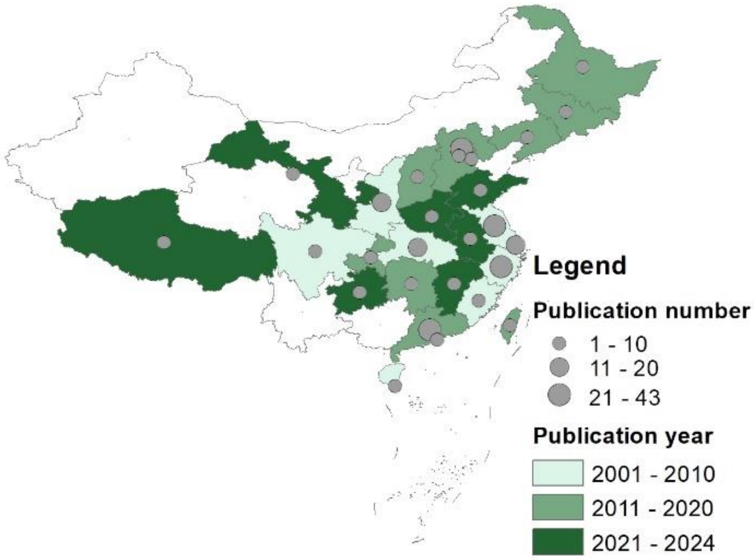

Figure 2.2: Map of the number and starting years of publications in the China Database.

2.5.2 Keyword clustering

The keyword *urbanization* appears most frequently in the Chinese Database, followed by *China* and *city*. Among the keywords, *land use* has the highest betweenness centrality, followed by *city* and *urbanization* (***Table 2.3***). In comparison, the betweenness centrality of these keywords is significantly higher than that of the high centrality keywords in the Global Database. This indicates that the China Database has fewer categories of keywords or that there is a higher focus on these high-frequency keywords in the Chinese Database.

Table 2.3: High-frequency keywords in the Chinese Database.

No.	Keywords	Centrality	Count	Year
1	urbanization	0.23	40	2012
2	city	0.26	27	2010
3	China	0.20	25	2006
4	urban fringe	0.12	22	2012
5	land use	0.28	18	2010
6	area	0.06	14	2015
7	pattern	0.04	11	2010
8	impact	0.02	11	2018
9	expansion	0.02	10	2013
10	growth	0.16	10	2010

By clustering the keywords, nine main clusters were generated (***Table 2.4, Appendix 2***). These clusters were further summarized into the following four themes:

(1) **Land use research**

This theme is composed of clusters #4, #5, #8, and #9. Land use changes in PUAs have received significant attention in China, particularly concerning the issue of farmland loss. For instance, in the southeastern coastal regions of China, where peri-urbanization is relatively advanced, Zou et al. (2019) found that land in these areas faces mounting pressure from expanding development, farmland reduction, and accelerated green space degradation. Due to the intense competition between different land use types, land use patterns in PUAs are highly complex. The dominant land use types in PUAs are agricultural land and built-up land, with the conversion of agricultural land to built-up land being the primary trend (Feng et al., 2015). Additionally, there is also a transition of some natural land into built-up areas (Salvati et al., 2015, Nickayin et al., 2021).

(2) **Land governance research**

This theme is composed of clusters #1 and #3. Land use patterns are shaped by policies and human activities (Cervelli et al., 2018); however, PUAs often lack clear land policy guidance in China (Tian and Ge, 2011). As a result, land patterns in PUAs are more strongly influenced by human activities, primarily driven by industrial transformation and the external effects of urban expansion (e.g., industrial relocation, infrastructure expansion, and rural-urban migration) (Ma et al., 2018). Overall, PUAs in China are characterized by inefficient land use, complex property rights, and intensive land utilization. These characteristics have led to a range of land use issues, including land supply-demand imbalances due to population changes, severe ecological degradation, and irrational land-use structures (Yang et al., 2023). In the process of policy implementation, PUAs have become the most prominent regions where local governments balance development and conservation. Unlike most countries with private land ownership, land in China is either state-owned or collectively owned, making land conversion subject to the authority of government and planning agencies. For the PUAs in China, land use conflicts primarily lie in the land resource competition between the central and local governments regarding the protection of farmland and urbanization development. (Lu et al., 2023b).

(3) **Ecological and environmental research**

This theme is composed of clusters #2 and #6. PUAs in China have long been overlooked by planning and regulatory authorities, leading to a complex interweaving of industrial and residential land uses, which poses a threat to environmental sustainability (Tian et al., 2017b). Numerous studies have found that factories in PUAs cause heavy metal contamination of farmland (Yang et al., 2024), degrade air quality (Qi et al., 2023), and pollute rivers (Zheng et al., 2024b).

(4) **Spatial morphology research**

This theme is represented by cluster #0, focusing on urban expansion and the spatial patterns of PUAs. China’s rapid urbanization, characterized by high intensity, high speed, and high density (Shi et al., 2021), has driven the expansion of numerous urban areas and influenced the development of PUAs. For example, Shi et al. (2012) found that in Lianyungang, urban growth was primarily driven by edge expansion, with PUAs experiencing the most prominent urbanization. Similarly, in the Xiaoshan District of Hangzhou, urban growth was predominantly edge expansion, accompanied by leapfrog development as a form of urban sprawl (Chen and He, 2022). In Beijing, peri-urban expansion exhibited a layered pattern and structure (Cao et al., 2012).

Table 2.4: Keyword clusters in the Chinese Database.

No.	Cluster	Keywords
0	Beijing city	Urbanization, city, pattern, area, sprawl, region, expansion, rural-urban fringe, et al.
1	Urban fringe	China, Urban fringe, village, property right, community, reform, et al.
2	antibiotics	Growth, agricultural soil, contamination, spatial distribution, identification, heavy metals, et al.
3	power-law distribution	Landscape, management, peri-urban areas, transition, dynamics, policy, land, challenge, attitude, et al.
4	urban fringe area	Impact, urban fringe area, model, quality, ecosystem service, landscape pattern, simulation, et al.
5	land cover change	Land use, land cover change, urban-rural integration, driving factors, et al.
6	absorption coefficient	Pollution, air quality, carbonaceous aerosol, et al.
8	Lake area	agriculture, lake area, land-use allocation.
9	soil texture	Nitrogen, soil organic carbon.

2.6 Identification of PUAs

In recent decades, there has been a significant increase in academic attention toward global peri-urbanization processes. Bartels et al. (2020) argued that this growing interest in peri-urban transformation stems from the challenge posed by the lack of clear or neatly defined boundaries between urban and rural areas (van Vliet et al., 2019). This spatial and conceptual fluidity challenges previous assumptions about the rigid distinction between urban and rural spheres and instead opens up ways to identify the continuum between them.

Due to the complexity and diversity of urban-rural interactions along city edges, spatial identification and classification of PUAs remain challenging (Buxton and Choy, 2007). To date, there is no clear, universally applicable definition for delineating PUAs. Although numerous researchers have proposed different methods to demarcate PUAs, these methods vary depending on regional and socio-spatial scales. Moreover, given the vastly different characteristics, formation processes, and ongoing development of PUAs worldwide, establishing a universal method for identifying PUAs on a global scale is challeging. For instance, peri-urban development in developing countries is often characterized by rural-urban migration, rapid land transformation, and mixed agricultural-industrial land use, whereas in developed countries, PUAs are more associated with urban amenities and residential suburbanization (Woltjer, 2014).

Therefore, in some studies on PUAs, administrative boundaries are directly used as the delineation of PUAs. However, many studies suggest that PUAs frequently extend beyond administrative boundaries, making such an approach inadequate for accurately depicting their spatial extent. Due to the lack of precise spatial demarcation, PUAs are often treated as part of urban areas in research, leading to the frequent conflation of their characteristics with those of urban regions. Consequently, the spatial and structural evolution of PUAs over time remains unclear. Nevertheless, their identification and classification are crucial for promoting sustainable urban planning and management. This need is particularly pressing in developing countries, where unplanned urban expansion, land-use conflicts, and environmental consequences continue to pose significant challenges (Sahana et al., 2023b). Clearly defined PUA boundaries not only clarify the scope of research but also provide a crucial foundation for analyzing their spatial evolution, land-use changes, and landscape dynamics.

Through a literature review on PUA identification methods, it is observed that PUA identification involves two stages: qualitative identification and quantitative identification. In early studies, PUAs were commonly delineated based on empirical classification. The extent of PUAs was typically defined as several kilometers beyond the built-up area, varying across different regions (Bryant et al., 1982, Barrington and Ilbery, 1987, Ilbery, 1988, Gu et al., 1993). For instance, based on McGee's observations of Southeast Asian cities, the rural-urban continuum consists of five major components: central cities, peri-urban regions, desakota regions, densely populated rural regions, and sparsely populated frontier regions (McGee, 2022). Another common approach defines PUAs based on their proximity to urban centers, where adjacent areas undergo transformations in land use, economic activity, and social composition due to urban influences (Petrovici and Poenaru, 2025).

Over time, qualitative classification has gradually given way to quantitative methods, marking a significant shift in research approaches (Li et al., 2023). Among quantitative methods, the threshold method emerged early and has been widely applied (Chettry, 2022). Subsequently, methodologies such as the breakpoint method (Dong et al., 2022, Qian et al., 2007, Cao et al., 2009, Zhang et al., 2016b), spatial clustering (Liu and Zhang, 2008, Moreira et al., 2016, Gonçalves et al., 2017, Diti et al., 2015), and principal component analysis have been employed in various study regions. For example, Gonçalves et al. (2017) applied principal component analysis to study PUA typologies and developed an interdisciplinary approach to delineate the boundaries of PUAs within the Lisbon Metropolitan Area. Similarly, Hamers and Piek (2012) used topological adjustment factors to map PUAs in the Netherlands, while Danielaini et al. (2018) combined multivariate, univariate, and multi-univariate clustering analyses to identify relevant clusters indicating PUAs in the Cirebon metropolitan region of Indonesia. Furthermore, Merciu et al. (2019) applied multi-criteria evaluation techniques to map urban influence zones in the Romanian context. Notably, with advancements in technology, machine learning techniques have also been introduced into PUA research, demonstrating significant potential for improving identification accuracy (Liu et al., 2020, Peng et al., 2020).

2.7 Studies on PULs

After reviewing studies related to PULs in the Global Database, it is evident that the vast majority of literature adopts case studies for empirical research, with a clear trend toward quantitative analysis. In quantitative studies, Landscape Metrics and Morphological Spatial Pattern Analysis (MSPA) are widely utilized, often in combination with Geographic Information System (GIS) and statistical analyses to examine the spatiotemporal evolution of various PULs. Additionally, research methods such as surveys and literature reviews have been employed in some studies. With the advancement of artificial intelligence, recent years have seen the application of artificial neural networks in PUL research. Regarding data usage, researchers tend to rely on multi-source data, particularly land use/land cover change data derived from remote sensing, as the foundational dataset for PUL classification. Population data, topographic maps, and statistical yearbooks serve as references for correlation analysis and investigations into the driving factors of PULs.

Through a comparative analysis of the literature, I identified significant common characteristics of PULs across different macro-regions. In previous studies, PULs have often been depicted as unattractive, untidy, or anonymous landscapes (Gallent and Andersson, 2007). Due to the intense competition among different types of landscapes, landscape fragmentation has become a widespread phenomenon in PUAs, with PULs frequently exhibiting a state of disorder and dynamic instability. Although the drivers of peri-urbanization in the Global North and Global South are typically different (Follmann, 2022), the outcomes of PUL changes and the loss of agricultural landscapes are similar (van Vliet et al., 2019).

In addition to common characteristics, I also identified regional features of PULs, illustrated with examples from Europe and China. In Europe, PULs are primarily composed of artificial functional landscapes shaped by the Industrial Revolution, post-war transportation infrastructure, and economic redundancy. The most typical manifestation is the interweaving of low-density industrial, residential, or commercial land with agricultural land (Schwarz, 2010, Dubbeling, 2011, Wandl et al., 2014b). New land uses have emerged in PUAs, such as golf courses, equestrian facilities, schools and their playing fields, allotments, and public utilities (Gant et al., 2011), contributing to an increase in land-use diversity (Salvati et al., 2017). Moreover, compared to urban areas, PUAs often host richer biodiversity resources (Hopkins, 2012).

At the same time, influenced by urban expansion, especially the expansion of polycentric cities, the construction of new residential areas and roads has often resulted in fragmented and dispersed PULs in Europe (Hietala et al., 2013, Li et al., 2013, Cervelli and Pindozzi, 2022b). In many cases, PULs lack effective public transportation, leading to traffic primarily relying on private cars around bus stations. This car-dependent, low-density development results in inefficient land and resource use and contributes to high energy consumption rates (Yiran et al., 2020). As early as the last century, farm fragmentation was observed at Coventry's urban fringe (Barrington and Ilbery, 1987). In the PUAs of Rome and the Vesuvius region of the Naples metropolitan area, significant fragmentation of vineyards, farmland, and pastures has been documented (Cervelli and Pindozzi, 2022b, Nickayin et al., 2021, Salvati et al., 2015).

In China, PULs often appear disordered and deteriorated due to insufficient planning and management. Peri-urbanization often leads to informal, illegal, and unplanned urban expansion, with a lack of access to essential services such as shops, schools, or healthcare (Follmann, 2022). The rapid pace of urbanization may result in high levels of pollution and waste management issues in these landscapes (Schindler, 2015, Spyra et al., 2025). As a result, the natural and semi-natural PULs tend to become fragmented and morphologically complex, while artificial PULs often lack coherent planning. The growing influence of human activities disrupts landscape continuity, resulting in a lack of harmony between natural and cultural landscapes. Moreover, this disruption contributes to a decline in habitat quality. In terms of PUL structure, the agricultural landscape typically serves as the basic landscape, while the industrial landscape tends to be the dominant one.

2.8 Research progress and limitations

Through the literature review, it is evident that PUA research has been widely conducted worldwide, driven by the globalization of peri-urbanization. Although PUAs exhibit diverse forms under different political, economic, and cultural contexts, researchers have consistently focused on land-use changes induced by peri-urbanization, along with the resulting environmental transformations, conflicts of interest, and urban restructuring. Discussions on these issues can significantly highlight the multifunctional role of PUAs in urban development, thereby ensuring they receive the attention they deserve.

However, considering the current state of research, defining PUAs remains a primary challenge. While there are some comparative studies on PUA identification, most of them take the form of case reviews. For instance, Cattivelli (2020) reviewed PUA identification methods in Europe and concluded that the most widely used approaches are those based on demographic and socioeconomic variables. Similarly, Mortoja et al. (2020) and Sahana et al. (2023b) emphasized the importance of delineating PUA boundaries for formulating conservation and management policies. Their reviews highlighted that due to the regional specificity of PUAs, no universal method exists for their classification. Although these literature reviews provide valuable insights into method selection, the presence of numerous variables, such as differences in study areas, indicators, and research units, makes it difficult to derive a clear comparative understanding of these methods. For researchers, before determining an appropriate identification approach, it is essential to conduct practical comparisons and screening of multiple methods within a specific study area. This step helps in selecting the most suitable approach for the given region. However, there remains a research gap in comparative studies that evaluate the effectiveness of different PUA identification methods within the same study area.

Secondly, although previous studies have addressed the dynamic changes in PUAs, such as population mobility (Iaquinta and Drescher, 2000), housing (Liu and Wong, 2018, Seto and Kaufmann, 2003), and spatial transformations (Seto and Kaufmann, 2003), there has been a lack of quantitative analysis in these areas. This has resulted in the evolution of PUAs lacking comparability and predictability, making it difficult to identify development patterns and trends. In particular, there is a lack of studies examining the spatiotemporal evolution of PUAs using polycentric cities as case studies. Therefore, I aim to provide digitized results through quantitative analysis, facilitating assessment and optimization. Quantitative analysis can also offer deeper insights into the multidimensional characteristics of PUAs, complementing qualitative analysis in the scientific decision-making process.

Additionally, most studies on PULs focus on historical and current conditions, with relatively limited research on future planning and practical applications. Sustainable peri-urban development requires a close and active relationship between humans and nature, which cannot be achieved without coordinated planning and implementation strategies. Despite growing research interest, the development of more integrated PUL planning approaches remains slow, leading to a significant mismatch between PUL research and practice (Tan et al., 2024).

3.MATERIALS AND METHODS

3.1 Study area overview

(1) Administrative divisions

Zhengzhou (112°42'–114°13' E, 34°15'–34°59' N) is located in central China and serves as the capital of Henan Province (***Figure 3.1a***). It covers an area of approximately 7,565 km². The administrative jurisdiction of Zhengzhou encompasses six districts, five county-level cities, and one county. The Central Urban Area (CUA) comprises five districts, functioning as the primary urban core of Zhengzhou. The county-level cities under its administration include Xingyang, Gongyi, Dengfeng, Xinmi, and Xinzheng. Shangjie District is an industrial-oriented enclave located within the boundaries of Xingyang but administratively affiliated with the CUA. In the following text, all references to Xingyang include Shangjie District. Zhongmu County is the only county under the jurisdiction of Zhengzhou (***Figure 3.1b***).

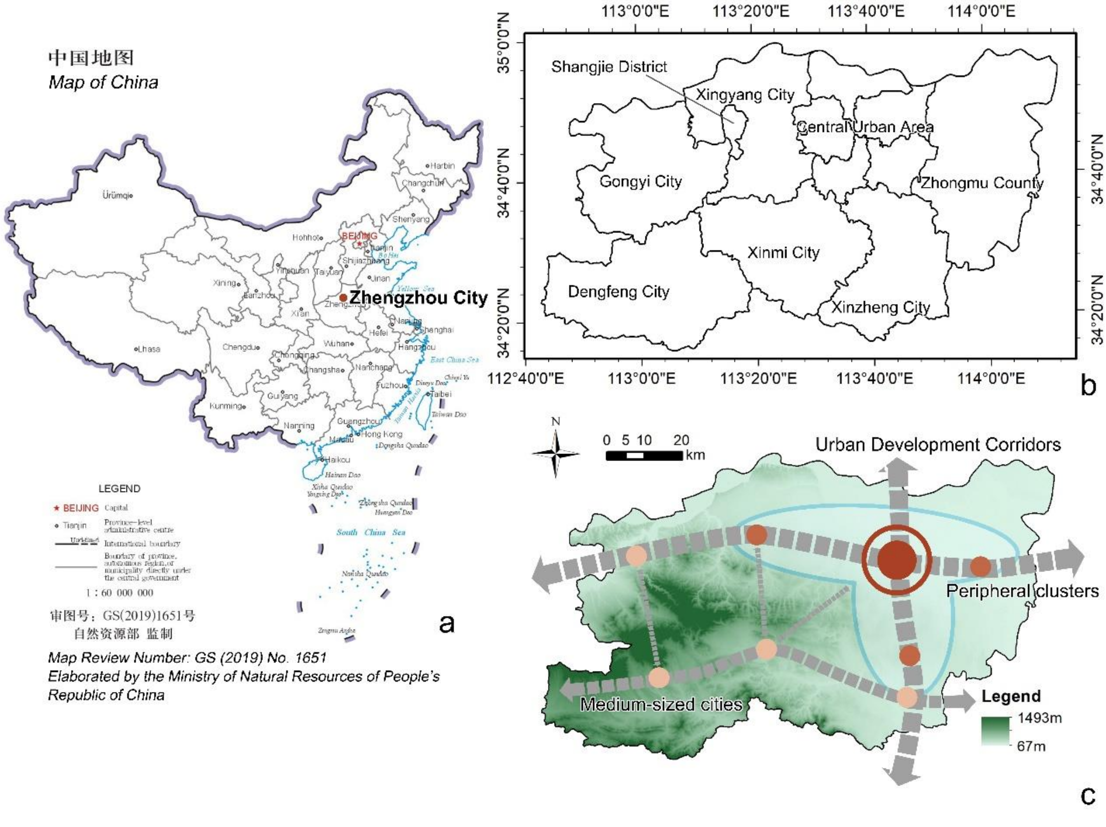

Figure 3.1: Location and administrative boundaries of the study area: a. Location of Zhengzhou in China[1]; b. Administrative divisions of Zhengzhou[2]; c. Topographic Map of Zhengzhou and Spatial Planning Structure in *The Master Plan for Zhengzhou Metropolitan Area (2012-2030)*.

(2) Natural Conditions

Zhengzhou is located in the northern temperate zone and experiences a semi-arid monsoonal continental climate, characterized by a warm temperate deciduous broadleaf forest vegetation type. The city has dry springs with little precipitation and frequent spring droughts, accompanied by

[1] http://bzdt.ch.mnr.gov.cn/

[2] https://www.zhengzhou.gov.cn/view/index.jhtml

variable temperatures and strong winds. Summers are relatively hot, with concentrated rainfall. Autumn is cool but short, while winters are long, cold, and dry, with minimal rain and snow. Precipitation is mainly concentrated between June and August, peaking in August. This city is home to 124 rivers of various sizes (***Figure 3.2a***), spanning the Yellow River (***Figure 3.2b***) and Huai River basins (***Figure 3.2d***).

The topography of Zhengzhou is relatively complex, generally sloping from high elevations in the southwest to lower elevations in the northeast. The highest point within the city is Mount Song (***Figure 3.2c***), located in Dengfeng, with an elevation of 1,512 m, while the lowest point, at 72 m, is in the eastern plain. Dengfeng and Xinmi feature typical mountainous terrain with significant elevation variations. Gongyi, Xinzheng, and Xingyang comprise a combination of hills and plains with moderate undulations. The CUA and Zhongmu are characterized by flat plains. Overall, Zhengzhou's land area consists of 31.6% mountainous terrain, 30.0% hilly terrain, and 38.4% plains (***Figure 3.1c***).

Figure 3.2: Natural Landscapes of Zhengzhou: a. Distribution map of green spaces and water bodies; b. The Yellow River; c. Mount Song; d. The Jialu River.

(3) Socioeconomic Conditions

Zhengzhou serves as the political, economic, educational, research, and cultural center of Henan Province and is a key central city in China's midland region. Between 2000 and 2020, the city's permanent population increased from 6.659 million to 12.617 million, and the urbanization rate rose from 55.1% to 78.4%. The influx of population into the CUA has become increasingly pronounced. In 2000, the CUA's population accounted for approximately 37.8% of Zhengzhou's total population; by 2020, it had grown by about 2.7 times, making up approximately 54.2% of the city's total population. Among other administrative regions, Xinzheng experienced the most significant population growth, surging approximately 2.9 times from being the least populated city in 2000 to becoming the most populated by 2020 (Zhengzhou Bureau of Statistics and Zhengzhou

Survey Team of the National Bureau of Statistics of China, 2021).

As a national transportation hub, Zhengzhou has witnessed rapid development over the past few decades, benefiting from an extensive and well-connected transportation network. Foreign investment and population inflows have driven continuous urban expansion. Meanwhile, policies such as village amalgamation and urban integration, and the growth of township enterprises, have accelerated non-agricultural development and urbanization in some rural areas. These factors collectively provide multiple driving forces for the formation and development of peri-urban areas (PUAs) in Zhengzhou.

(4) Reasons for Case Selection

The *Master Plan for Zhengzhou Metropolitan Area (2012–2030)* proposes a networked urban system centered around the CUA, with peripheral clusters and medium-sized cities serving as sub-centers, key towns functioning as nodes, and smaller towns forming a supporting structure (Figure 3.1c). This planning strategy has facilitated a polycentric spatial development pattern in Zhengzhou. As a typical polycentric city, Zhengzhou exhibits a particularly complex peri-urbanization phenomenon. Studying Zhengzhou as a case for identifying and analyzing the spatiotemporal evolution of PUAs will contribute to a deeper understanding of these regions.

Furthermore, Zhengzhou represents an emerging megacity. Since 2015, its permanent population has surpassed 10 million, meeting the criteria for a megacity. Megacities, characterized by high economic development levels and strong regional influence, often exhibit distinct peri-urbanization patterns. The peri-urbanization phenomenon in emerging megacities is typically at a clearly defined stage, providing favorable conditions for the identification of PUAs and the analysis of their spatiotemporal evolution (Aguilar, 2003).

Additionally, under the influence of policies promoting urban-rural integration and rural revitalization, Zhengzhou's peri-urbanization processes are expected to become more pronounced. As transitional zones between urban and rural areas, PUAs will play a more significant bridging role in the implementation of these policies. Therefore, precise identification and spatiotemporal analysis of PUAs in Zhengzhou are necessary to examine their characteristics, morphology, and structure, with the ultimate goal of informing sustainable planning practices.

3.2 Data collection and processing

3.2.1 Multi-source indicators and data

Existing studies emphasize that the classification of PUAs should be based on land use data, supplemented by environmental parameters, socioeconomic data, migration information, housing conditions, and cultural attributes (Amirinejad et al., 2018, Butt and Fish, 2016, Buxton and Choy, 2007). Given the extended temporal scope of this study, acquiring historical data on commuting patterns and housing conditions presents significant challenges. Therefore, the selection of indicators and datasets prioritizes accessibility and broad applicability, favoring globally available data to enhance the study's comparability and provide insights for other research regions.

Compared to single-indicator approaches, which offer faster results, the accuracy of individual data significantly influences outcomes. To mitigate this limitation, a multi-indicator system integrating diverse datasets is preferred, as it minimizes the impact of any single data source on the results. Consequently, multi-indicator frameworks have been increasingly adopted in research. To avoid multicollinearity among indicators, four indicators were selected from distinct dimensions (construction, economy, naturalness, and population) to identify PUAs. These indicators include Imperviousness Density (ID), Nighttime Light Intensity (NLI), Proportion of (semi-) natural land (PNL), and Per Capita Land Area (PCLA). Given the mixed attributes of PUAs, I hypothesized that these indicators exhibit values that fall between those of urban and rural areas.

ID reflects the construction intensity of a region and has been previously used to identify PUAs in Beijing and Wuhan (Peng et al., 2018, Long et al., 2023). Impervious surfaces, formed by buildings, roads, and other infrastructure, contribute to soil sealing (Salvati et al., 2016b). This data was sourced from the *Global 30m Resolution Impervious Surface Dataset* (Zhang et al., 2022). NLI serves as a proxy for economic activity and is widely used to differentiate urban, peri-urban, and rural areas (Zhu et al., 2022, Zeng et al., 2022). The dataset I used is derived from a *Global NPP-VIIRS-like Nighttime Light Dataset* obtained through cross-sensor calibration, with a spatial resolution of approximately 500 m (Chen et al., 2021). These two indicators typically exhibit higher values in urban areas and lower values in rural areas.

PNL reflects the natural or semi-natural extent of an area, showing significant differences between urban and rural regions. This indicator is calculated using *China's multi-period land use and land cover remote sensing monitoring dataset*, which has a resolution of 30 m (Xu et al., 2018). The dataset contains six types of land: agricultural land, forest land, grassland, water bodies, built-up land, and unused land. For the case of Zhengzhou, I reclassified the land use types into four categories: agricultural land, green land (including forest and grassland), water body, and built-up land. Among them, agricultural land, green land, and water body belong to natural or semi-natural land. The PCLA primarily relies on population data to represent the demographic situation of a region. The population data I used includes both the census data from the Zhengzhou Bureau of Statistics (2021) and the WorldPop population dataset (WorldPop et al., 2018). The census data is statistical data organized by administrative districts, and I used it in the Threshold method. The WorldPop population dataset, with a 100 m grid as its statistical unit, was used for the Breakpoint Clustering and Multilayer Perceptron model. Typically, the PNL and PCLA are highest in rural areas and lowest in urban areas.

Additionally, Landsat series remote sensing images were downloaded from the USGS[3] to assist in the selection of sample points. The specific information for the remote sensing images used is as follows: Landsat 7_20000405, Landsat 7_20100519, and Landsat 8_20200522.

3.2.2 Spatialization of indicators

Due to the varying resolutions of the indicator data, it is necessary to perform a unified spatialization process. This involves partitioning and aggregating all the indicator data using the same research units. The specific calculation methods are detailed in ***Table 3.1***. All data spatialization was carried out using ArcGIS 10.8.1, with the data coordinate systems adopting the GCS_WGS_1984_49N projection coordinate system. Using 2020 data as a reference, a comparison was conducted among the Threshold method, the Breakpoint Clustering, and the Multilayer Perceptron model.

[3] https://earthexplorer.usgs.gov/

Table 3.1: Formulas and annotations for the spatialization of indicators.

Indicator	Formula	Annotation
Imperviousness density (ID)	$ID_i = \frac{A_{impervious,i}}{A_{total,i}} \times 100\%$	$A_{impervious,i}$ is the impervious surface area in the i-th unit, $A_{total,i}$ is the total area of the i-th unit.
Nighttime light intensity (NLI)	$NLI_i = \frac{1}{n}\sum_{j=1}^{n} L_{ij}$	L_{ij} is the nighttime light intensity at the *j*-th pixel within the i-th unit, n is the total number of pixels in the i-th unit.
Proportion of (semi-) natural land (PNL)	$PNL_i = \frac{A_{NL,i}}{A_{total,i}} \times 100\%$	$A_{NL,i}$ is the combined area of agricultural land, forest land, grassland, and water body in the i-th unit.
Per capita land area (PCLA)	$PCLA_i = \frac{A_{total,i}}{P_i}$	P_i is the total population in the i-th unit.

The Threshold method uses the smallest administrative units of Zhengzhou, villages and neighborhoods, as the research units, totaling 2461. Using the *Zonal Statistics* tool in ArcGIS 10.8.1, the values of the indicators for each unit were calculated (***Figure 3.3***). Given that the smallest statistical unit in the census data is towns and neighborhoods, not individual villages, I assumed a uniform population distribution within each town, resulting in identical PCLA values for villages within the same town. This assumption affects the precision of the PCLA in rural areas. The Breakpoint Clustering and Multilayer Perceptron model use grids with a side length of 1 km as research units, resulting in a total of 7,898 grids within the study area. All indicator values were recalculated based on these grid units (***Figure 3.4***).

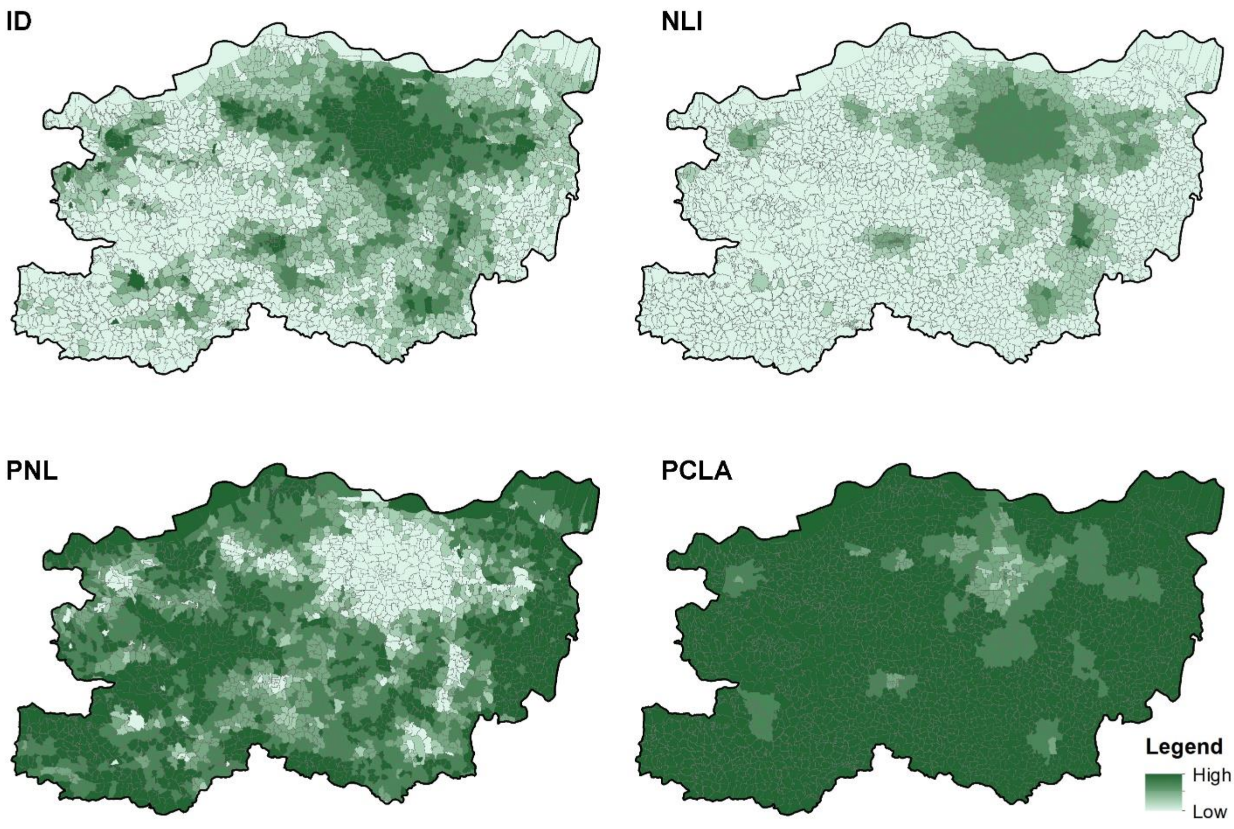

Figure 3.3: The indicator values within the villages and neighborhoods in 2020.

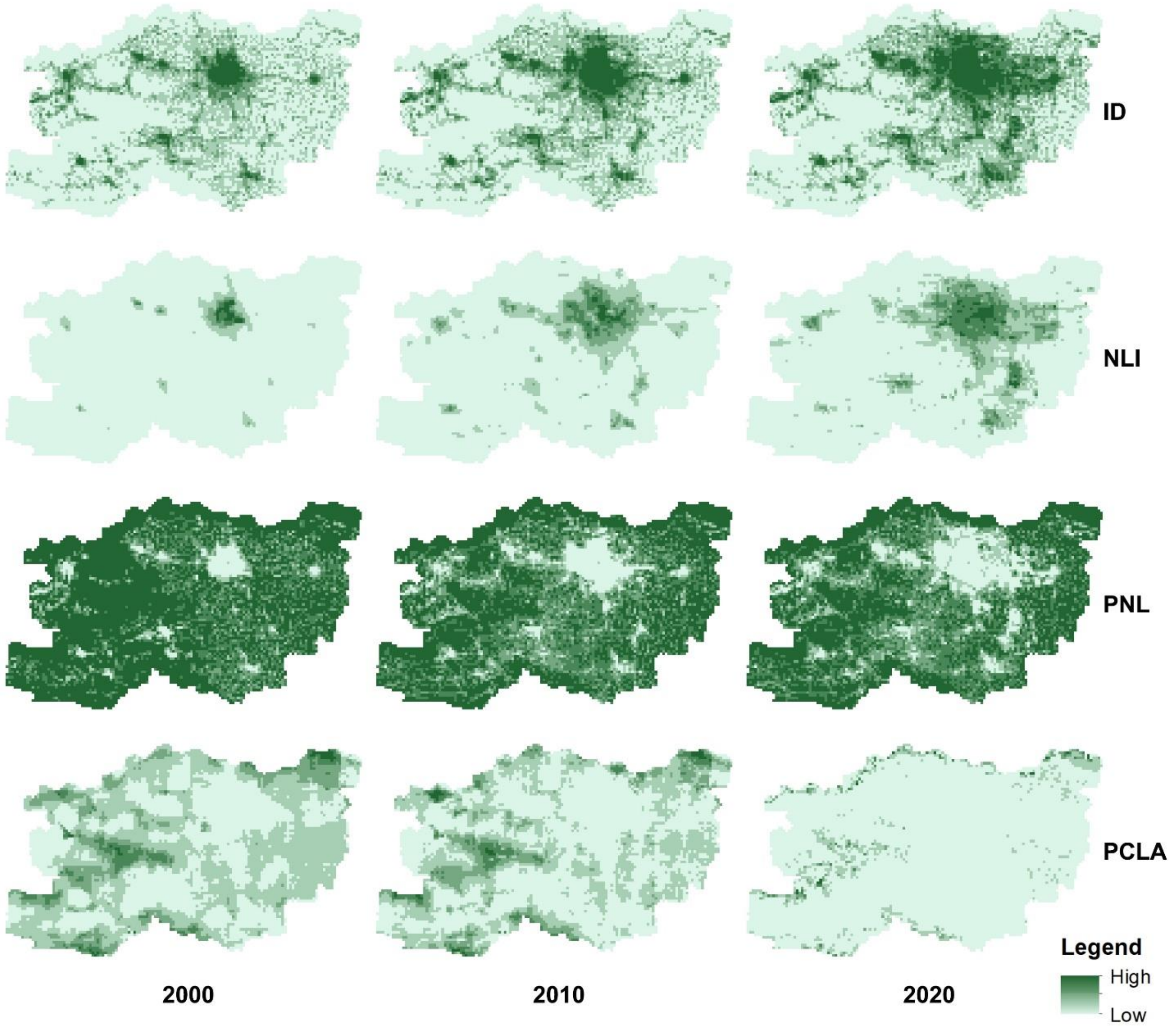

Figure 3.4: The indicator values within the grid units in 2000, 2010, and 2020.

After obtaining the indicator values for each research unit, the range normalization method was applied to standardize the data and eliminate dimensional effects. To facilitate subsequent calculations, I aggregated the indicators into a composite index, which was then applied in both the Threshold method and the Breakpoint Clustering (***Figure 3.5***). The composite index requires alignment in the directionality of the indicators. Among these indicators, ID and NLI are positive indicators, where higher values denote more pronounced urban characteristics, and lower values reflect rural characteristics. In contrast, PNL and PCLA are negative indicators, where higher values suggest rural characteristics. To ensure consistency, I reversed the direction of the negative indicators, making all indicator values highest in urban areas and lowest in rural areas. I then calculated the composite index value using the following formula:

$$C = \sum_{i=1}^{n} w_i x_i \qquad (1)$$

Where C represents the value of the composite index, w_i is the weight of the i-th indicator, x_i is the value of the i-th normalized indicator, and n is the total number of indicators (Freudenberg, 2003). I used the entropy method (Zhu et al., 2020) to calculate the objective weights of the indicators. Since the Threshold method and the Breakpoint Clustering use different research units, their weights and complex indices also vary (***Table 3.2***).

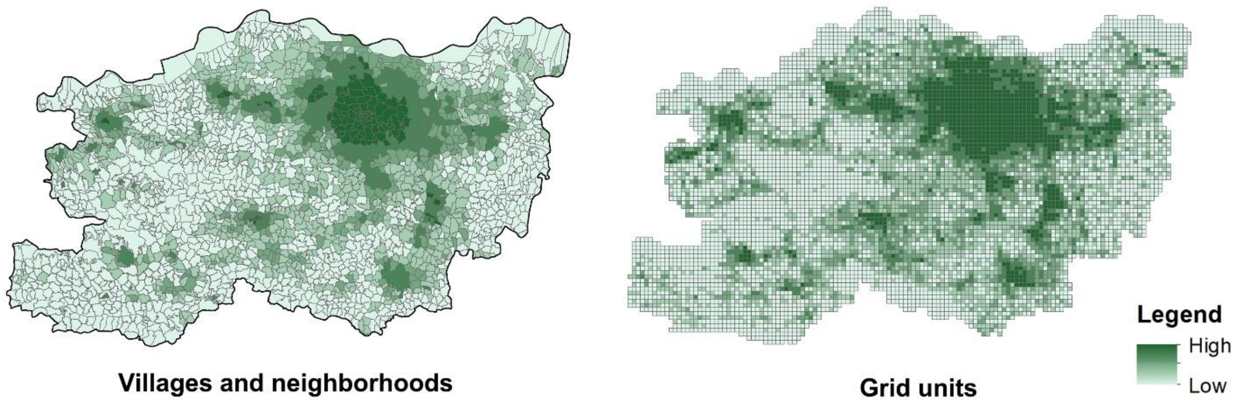

Figure 3.5: The composite indices within the villages and neighborhoods and grid units in 2020.

Table 3.2: Directions and weights for the spatialization of indicators.

Indicator	Indicator Direction	Weight（Threshold method）	Weight (Breakpoint Clustering)
Imperviousness density (ID)	Positive	0.1460	0.2393
Nighttime light intensity (NLI)	Positive	0.3171	0.1365
Proportion of (semi-) natural land (PNL)	Negative	0.1244	0.1871
Per capita land area (PCLA)	Negative	0.4125	0.4370

3.3 Comparison of PUA identification methods

3.3.1 Threshold method

The Threshold method classifies the composite index based on thresholds automatically identified through data analysis. I used the Jenks natural breaks method to obtain thresholds, which offers greater objectivity and data-driven insight compared to predefined thresholds. This method classifies data into several categories based on the inherent distribution characteristics of the data, minimizing within-class variance while maximizing between-class variance to achieve a reasonable classification of the data (Jenks, 1967). ArcGIS 10.8.1 provides this classification method, allowing the composite index values of 2,461 administrative units to be divided into high, medium, and low categories. The administrative units with composite index values in the middle category will be identified as PUAs.

3.3.2 Breakpoint Clustering

The Breakpoint Clustering operates on the assumption that there are distinct breakpoints between urban, peri-urban, and rural areas when viewed from any complete urban-rural gradient. By identifying and clustering these breakpoints, the inner boundary (the boundary between peri-urban and urban areas) and the outer boundary (the boundary between peri-urban and rural areas) of PUAs can be delineated, thus determining their spatial extent.

To comprehensively simulate the urban-rural gradient, I created a sampling array that radiates outward from the CUA. The procedure was as follows: the geometric center of the CUA (34.77° N, 113.65° E) was used as the focal point to draw 360 radial lines at 1° intervals. Additionally, concentric circles with 1 km intervals were constructed, totaling 97 circles, to cover the entire study area. The intersections of the radial lines and concentric circles yielded 16,334 sample points within the study area (***Figure 3.6***). These sample points were connected to all grid units, allowing each sample point to obtain the composite index value of its corresponding grid unit. In other words, the composite index value of each grid will be linked to one or more sample points.

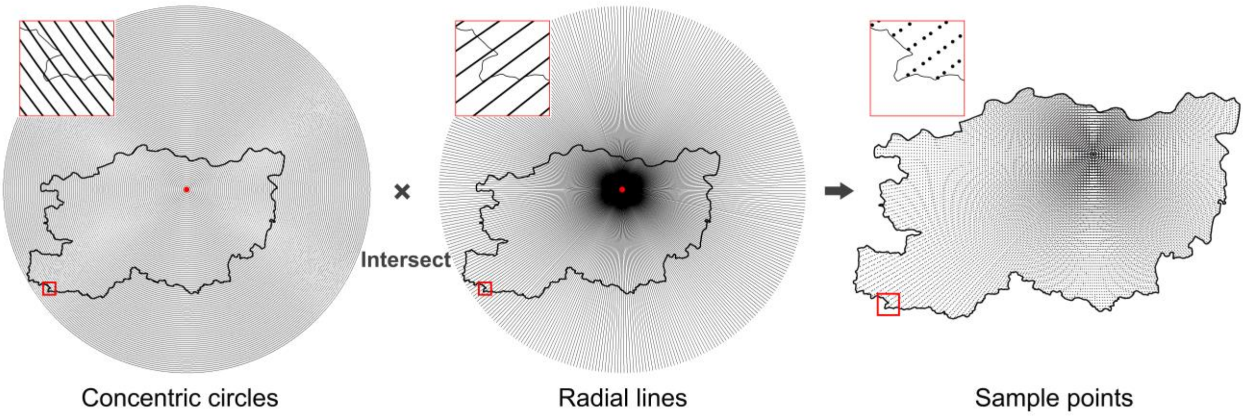

Figure 3.6: The process of establishing sample points in the Breakpoint Clustering.

Next, the sample points were divided into groups based on their radial lines, resulting in 360 data series representing the urban-rural gradients. I conducted ***moving t-tests*** on these data series using MATLAB R2018a. Moving t-test is a statistical method based on examining whether the difference in the means of two sample groups is significant, which allows for the effective identification of breakpoints within the data series. Experimental analysis revealed that a test step size of 3 yielded the most accurate and reliable results. As shown in the data series cases in ***Figure 3.7***, data peaks exceeding the red line or falling below the yellow line were considered breakpoints. Specifically, data points exceeding the red line indicate a downward shift in the composite index values, while those below the yellow line indicate an upward shift. To ensure the accuracy of the findings, I further cross-validated these breakpoints using remote sensing imagery and removed outliers.

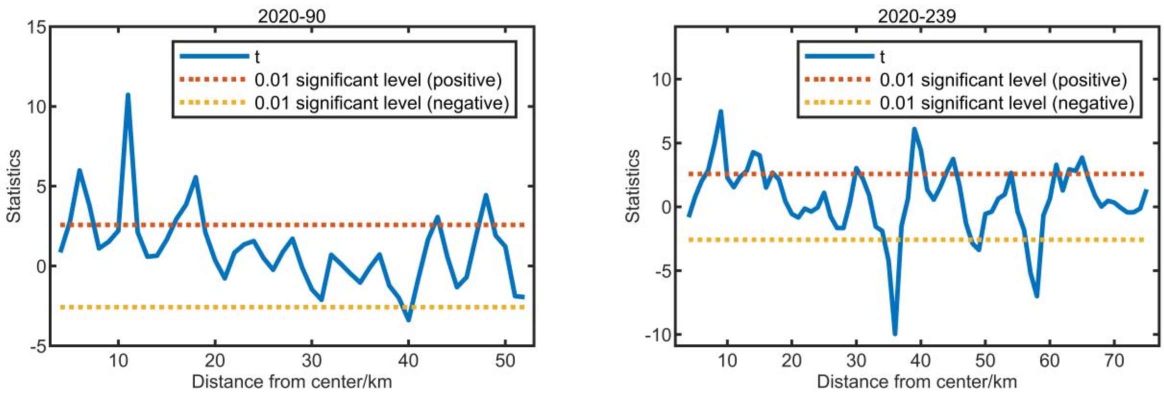

Figure 3.7: The results of the moving t-tests for the 90th and 239th data series.

Following the classification of breakpoints with upward and downward shifts, I imported these categories into QGIS to perform K-means clustering using the *Clustering* tool. As an unsupervised clustering algorithm, the primary function of the K-means algorithm is to automatically group similar samples into a collection. The breakpoints with upward shifts were observed to fall into two categories: those located at the outer boundaries and those at the inner boundaries. K-means clustering facilitated the differentiation between these scenarios. Breakpoints with higher composite index values were considered situated at the inner boundaries, while those with lower values were deemed to be at the outer boundaries. A similar approach was employed for breakpoints with downward shifts to determine the inner and outer boundaries. Consequently, the breakpoints were categorized into four types: Urban to Peri-urban (UP) breakpoints, Peri-urban to Rural (PR) breakpoints, Rural to Peri-urban (RP) breakpoints, and Peri-urban to Urban (PU) breakpoints (***Figure 3.8***). Additionally, these breakpoints may also be located on the boundaries between urban and rural areas, which I did not specifically list for analysis, but I took note of them in subsequent identification processes. Upon mapping these breakpoints to the corresponding grid units, I assessed other grid units based on these classifications to delineate PUAs.

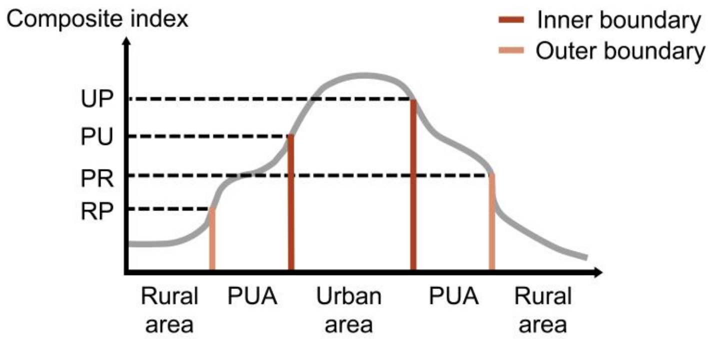

Figure 3.8: The inner and outer boundaries and breakpoints of PUAs.

3.3.3 Multilayer Perceptron model

The Multilayer Perceptron model is based on principles of machine learning. It constructs a neural network to perform high-level abstraction and classification of the input indicator data, enabling effective regional delineation.

This model consists of the input layer, hidden layer, and output layer. The input layer receives preprocessed data and relays input vectors to the hidden layers, which are responsible for feature extraction. The output layer presents the model's final processing results of the input data. Each layer in the model comprises one or more artificial neurons, mimicking the neurons in the brain's neural network.

I initially selected samples based on distinct characteristics of urban, peri-urban, and rural areas from the grids for model training. A total of 500 sample grids were chosen based on remote sensing imagery combined with field surveys: 180 urban, 50 peri-urban, and 270 rural (***Figure 3.9***). The sample grids were divided into 80% training data, 10% validation data, and 10% test data, using a random selection approach.

Subsequently, a Multilayer Perceptron model was established using PyTorch, a deep-learning platform. The standardized and normalized values of all four indicators, both for the samples and the entire dataset, were used as input neurons in the input layer. A hidden layer comprising 64 neurons was constructed through training and evaluation, utilizing the ReLU activation function, which closely approximates human cognitive processes. The ReLU function is defined as:

$$ReLU(x) = \max(0, x) \qquad (2)$$

Where x represents the input value. To ensure the rationality of the output data, the Softmax function, commonly used in multicategory tasks, was selected as the activation function for the output layer. The function is defined as:

$$Softmax(z_i) = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}} \qquad (3)$$

Where z_i represents the input value for each neuron in the output layer, and K denotes the number of categories. Given that the output layer is divided into three categories: urban, peri-urban, and rural areas, K is set to 3. The variable j iterates over all category values of e^{z_j} during the normalization process, ensuring that the sum of output probabilities equals 1.

The model was trained using the training data with a learning rate set to 0.001 and allowed to iterate for up to 1000 epochs. The Cross-Entropy Loss function, commonly used in neural network classification problems, particularly in multi-class classification tasks, was employed. AdamW was used as the optimizer. It combines the principles of the Adam optimizer with weight decay, effectively mitigating the risk of model overfitting. The model was trained until the global error decreased to 0.001, which served as the convergence criterion to halt the training process. Subsequently, the model was assessed using validation data to identify the optimal model configuration. The model was then assessed using the test data, and it was saved and applied to the fitting of all data only if it met the predetermined accuracy requirements. Finally, the identification of urban, peri-urban, and rural areas was achieved.

Figure 3.9: Examples of urban, peri-urban and rural sample grids in the Multilayer Perceptron model.

3.3.4 Kappa coefficient

After obtaining the identification results from the three methods, I calculated the kappa coefficients to assess their accuracy. The kappa coefficient quantifies the consistency between the results and the actual conditions by establishing a confusion matrix (Chettry, 2022). I randomly selected 900 validation points within the study area and manually classified them with the assistance of remote sensing imagery and field surveys to simulate actual conditions. These validation points included 200 urban points, 180 peri-urban points, and 520 rural points. Subsequently, I compared the manually classified results of these points with the results from the three methods using the *Compute Confusion Matrix* tool in ArcGIS 10.8.1, which yielded kappa coefficients for each method.

3.4 Spatiotemporal analysis of PUAs

After comparing the three identification methods, I selected the multilayer perceptron model to identify PUAs for additional years. The indicator values for the years 2000 and 2010 were also standardized and spatialized (Figure 3.4). Based on remote sensing imagery, I selected 70 urban grids, 35 peri-urban grids, and 395 rural grids as sample data for the year 2000. For the year 2010, 120 urban grids, 50 peri-urban grids, and 330 rural grids were selected as sample data.

The classification results derived from the Multilayer Perceptron model exhibited considerable spatial fragmentation and discontinuity. To facilitate subsequent macro-scale spatial analysis, *Kriging interpolation* was applied in ArcGIS 10.8.1 to convert the classification results into a raster map with a resolution of 100 meters, resulting in a more spatially continuous representation of PUAs. However, it should be noted that the interpolation process tends to enlarge the extent of PUAs, which may affect the overall accuracy of the results to some extent.

After obtaining the spatial extents of PUAs for the three years, a series of spatiotemporal analyses were conducted from four perspectives: spatial transition, spatial expansion, land use changes, and location types. Among these analyses, the location type analysis is a static analysis based on the identification results of three years, while the others are dynamic analyses based on the two time periods of 2000-2010 and 2010-2020.

3.4.1 Spatial transition analysis

Since PUAs are often regarded as transitional spatial entities, it is essential to clarify the direction of their spatial transitions. To this end, I overlaid the identification results from three years, capturing the spatial changes of PUAs during the periods 2000-2010 and 2010-2020. Based on area statistics, I calculated the proportions of spatial transitions into and out of PUAs for each time interval.

3.4.2 Spatial expansion analysis

The development of PUAs is directly related to urban sprawl at the city periphery and land use changes (Angel et al., 2005). I used the Normalized Difference Expansion Index (NDEI) to assess the expansion of PUAs in two time periods. NDEI is commonly employed to evaluate the compactness of urban expansion and determine its extent (Lu et al., 2023b, Liu et al., 2010).

First, newly grown PUAs need to be classified. Based on their location, expansion can be categorized into three types: infilling, edge, and outlying expansion. The classification process involves selecting newly grown PUAs from the identification results. A buffer zone of a certain width is then established around these areas. According to Liu et al. (2010), the buffer width in this study is set at 1 m. Next, the overlap area between the buffer zone and the original PUAs is calculated. If the overlap exceeds 50% of the buffer zone area, the expansion is classified as infilling. If the overlap ranges between 0% and 50%, the expansion is classified as edge expansion. If there is no overlap, the expansion is classified as an outlying expansion.

Based on this classification, the NDEI is calculated for each administrative region in Zhengzhou. The calculation formula is as follows:

$$NDEI = \frac{(Area\ under\ infilling - Sum\ area\ under\ edge\ expansion\ and\ outlying)}{(Area\ under\ infilling + Sum\ area\ under\ edge\ expansion\ and\ outlying)} \quad (4)$$

Where the NDEI value ranges from -1 to +1, indicating the compactness of urban expansion. A positive NDEI value suggests that inward expansion dominates, whereas a negative NDEI value indicates that outward expansion is predominant.

3.4.3 Land use analysis

Land use change plays a crucial role in the urbanization process, as it is both a result of human activities related to land development and a catalyst for altering the natural environment. Consequently, land use planning is often a priority in city planning processes. Analyzing land use within PUAs allows for the effective allocation of different land uses to ensure optimal and appropriate utilization (Akaateba, 2023, Mamun et al., 2024).

Land Cross Transition Matrix enables the analysis of category transitions at different spatial scales (e.g., local and regional levels) to identify factors influencing land use changes (Mamun et al., 2024). Taking the 2020 PUA spatial extent as the standard, and using land use and land cover data of 2000 and 2020, I calculated the ***Land Cross Transition Matrix***, thereby performing a quantitative analysis of the changes in land types within the PUAs.

3.4.4 Location analysis

Although PUAs are geographically situated in the transitional zone between urban and rural areas (Transitional PUA), in polycentric cities, the formation of PUAs is influenced by both the radiative effects of multiple urban centers and rural revitalization efforts. Therefore, I hypothesize that some PUAs may exist within rural areas without direct adjacency to urban regions (Isolated PUA), while others may be located between urban centers (Interurban PUA). These three types of PUAs may exhibit distinct characteristics. Drawing on the buffer zone method used in **Section 3.4.2** ***Spatial expansion analysis***, I classified PUAs into these three categories and further explored their similarities and differences in the subsequent analysis.

The specific classification method for the three types of PUAs is as follows: buffer zones surrounding urban areas were delineated to represent the radiation range of urban influence. Based on experimental analysis, a radius of 5000 m is selected for the buffer zone (***Appendix 3***). This distance effectively encompasses PUAs located at the urban periphery while also distinguishing PUAs situated between adjacent urban areas, where they are influenced by multiple urban centers. ***Figure 3.10*** illustrates the classification process for these three types of PUAs.

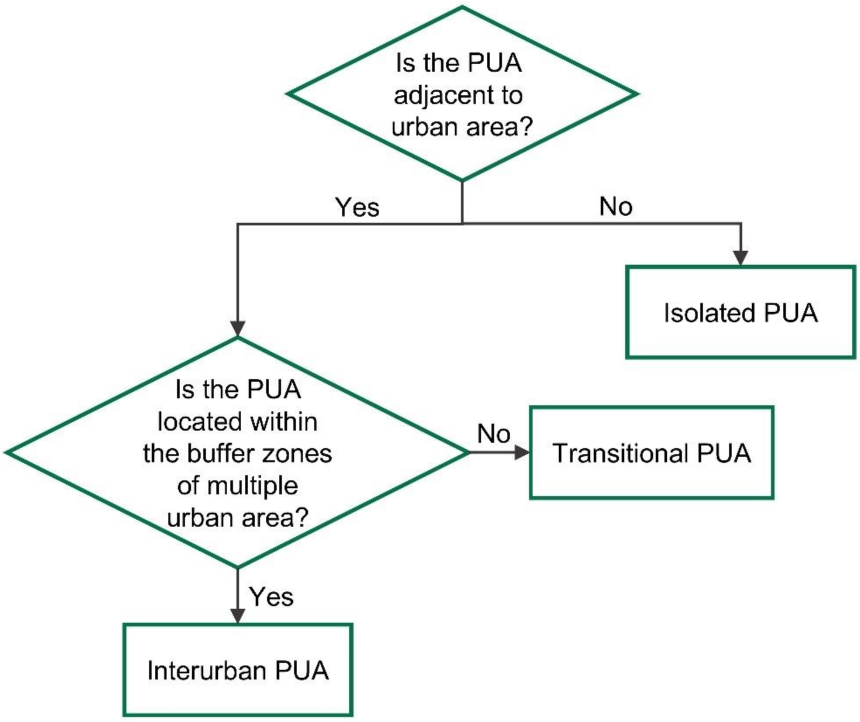

Figure 3.10: Classification process of the three location types of PUAs.

3.5 Evolution analysis of indicators along the urban-rural gradient

Although there are different theoretical perspectives and research sites on PUAs, what ultimately drives the exploration of these spaces seems to be the attempt to clarify their main characteristics. The exploration of the features of PUAs helps in understanding and explaining their value and uniqueness (Kropf, 2012). Currently, many studies have not yet quantitatively clarified the heterogeneity of PUAs, whether in relation to rural and urban areas or the differences between various categories within them (Petrovici and Poenaru, 2025).

In Section 3.2.1, four indicators were selected to identify PUAs, and the hypothesis was proposed that PUA indicator values fall between those of urban and rural areas. However, the specific range of indicator values for PUAs along the urban-rural gradient remains to be explored. Previous studies have suggested that within the continuum from urban to rural areas, there is a gradient characterized by decreasing population density and increasing agricultural intensity (Ginsburg et al., 1991). However, the quantification of these gradient changes remains ambiguous. Furthermore, in polycentric cities, the gradient zone spanning both primary and secondary urban centers encompasses a greater diversity of spatial types, making the patterns of indicator variation along the urban-rural gradient even more complex.

To visually illustrate the variation of indicator values along the urban-rural gradient, I delineated cross-sectional profiles extending from the CUA of Zhengzhou to its various sub-centers as the urban-rural gradient zones. The specific procedure is as follows: First, all urban areas from the year 2000 were extracted. Next, the centroid of the CUA was identified as the origin, and lines were drawn connecting this point to the centroids of other urban areas, extending outward to the boundary of the study area. Since Xingyang contains two centroids, one representing the urban center of Xingyang and the other representing the urban center of Shangjie District, the gradient zone from the CUA to Xingyang was drawn to pass through the midpoint between these two centroids. Ultimately, six gradient lines were obtained, each representing a transition from the primary urban center outward to secondary centers and further into rural areas. PUAs are expected to appear along these gradient zones to varying extents. These gradient zones are likely to encompass different stages of urban-to-rural transformation.

Finally, indicator data were sampled at 1 km intervals along these gradient zones, and profile line charts were plotted. This resulted in seventy-two line charts representing the four indicators over three years across six directions. These will be used for spatiotemporal evolution analysis categorized by indicators. One-way analysis of variance (ANOVA) and Tukey HSD post-hoc test were used to test the significance of differences in the indicators on these gradient zones among different spatial types. These operations were performed in IBM SPSS Statistics 26.

Additionally, three types of PUAs along the gradient zones were selected, and their indicator values were subjected to normality tests, variance tests, and post-hoc tests to determine differences between them. If the values follow a normal distribution, one-way ANOVA and Tukey's test will be used for inter-category difference analysis. If the data do not follow a normal distribution, the non-parametric Kruskal-Wallis H test will replace one-way ANOVA, and pairwise comparisons will be conducted using the Mann-Whitney U test with Bonferroni correction to control the error rate.

3.6 Morphological spatial pattern analysis (MSPA)

Morphological Spatial Pattern Analysis (MSPA) is used to detect the morphological characteristics of images and classify them into seven morphological types: *Core*, *Islet*, *Loop*, *Bridge*, *Perforation*, *Edge*, and *Branch* (***Table 3.3***) (Soille and Vogt, 2009). In this study, MSPA was primarily used for the analysis of PULs.

Before conducting MSPA, it is necessary to reclassify the PULs in ArcGIS 10.8.1. The analyzed landscape types are reclassified as the foreground, while other landscape types are reclassified as the background. The reclassified image is then imported into the *Guidos Toolbox*, where the eight-neighborhood analysis method is selected. The edge width is set to a maximum value of 10. The transition parameter is set to 1 to emphasize the role of linear elements as connectors, thereby highlighting bridging areas rather than patch edges (Valeri et al., 2021). The intext parameter is set to 0, ensuring no distinction between the interior and exterior of the landscape types. Once these settings are applied, the analysis is executed to obtain the final classification results.

Table 3.3: Foreground classes and their definitions in MSPA.

MSPA foreground classes	Definitions
Core	Interior area excluding perimeter
Islet	Disjoint and too small to contain Core
Loop	Connected to the same Core area
Bridge	Connected to different Core area
Perforation	Internal object perimeter
Edge	External object perimeter
Branch	Connected at one end to Edge, Perforation, Bridge, or Loop

3.7 Landscape Metrics

Landscape Metrics are tools used to describe the geometric and spatial characteristics of patches (spatially homogeneous entities) or patch mosaics at a specific point in time. They provide information about the composition of the mosaic, such as the proportion of each landscape type or category present within the study area, as well as the shape of the landscape elements. Therefore, Landscape Metrics allow for the measurement of the spatial and temporal arrangement of landscape elements (Leitao and Ahern, 2002). In particular, Landscape Metrics used to assess urban growth provide a range of values that reflect different growth patterns, such as variation, clustering, fragmentation, division, and physical connectivity (Cervelli and Pindozzi, 2022a, Kaminski et al., 2021). When these metrics are used in combination, they form a comprehensive framework for understanding the complexity of the structure and composition of landscapes undergoing urban expansion (Akın and Erdoğan, 2020, Salem and Tsurusaki, 2024). For example, Landscape Metrics have been widely applied to analyze the impact of urban growth on the fragmentation of peri-urban farmland (Yu et al., 2018, Zhou et al., 2022).

Currently, more than one hundred Landscape Metrics exist. Many of these metrics are often highly correlated and can be easily confused. Therefore, when selecting metrics, their relative independence should be considered. In previous studies, methods such as PCA and correlation matrices have been commonly used to filter Landscape Metrics (McGarigal, 1995). Building on these studies, I primarily reference the work of Leitao and Ahern (2002). In their study, landscape structure is described as comprising two fundamental components: *Composition* and *Configuration*. Based on this structure, a set of fundamental metrics suitable for sustainable planning was proposed.

Composition is a non-spatially explicit characteristic. It does not measure or reflect the geometric shape, geographic location, or spatial arrangement of patches but instead quantifies landscape attributes such as the number, proportion, richness, evenness, and diversity of landscape patch types (McGarigal, 1995). The Landscape Composition Metrics I selected include Percentage of Landscape (PLAND), Patch Density (PD), Mean Patch Area (AREA_MN), and Shannon's Diversity Index (SHDI) (***Table 3.4***).

In contrast, Configuration pertains to the spatially explicit characteristics of land cover types within a given landscape, specifically relating to the geometric shape of patches or their spatial distribution. Configuration metrics measure spatial characteristics such as size and shape (Forman, 1995); the number and type of edges, including edge contrast; or the relative position of patch types in relation to one another. The Landscape Configuration Metrics I selected include Mean Perimeter-Area Ratio (PARA_MN), Total Edge Contrast Index (TECI) (with edge contrast values for different landscape types set as shown in ***Table 3.5***), Mean Proximity Index (PROX_MN) (with search radius of 1000 m), and Contagion (CONTAG) (***Table 3.4***).

These Landscape Metrics were calculated using the *Fragstats* software. The analysis of landscape-level and class-level metrics in Fragstats provides a strong conceptual and theoretical foundation for understanding landscape structure and change (Singh et al., 2014). The selected Landscape Metrics were computed at both the landscape and class levels within PUAs. Subsequently, these metrics were analyzed across spatial and temporal dimensions to identify the structural evolution of PULs.

Table 3.4: Landscape structure and Landscape Metrics.

Landscape structure	Landscape Metrics	Unit	Annotation
Composition	Percentage of Landscape (PLAND)	%	PLAND measures the proportion of each category within the landscape (Weng, 2007). In PUAs, variations in PLAND provide valuable information about the distribution and prevalence of land expansion, marking a shift in landscape patterns (Salem, 2024).
	Shannon's Diversity Index (SHDI)	Unitless	SHDI measures the diversity of landscape types. A higher value indicates a richer variety of different land cover types in the landscape, signifying greater landscape diversity; a lower value indicates fewer landscape types, potentially leading to a more homogeneous landscape.
	Patch Density (PD)	Patches/km^2	PD measures the spatial distribution of patches in the landscape. It represents the number of patches per unit area and reflects the degree of landscape fragmentation and heterogeneity.
	Mean Patch Area (AREA_MN)	km^2	AREA_MN measures the average patch size of a particular patch type. If the AREA_MN is small, it indicates that the landscape is fragmented.
Configuration	Mean Perimeter-Area Ratio (PARA_MN)	m/ha	PARA_MN measures the shape complexity of patches. A lower value indicates that the patches have regular shapes with simpler boundaries, while a higher value suggests that the patches are irregular in shape with more complex boundaries. This index is associated with edge effects and landscape fragmentation.
	Total Edge Contrast Index (TECI)	Unitless	TECI reflects the heterogeneity of the landscape and the intensity of edge effects by calculating the boundary contrast between different patch types. Higher values indicate greater boundary contrast between different patch types in the landscape, which may lead to more pronounced edge effects.
	Mean Proximity Index (PROX_MN)	ha/m^2	PROX_MN measures the degree of proximity between patches, reflecting the spatial connectivity of the landscape. It not only considers the distance between patches but also incorporates patch area and distribution density, providing a more comprehensive assessment of landscape connectivity. Higher values indicate that patches are closer together, suggesting greater connectivity in the landscape; lower values indicate greater distances between patches, resulting in habitat fragmentation and reduced connectivity.
	Contagion (CONTAG)	%	CONTAG measures the relative aggregation of different patch types at the landscape scale. High levels of

Landscape structure	Landscape Metrics	Unit	Annotation
			CONTAG may indicate that patches are highly aggregated, suggesting a relatively intact landscape. Low values indicate that patches are dispersed, which may be caused by human activities such as urbanization and agricultural development.

Table 3.5: Edge contrast settings for different landscape types.

Landscape type	Agricultural landscape	Green landscape	Water landscape	Artificial landscape
Agricultural landscape	0	0.4	0.6	0.8
Green landscape	0.4	0	0.5	0.7
Water landscape	0.6	0.5	0	0.9
Artificial landscape	0.8	0.7	0.9	0

3.8 Planning framework of PUAs and PULs

Early discussions on PULs regarded these areas as chaotic and wild (MacKaye, 1990). However, recent literature offers an alternative interpretation, recognizing their unique value in mitigating urban-rural polarization and controlling urban sprawl (Arts et al., 2017, Olwig, 1996, Wu, 2020, Tan et al., 2024). Therefore, planning these areas is crucial for the provision of important landscape services and management. Such planning does not necessarily have to be implemented through rigid frameworks but can also be integrated and harmonized with urban and rural planning across different spatial scales (Gottero et al., 2023).

This section synthesizes PUL planning experiences from various case studies through a literature review and analyzes the current challenges faced by PUAs in Zhengzhou. Based on these experiences and challenges, regional-level and local-level planning guidelines are proposed for the PULs in the study area.

The challenges of PUAs in Zhengzhou are identified through an overlay analysis of the Built-up Areas and PUAs, as well as by summarizing the structural and morphological issues within the PULs. In China's urban planning, the determination of urban development boundaries and the delineation of land use areas are typically achieved through the designation of Built-up Areas. A Built-up Area specifically refers to land within an administrative boundary that has been requisitioned for non-agricultural production and construction, including both contiguous urbanized areas and suburban areas with relatively well-developed municipal infrastructure. Areas included within the Built-up Areas generally receive greater attention from local governments and are subject to detailed planning and management. Therefore, analyzing the overlap between Built-up Areas and PUAs can provide a rough estimate of the proportion of PUAs that are under formal planning and governance versus those that are undergoing unregulated development. The boundary of the Built-up Areas in Zhengzhou is issued by the Zhengzhou Municipal Government, and currently, only the Built-up Areas maps from 2018 and onwards have been published. Therefore, I only compared the Built-up Areas and PUAs for the year 2020.

At the regional level, quantitative data on the morphological and structural evolution of PULs across spatial and temporal dimensions serve as a key foundation. These data assist planners in developing context-specific sustainable planning strategies, predicting the ecological impacts of planning activities, and monitoring the evolution of PULs.

Currently, the concept of PUAs is not explicitly recognized in China's urban planning framework. However, certain policy documents describe transitional zones between urban and rural areas. For example, in the *Key Tasks for New Urbanization and Urban-Rural Integration Development in 2022* issued by the State Council of the People's Republic of China, one of the key objectives is to "continuously optimize the spatial layout and form of urbanization." Specifically, this includes promoting coordinated development among large, medium, and small cities as well as towns. On one hand, megacities experiencing high population density and continued population inflows are encouraged to implement orderly functional decentralization and improve suburban new towns. On the other hand, promotes urbanization with towns as key carriers.

There is a degree of overlap between towns and PUAs, as both play a crucial role in linking urban and rural areas. Therefore, at the local level, three towns with prominent peri-urbanization phenomena were selected from the study area as case studies (***Figure 3.11***). Their evolution and existing issues were analyzed using a combination of historical imagery, street view maps, and field surveys. Based on the specific characteristics of these areas, targeted landscape planning guidelines were proposed.

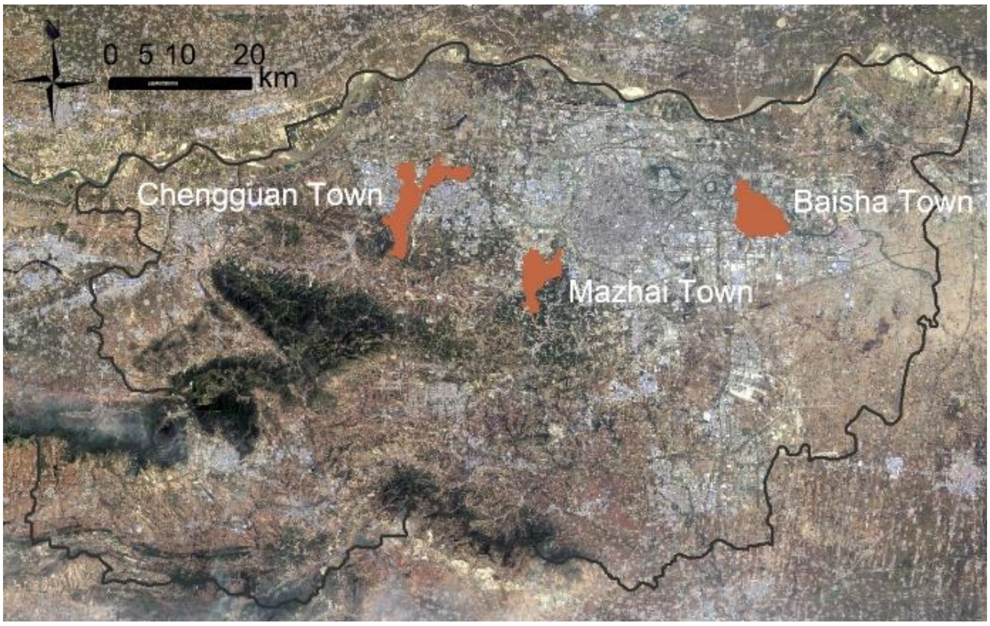

Figure 3.11: Three case towns in the PUAs and PUL planning at the local level.

4. RESULTS AND DISCUSSION

4.1 Comparison of identification results

I obtained three identification results from the above methods. For peri-urban areas (PUAs) identified by the threshold method, the range of the comprehensive index value is from 0.0927 to 0.2148. The PUAs encompass 468 administrative units, covering an area of 1215.15 km², which accounts for 16.06% of Zhengzhou's total area (***Figure 4.1***). The Breakpoint Clustering identified 2251 breakpoints, comprising 1702 breakpoints with downward shifts (719 Urban to Peri-urban (UP) breakpoints and 983 Peri-urban to Rural (PR) breakpoints) and 549 breakpoints with upward shifts (186 Peri-urban to Urban (PU) breakpoints and 363 Rural to Peri-urban (RP) breakpoints). Based on these points, the boundaries of the PUAs were delineated (***Figure 4.2***), covering an area of 1138.30 km², representing 15.08% of the total city area. The PUAs identified by the Multilayer Perceptron model span 1074.00 km², making up 14.19% of the total city area (***Figure 4.3***).

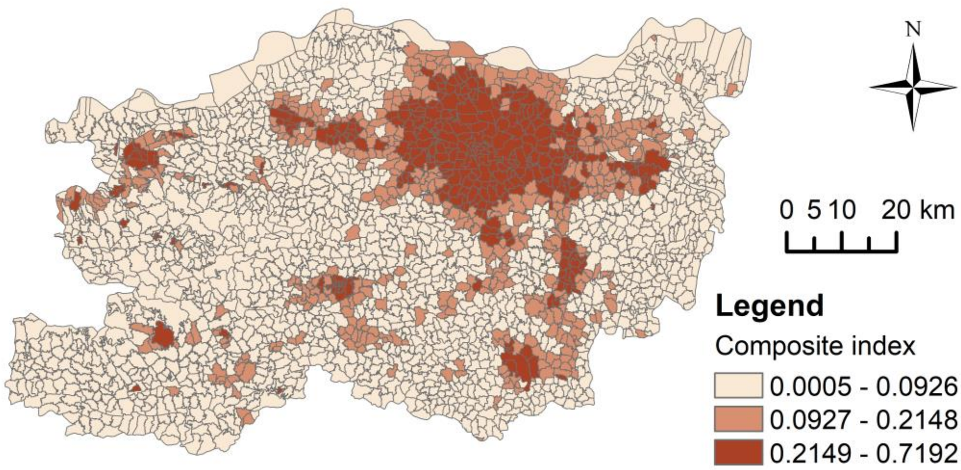

Figure 4.1: Identification result of the Threshold method.

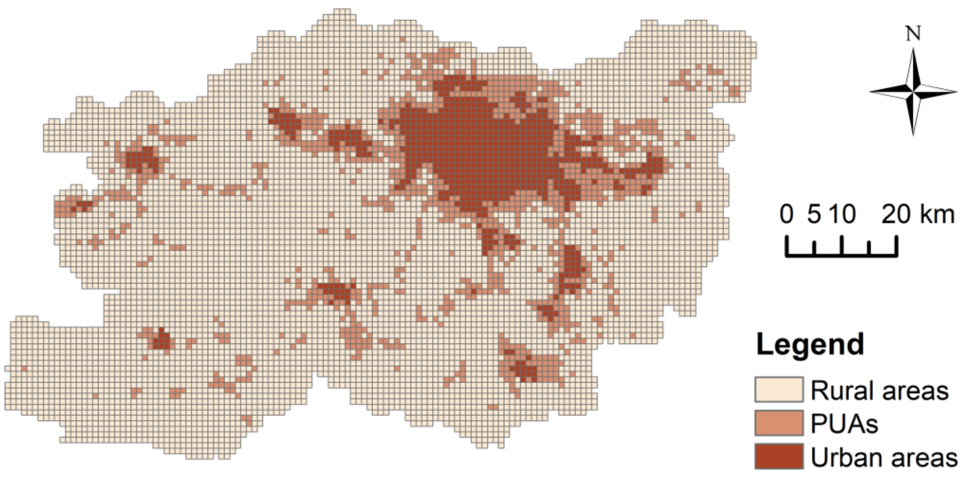

Figure 4.2: Identification result of the Breakpoint Clustering.

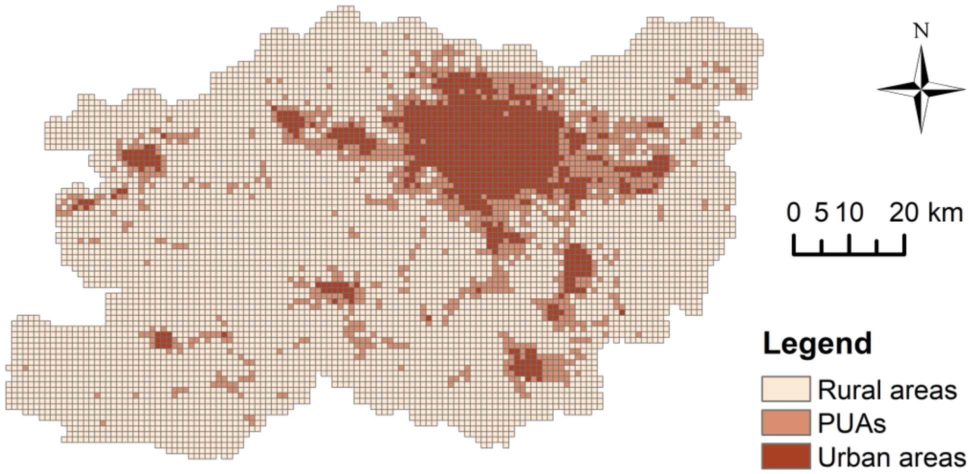

Figure 4.3: Identification result of the Multilayer Perceptron model.

The similarities and differences in the identification results of the three methods can be observed in ***Table 4.1***. These results collectively demonstrate that urban areas have the smallest area, while rural areas have the largest. The area of PUAs is slightly larger than that of urban areas but significantly smaller than that of rural areas. For PUAs, the Threshold method identified the largest area, while the Multilayer Perceptron model identified the smallest area. Conversely, the situation was entirely opposite in rural areas, with Multilayer Perceptron model results closely resembling those of the Breakpoint Clustering. For urban areas, the Threshold method identified the largest area, followed by the Multilayer Perceptron model, with the Breakpoint Clustering identifying the smallest area.

Table 4.1: The areas of urban, peri-urban and rural areas identified by the three methods.

Method	**Urban areas (km^2)**	**PUAs (km^2)**	**Rural areas (km^2)**
Threshold method	890.96	1215.15	5458.75
Breakpoint Clustering	719.00	1141.00	6038.00
Multilayer Perceptron	773.00	1074.00	6051.00

The kappa coefficient for the Threshold method was 0.8504, for the Breakpoint Clustering it was 0.9149, and the Multilayer Perceptron model achieved the highest kappa coefficient at 0.9422. Further analysis using the *Intersect* tool in ArcGIS 10.8.1 revealed that the identification results of PUAs by the Breakpoint Clustering and Multilayer Perceptron model exhibited higher overlap, indicating greater consistency. The overlapping area of PUAs identified by all methods amounted to 590.98 km^2, which accounts for approximately half of the area of PUAs in each result. In the non-overlapping areas, the area of non-overlapping PUAs identified by the Threshold method significantly exceeds that identified by the other methods, suggesting substantial differences between this result and the other two (***Figure 4.4***).

Previous studies have documented the significance of spatial identification of PUAs; Mortoja and Yigitcanlar (2022), for example, provide evidence from the case of the Brisbane metropolitan area in Australia regarding the consequences of unclear boundaries for PUAs, including misalignment in regional planning, the transition of green spaces to urban land, and obstacles to sustainable development. Cattivelli (2021b) introduced legislation and planning documents related to PUAs in Italy, but analysis revealed that the lack of specific spatial delineation for PUAs hindered the effective implementation of these laws and plans. However, there is currently a lack of comparative studies that visually contrast various PUA identification methods, which could serve as a reference for researchers when selecting the most suitable method.

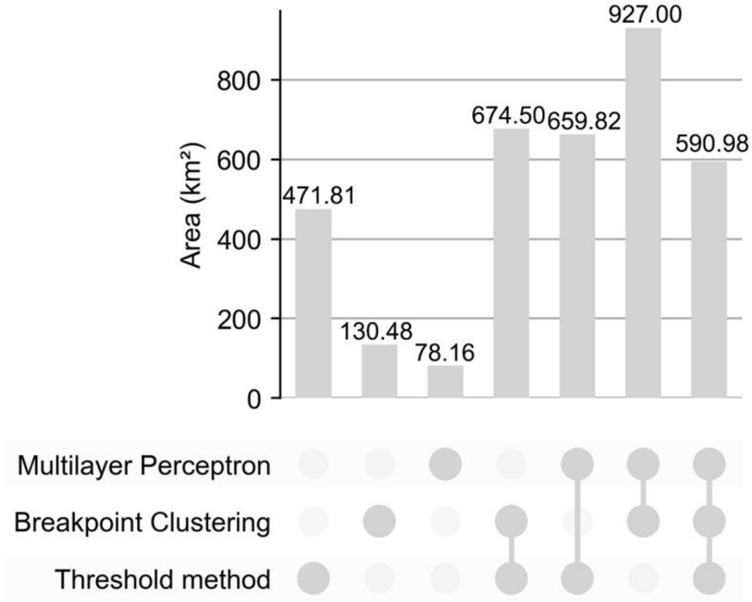

Figure 4.4: Overlapping areas of PUAs identified by three methods (The bar chart displays the overlapping areas of PUAs identified by the methods corresponding to the deep grey circles at the bottom).

In this study, I provided detailed examples of quantitative identification methods for PUAs. The use of the same study area and indicator system allows for comparability among the PUA identification results obtained through different methods, leading to intuitive comparative outcomes. Additionally, I further evaluated these methods from the perspectives of research units, operational processes, and applications.

Firstly, regarding the selection of research units, the Threshold method employs units whose area is not fixed, contrasting with the fixed-size units used by the other two methods. Among the 2,461 administrative units, only 217 units are smaller than 1 km^2 . The largest administrative unit even reaches 42.25 km^2 . This inconsistency in the size of units could impact the accuracy of indicator calculations, thereby reducing the precision of results to some extent.

Secondly, in terms of the operational process, the complexity of the Breakpoint Clustering and Multilayer Perceptron model is significantly higher than that of the Threshold method. The Breakpoint Clustering involves multiple steps and tools, primarily relying on statistical theories to conduct detailed data analysis, which is time-consuming. The Multilayer Perceptron model requires high accuracy for samples and often necessitates the integration of various methods, such as remote sensing imagery and field surveys for sample selection. Additionally, it demands substantial training data and expertise in machine learning, which could become a barrier to its widespread adoption. In contrast, the Threshold method is the simplest in terms of operational steps and can directly utilize existing government data.

On the application level, the Threshold method is widely used in studies concerning PUAs. In contrast, the Breakpoint Clustering and Multilayer Perceptron model can more accurately capture the complex boundaries of PUAs. From a macro perspective, the PUA identification results obtained using the Threshold method have a broader range and are based on administrative units, making them more conducive to planning and policy formulation. In contrast, the Breakpoint

Clustering and Multilayer Perceptron model can identify PUAs not only at a macro level but also play a role in refined design and management phases. The Breakpoint Clustering combines the commonly used breakpoint approach and spatial clustering from previous research and can be applied to identifying PUAs across various scales and regions. The application of machine learning in PUA identification is still in its early stages, and the use of the Multilayer Perceptron model in this field has not yet become widespread. In the future, exploring the extension of this method to more areas holds potential research value.

Ultimately, I chose the Multilayer Perceptron model with higher accuracy and broader applicability for the analysis of spatiotemporal evolution. In polycentric cities, the multi-dimensional indicators of PUAs exhibit more complex changes, and there are regional differences. This model has a strong learning ability for the selected samples. Moreover, after setting the parameters and functions, I can quickly obtain the classification results for multiple years. However, my comparison results also have limitations. Firstly, I only used one year of data and one research area. Further research can use data from multiple years and increase the number of comparison areas. Secondly, I only selected three identification methods. In future research, more methods such as random forests and principal component analysis can be compared to obtain more comprehensive conclusions.

4.2 Spatiotemporal evolution of PUAs

I employed the Multilayer Perceptron model to identify the PUAs of Zhengzhou for the years 2000, 2010, and 2020. The results were then interpolated to a 100 m resolution for further analysis (***Figure 4.5***). Both urban areas and PUAs exhibit an expanding spatial extent over time. Correspondingly, the area of rural regions has gradually decreased. This phenomenon is likely a common trend in most regions under the global urbanization context.

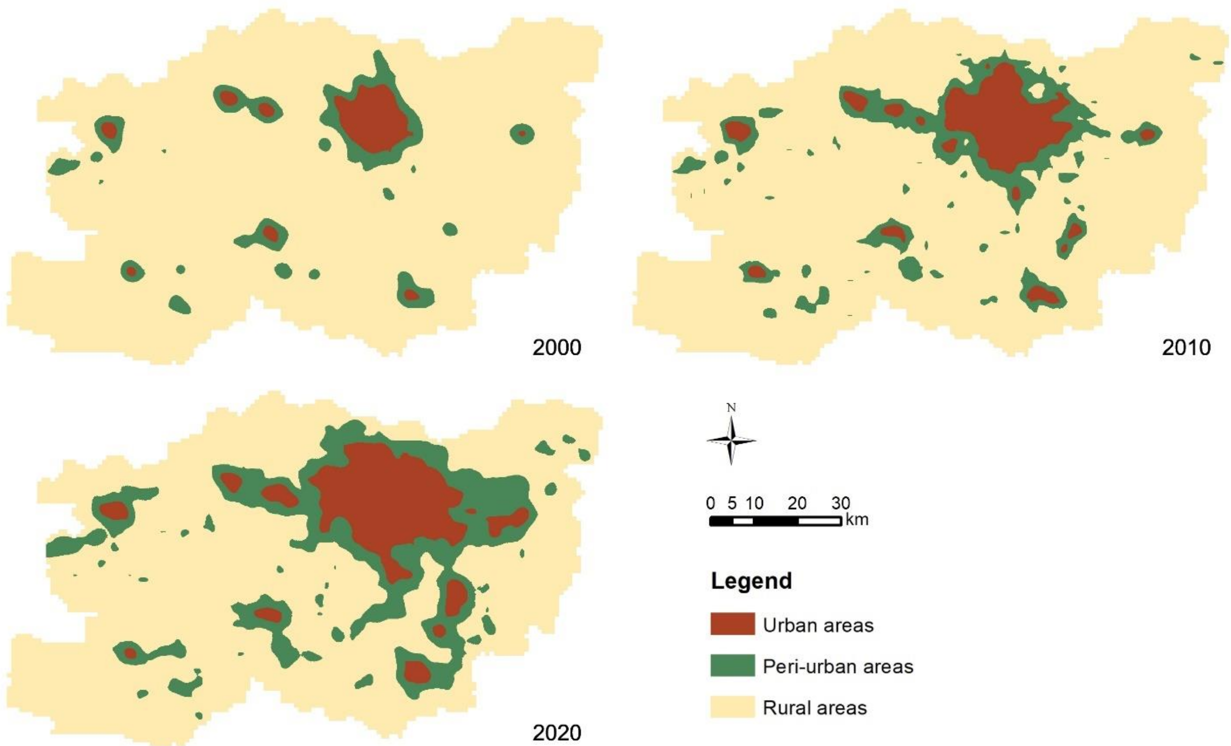

Figure 4.5: Interpolated identification results obtained using the Multilayer Perceptron model.

In the case of Zhengzhou, from 2000 to 2020, the proportion of urban areas consistently remained the lowest, while the proportion of rural areas was always the highest. The area of urban areas expanded by 580.17 km² from 2000 to 2020. The growth in urban areas between 2000 and 2010 (292.48 km²) was similar to that between 2010 and 2020 (287.69 km²). The area of rural areas decreased by 1,513.09 km² from 2000 to 2020, with a reduction of 631.95 km² between 2000 and 2010 and a further decrease of 881.14 km² between 2010 and 2020 (***Figure 4.6***).

The proportion of PUAs was consistently slightly higher than that of urban areas. The area of PUAs increased by 932.92 km² from 2000 to 2020, with more growth occurring between 2010 and 2020 (593.45 km²) than between 2000 and 2010 (339.47 km²) (***Figure 4.6***).

These data indicate that the rate of urban expansion remained relatively stable across the two periods, while the expansion of PUAs accelerated in the latter decade. Consequently, the rate of rural land conversion also increased.

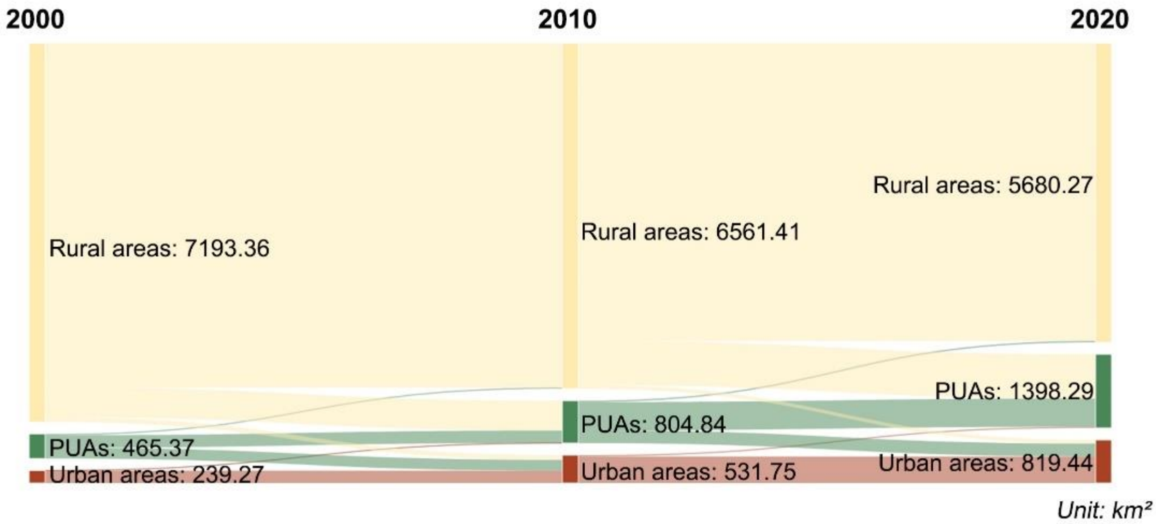

Figure 4.6: Sankey diagram of land area transitions among urban, peri-urban, and rural areas across two time periods.

4.2.1 Spatial transition

Subsequently, I conducted an overlay analysis to explore the spatial transitions of PUAs (***Figure 4.7***). Between 2000 and 2010, 235.74 km² of PUAs remained unchanged. These PUAs are sparsely distributed in the Central Urban Area (CUA), with the majority located in other administrative regions. A total of 205.81 km² of PUAs from 2000 were transformed into urban areas by 2010. These areas were mostly located adjacent to the urban areas, making them the most likely zones to undergo transformation during the urban expansion process. In addition, a portion of PUAs that were not adjacent to urban areas transformed into new urban centers. One such center is located in the southwestern part of the CUA, which is Mazhai Town, primarily a food processing industry cluster and home to three universities (***Figure 4.8a***). The other two centers are situated in Xinzheng: one near the airport (***Figure 4.8b, c***) and the other in Longhu Town (***Figure 4.8d***). The presence of nine universities and an ultra-large-scale commercial and logistics hub has played a significant role in the development of Longhu Town. These three new urban centers demonstrate the leapfrog development of urban areas. The conversion into PUAs was primarily driven by the transformation of rural areas, totaling 565.65 km².

Between 2010 and 2020, an area of 533.24 km² of PUAs remained unchanged. Meanwhile, 243.66 km² of PUAs near urban areas were converted into urban areas. The growth of PUAs in this period, similar to the previous one, primarily resulted from the conversion of rural areas, totaling 840.06 km². Most of these areas transformed from rural areas to PUAs exist in the form of linear strips, connecting many isolated patches and thereby further enhancing the connectivity of PUAs.

Overall, over the past two decades, PUAs have primarily converted into urban areas, with 44.23% and 30.27% of PUAs transforming into urban areas in the two time periods, respectively. At the same time, the increase in PUAs was mainly driven by the conversion of rural areas, and the proportion of these areas that transformed from rural areas in PUAs was 70.28% and 60.08% in the two periods, respectively. Additionally, some reverse transitions have occurred, such as urban areas converting to PUAs or PUAs reverting to rural areas, but these proportions remain minimal.

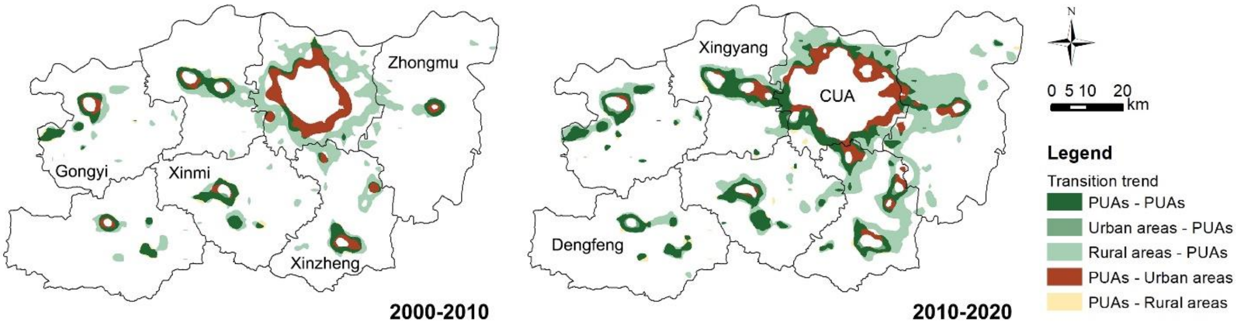

Figure 4.7: Spatial transition maps of PUAs for two time periods.

Figure 4.8: Independent urban centers transformed from PUAs during the period from 2000 to 2010.

4.2.2 Expansion patterns

After classifying the expansion types of the newly grown PUAs, I found that edge expansion has consistently been the dominant expansion type during the research period (***Table 4.2***). Between

2000 and 2010, edge expansion-type PUAs were primarily characterized by ring-shaped and belt-shaped patterns; Infilling expansion-type PUAs were mostly concentrated in Xingyang, where they connected two original PUAs within the city. An infilling expansion-type PUA was also found on the outskirts of the urban area in Xinmi; Outlying expansion-type PUAs, in the form of patches of varying sizes, were scattered across different regions. During the 2010-2020 period, the distribution of infilling expansion-type PUAs expanded. The appearance of some of these areas was closely related to the shifting boundaries of urban areas; The area of each patch of edge expansion-type PUAs increased overall during this period, and there was a trend of integration among the PUAs in the CUA, Xingyang, Xinzheng, and Zhongmu; Outlying expansion-type PUAs were distributed in Zhongmu, Xinzheng, and Xinmi, with both the area and number decreasing compared to the previous period (***Figure 4.9***).

Table 4.2: Expansion areas of newly grown PUAs in the two time periods.

Expansion type	2000-2010 (km^2)	2010-2020 (km^2)
Infilling expansion	20.46	45.07
Edge expansion	478.69	761.75
Outlying expansion	70.04	58.23

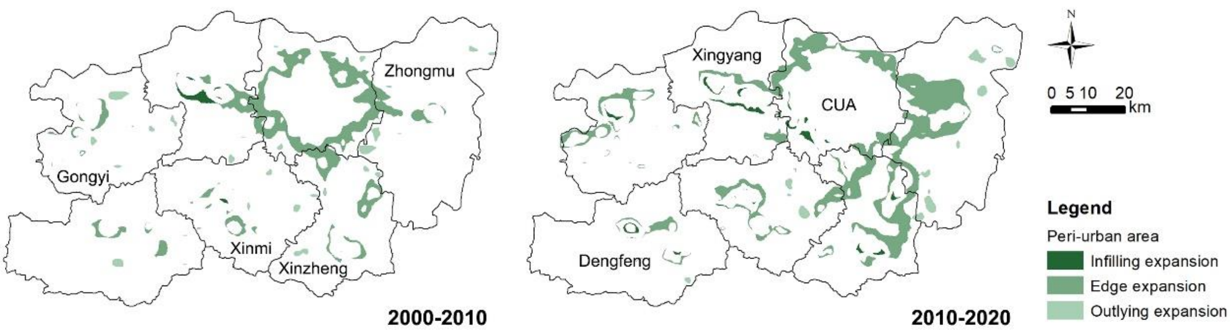

Figure 4.9: Distribution map of expansion types for newly grown PUAs in the two time periods.

Based on ***Table 4.2***, I calculated the overall NDEI of Zhengzhou's PUAs. The PUAs in Zhengzhou exhibit an overall trend of outward expansion. During the period from 2000 to 2010, the NDEI of PUAs was -0.9281. In the following period from 2010 to 2020, the NDEI increased slightly to -0.8958, indicating a marginal weakening in the outward expansion trend of PUAs compared to the previous period.

Subsequently, I calculated the NDEI of PUAs within the seven administrative regions of Zhengzhou. From 2000 to 2010, Xingyang demonstrated the lowest outward expansion trend, while the remaining areas exhibited expansion trends close to absolute outward expansion. In the period from 2010 to 2020, Xingyang continued to have the highest NDEI. Meanwhile, Dengfeng showed a weakening outward expansion trend, as reflected by an increase in its NDEI value. The other areas experienced minimal change (***Figure 4.10***).

Previous studies have made notable findings regarding the expansion of PUAs. For instance, Shi et al. (2012) found that in the period from 2000 to 2008, urban growth in Lianyungang City was primarily characterized by edge expansion, with the continuous urbanization trend of PUAs being the most prominent. Gonzalez-Avila et al. (2020) found that the expansion process of the PUAs in Spain occurred in two stages: the *emergence stage* and the *expansion stage*. Follmann et al. (2023) highlighted that edge expansion and leapfrog development are major patterns observed in many cities in the Global South. These patterns reflect the common trend of urban development in rapidly growing urban areas, where urbanization tends to extend outward from existing urban cores, gradually expanding built-up areas along the periphery and transportation corridors (Follmann, 2022).

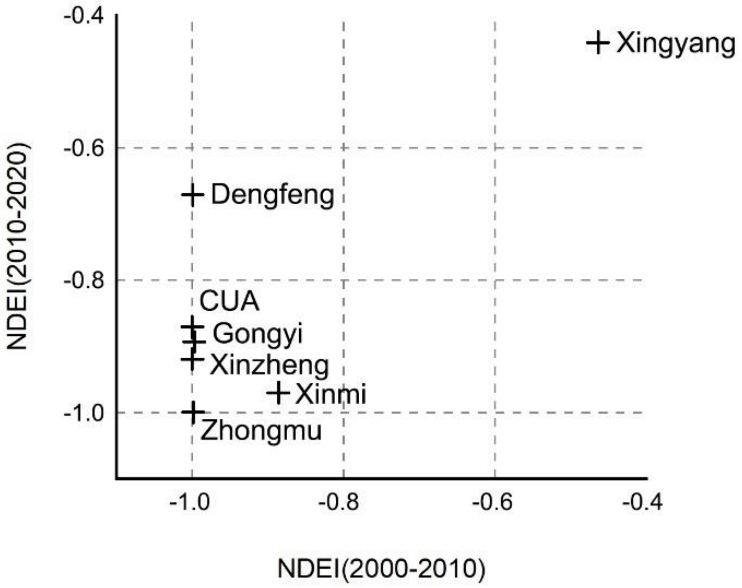

Figure 4.10: NDEI of PUAs within the administrative regions in Zhengzhou during two time periods.

Edge and outlying expansion are often driven by the development of new residential and industrial areas, which signifies the gradual encroachment of PUAs into existing rural areas. As PUAs extend into previously undeveloped regions, fertile land faces growing pressure, exacerbating land fragmentation and degradation. In Cordoba, with population growth and migration flows, the city expanded primarily through edge and outlying expansion, and to a lesser extent, through infill development within the city (Wei and Ewing, 2018). This phenomenon poses significant challenges to agricultural sustainability and food security (Salem et al., 2020), while also having harmful effects on natural ecosystems, severely undermining urban sustainability (Silva and Vergara-Perucich, 2021).

In contrast, infilling expansion is considered more sustainable than edge and outlying expansion because it involves incorporating underutilized land into the urban structure and concentrating land use within already built-up areas. This helps mitigate human pressures caused by daily commuting, energy consumption, air pollution, land use change, and general environmental degradation (Silva and Vergara-Perucich, 2021, Wei and Ewing, 2018). However, infilling expansion may reduce ecological connectivity between green spaces. Therefore, special attention should be paid to supervising the filling process in PUAs to minimize irreversible damage to the surrounding landscape and the loss of sustainability (Akpinar et al., 2016, Marzialetti et al., 2023).

4.2.3 Land use change

Among all land use types in PUAs, agricultural land and built-up land accounted for the largest proportions. In both 2000 and 2010, agricultural land was the dominant land type. However, by 2020, the area of built-up land surpassed that of agricultural land, becoming the most prevalent land type. In contrast, green land and water bodies occupied relatively small proportions. The area of green land showed a slight decline followed by an increase during the study period, while water bodies exhibited a steadily increasing trend (***Figure 4.11***).

The Land Cross Transition Matrix reveals a large-scale conversion of agricultural land into built-up land, reflecting the encroachment of urban expansion on rural areas (***Table 4.3***). Additionally, parts of green land and water bodies were absorbed by urban expansion, while a small portion of these landscapes was converted into agricultural land. Although built-up land exhibited an overall expansion, some areas were reclaimed for agriculture or underwent greening. Overall, agricultural land and built-up land experienced the most significant changes during the peri-urbanization process, whereas green land and water bodies exhibited relatively minor changes.

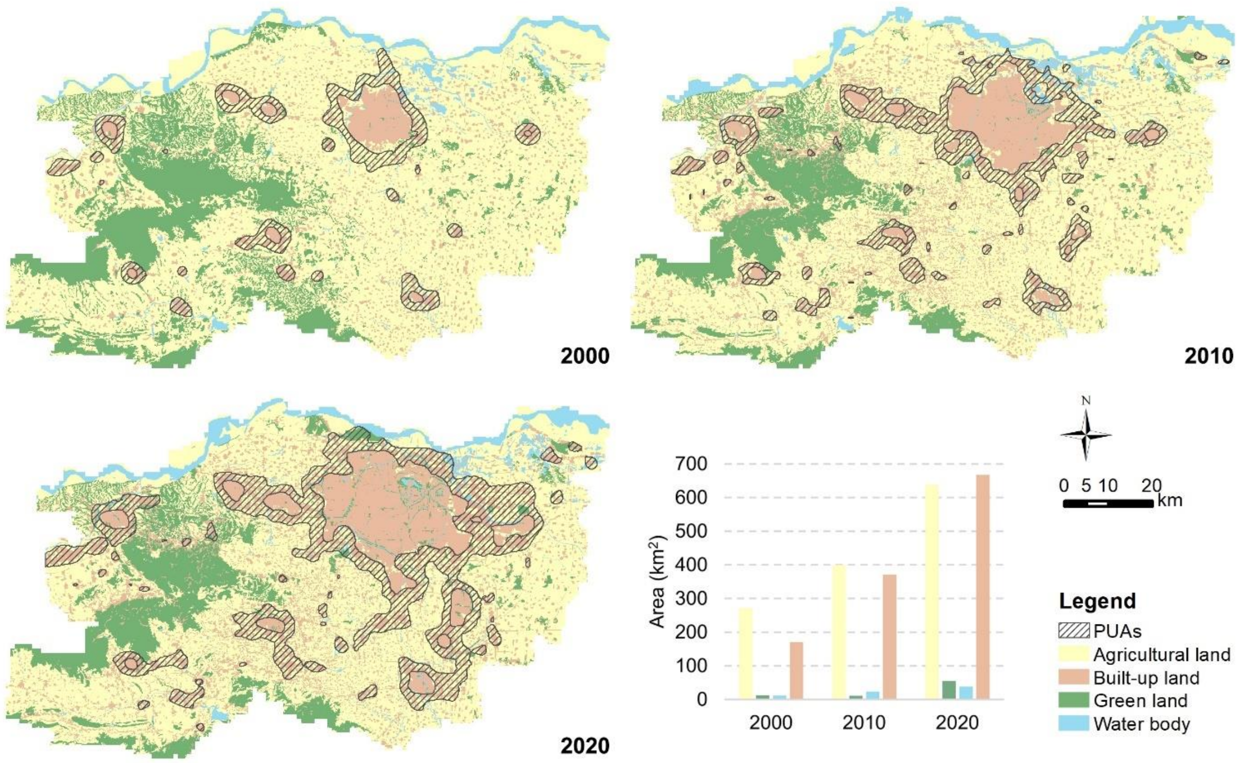

Figure 4.11: Land use maps and area bar chart of PUAs.

Table 4.3: Land Cross Transition Matrix from 2000 to 2020.

Land use type		**2020**			
		Agricultural land	**Green land**	**Water body**	**Built-up land**
2000	**Agricultural land**	558.0508	33.4272	21.655	435.7255
	Green land	20.3759	14.8186	0.383	24.8437
	Water body	8.4161	4.229	14.5486	16.5706
	Built-up land	50.6231	2.6594	1.4741	190.485

Urban expansion is a major driver of agricultural land conversion in urban peripheries (Bren d'Amour et al., 2017, Güneralp et al., 2020, Huang et al., 2019, Zhang et al., 2016a, Zheng et al., 2024a). Over the past two decades, the conversion of agricultural and natural land into built-up land has become a dominant trend in global spatial management. This trend has been observed in various regions, including Poland (Cegielska et al., 2018a, Noszczyk et al., 2017, Cegielska et al., 2024), the United States (Li et al., 2019), China (Fan et al., 2020), Vietnam (Kontgis et al., 2014), and Africa (Asabere et al., 2020). The intensity of this land conversion exhibits significant spatial variability between high-income and developing countries, with a pronounced trend of reducing agricultural areas (Azadi et al., 2021, Zhang et al., 2023).

In China, the per capita agricultural land area is only 0.09 hectares, significantly lower than the global average (Food and Agriculture Organization (FAO), 2022). As a result, the Chinese government places great emphasis on farmland protection and has implemented strict policies to safeguard it (Huang et al., 2019, Lichtenberg and Ding, 2008). However, the inevitable urban expansion driven by China's urbanization process has had a profound impact on peri-urban farmland (Chen, 2007, Güneralp et al., 2020, Wang, 2023, Zhang et al., 2016a), particularly in major cities (Bren d'Amour et al., 2017). Between the 1970s and 2020, 75 major cities in China acquired 55.17% of their newly developed urban land by encroaching on peri-urban farmland (Liu et al., 2021). Moreover, high-quality farmland constitutes the majority of the agricultural land lost to urban expansion, leading to a decline in overall farmland quality (Hu et al., 2018, Song et al., 2015, Wu et al., 2017). The process of peri-urbanization has resulted in significant cropland loss, posing a severe threat to national food security both in terms of quantity and quality (Chen, 2007, Song and Pijanowski, 2014).

In Zhengzhou, real estate developers, factory enterprises, and other investors have shifted their focus to PUAs in pursuit of inexpensive land, while the local government has sought to expand built-up areas to promote economic growth. These factors have driven significant urban land expansion over the past two decades, accompanied by the demolition and urbanization of peri-urban villages. This process involves the removal of dispersed rural settlements and their consolidation into high-rise buildings, while the reclaimed land, along with nearby agricultural land, is repurposed for urban development. Additionally, the large-scale migration of rural labor to urban areas has led to land abandonment, further threatening food security (Song and Pijanowski, 2014, Liu et al., 2016). Thus, similar to most PUAs worldwide, the encroachment on peri-urban farmland during peri-urbanization presents a major challenge for Zhengzhou's PUAs (Zheng et al., 2024a).

4.2.4 Location types

Based on the previously established criteria (***Figure 3.10***), PUAs were geographically classified. In all three years, Transitional PUAs occupied the largest proportion of the total area, making them the most typical type of PUAs. The formation of these PUAs is primarily driven by the radiative influence of urban areas. They are nearly all distributed in a circular or strip-like pattern around the urban periphery (***Figure 4.12***). Although the number of such PUAs initially increased and then decreased, their overall area continued to grow (***Figure 4.13***). This phenomenon reflects, to some extent, the expansion and integration process of urban areas.

Isolated PUAs also experienced an initial increase followed by a decrease in number, while their area continued to grow. In contrast, the Isolated PUAs in 2010 displayed the most fragmented distribution (***Figure 4.12***). This could be due to the fact that in 2000, the peri-urbanization driven by rural industrialization was not yet prominent in Zhengzhou. On the other hand, by 2020, with urban expansion, Isolated PUAs closer to urban areas were transformed into Transitional PUAs, leading to a decrease in their number. However, Isolated PUAs farther from urban areas saw an increase in their area (***Figure 4.13***).

The number and area of Interurban PUAs changed relatively steadily, with an increase observed only during 2000-2010 (***Figure 4.13***). In 2000, there was only one Interurban PUA located between two city centers in Xingyang. By 2010, this Interurban PUA expanded in area as the urban region grew. Additionally, several new urban centers emerged in 2010, and the overlapping radiative influence of these centers on nearby urban areas contributed to the increase in the number of Interurban PUAs. Among the newly generated Interurban PUAs, three were adjacent to CUA, and one was located in Xinzheng. Between 2010 and 2020, there were minimal changes in the number and area of Interurban PUAs, but as shown in ***Figure 4.13***, their geographical locations underwent some shifts. Notably, a large Interurban PUA appeared in the eastern part of the CUA, filling the space between the CUA and the urban region of Zhongmu.

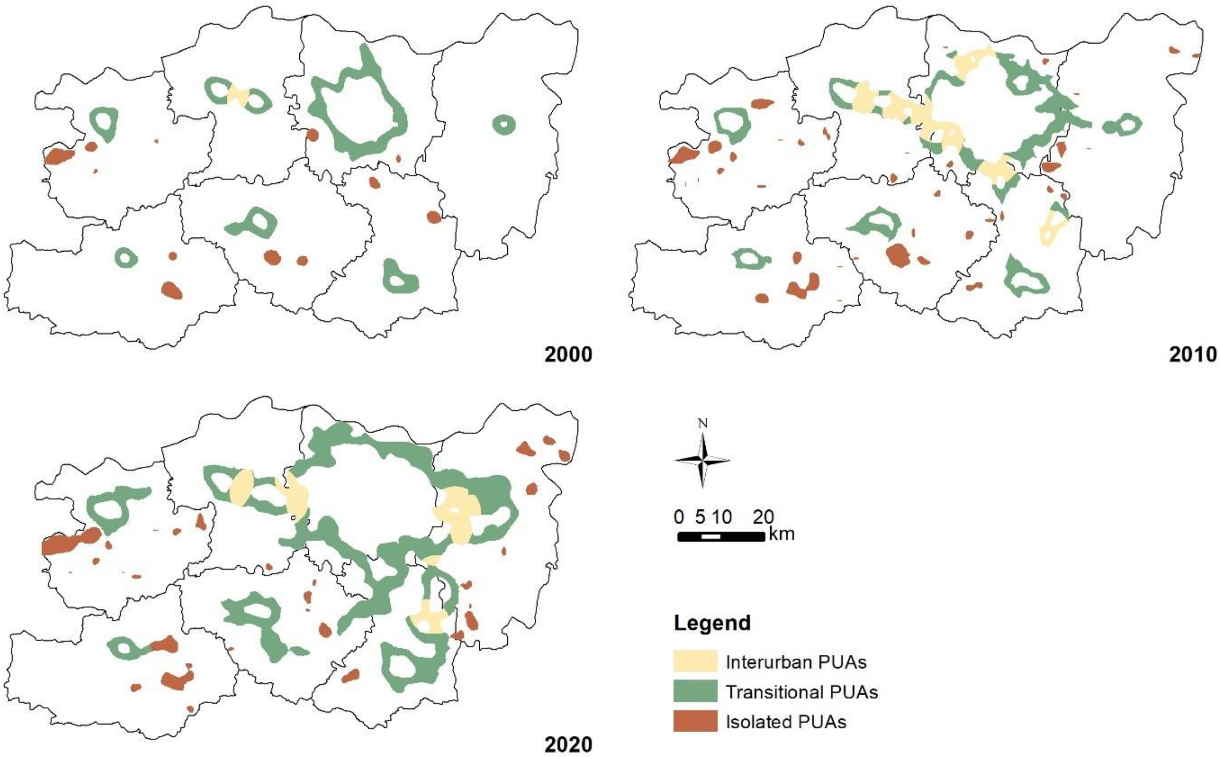

Figure 4.12: Distribution maps of three location types of PUAs.

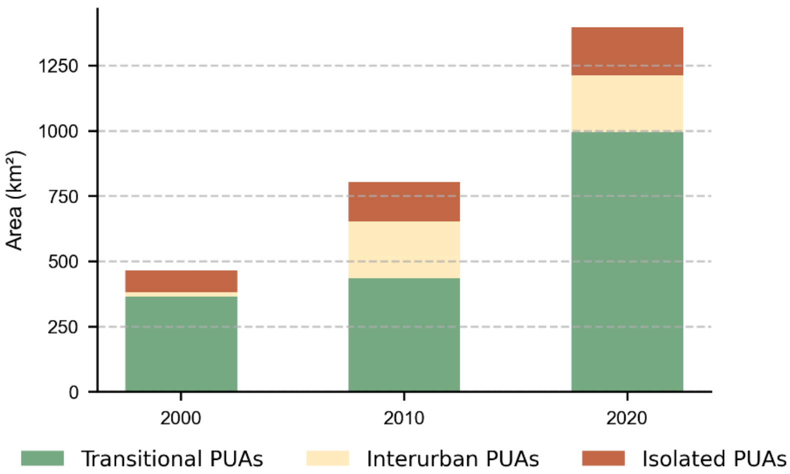

Figure 4.13: Area of the three location types of PUAs.

The different locations of these three types of PUAs result in their varying roles in influencing urban expansion, land use, and socio-economic development. Therefore, different planning strategies should be adopted for each type of PUA in urban planning. For example, Interurban PUAs are typically strongly connected to the transportation and economic networks of urban areas, making them suitable for planning as industrial parks, logistics centers, or new city development zones. However, Interurban PUAs are also highly susceptible to becoming areas of unplanned urban sprawl. To prevent urban disorder and land waste, coordinating the infrastructure in Interurban PUAs to avoid redundant construction should become a key focus of planning in these areas.

Transitional PUAs, as a typical type, often face classic issues associated with PUAs, such as complex and inefficient land use. The conflict between rural collective land and urban state-owned land under China's land system is often a significant problem. In most cases, the expansion of urban state-owned land tends to prevail. However, consideration should also be given to whether rural collective land can find new ways of survival through the development of rural industries (such as urban farms or eco-tourism).

As for Isolated PUAs, their highly bottom-up nature makes them likely to drive the revitalization of surrounding rural areas. However, their island characteristics significantly increase their vulnerability. Due to their smaller size, they currently lack connectivity and should be viewed as potential areas for further development and expansion. Therefore, Isolated PUAs should focus on improving connectivity with external transportation networks and infrastructure to enhance their stability as independent economic centers.

4.3 Multidimensional characteristics of PUAs

Figure 4.14 shows the distribution of six urban-rural gradient zones. Among these gradient zones, the CUA-Dengfeng gradient zone is the longest (92 km) and spans across four administrative regions. The distance between the urban centroids in this gradient zone is also the greatest, at 66 km. In contrast, the distance between the urban centroids in the CUA-Xingyang gradient zone is the shortest, only 24 km. The CUA-Gongyi gradient zone passes through Xingyang and has been crossing through Xingyang's urban areas since 2010, which is in line with the expansion of Xingyang's urban areas. The CUA-Xinmi gradient zone has shown very stable characteristics in terms of spatial type evolution. Spatially, the CUA has exhibited a clear urban expansion trend in the southern and eastern directions, which is clearly evident in the CUA-Xinzheng and CUA-Zhongmu gradient zones (***Figure 4.15***).

These gradient zones also contain PUAs of all three locational types. Transitional PUAs, the most common type, are present across all gradient zones. Interurban PUAs can be found in all gradient zones except the CUA-Xinmi gradient. Isolated PUAs are identified along the CUA-Dengfeng, CUA-Gongyi, and CUA-Xinzheng gradients.

Subsequently, I examined the differences in the performance of the indicators across urban, peri-urban, and rural areas within these gradient zones, as well as the variations among PUAs of the three locational types.

Figure 4.14: Urban-rural gradient zones based on the centroids of urban areas in 2000.

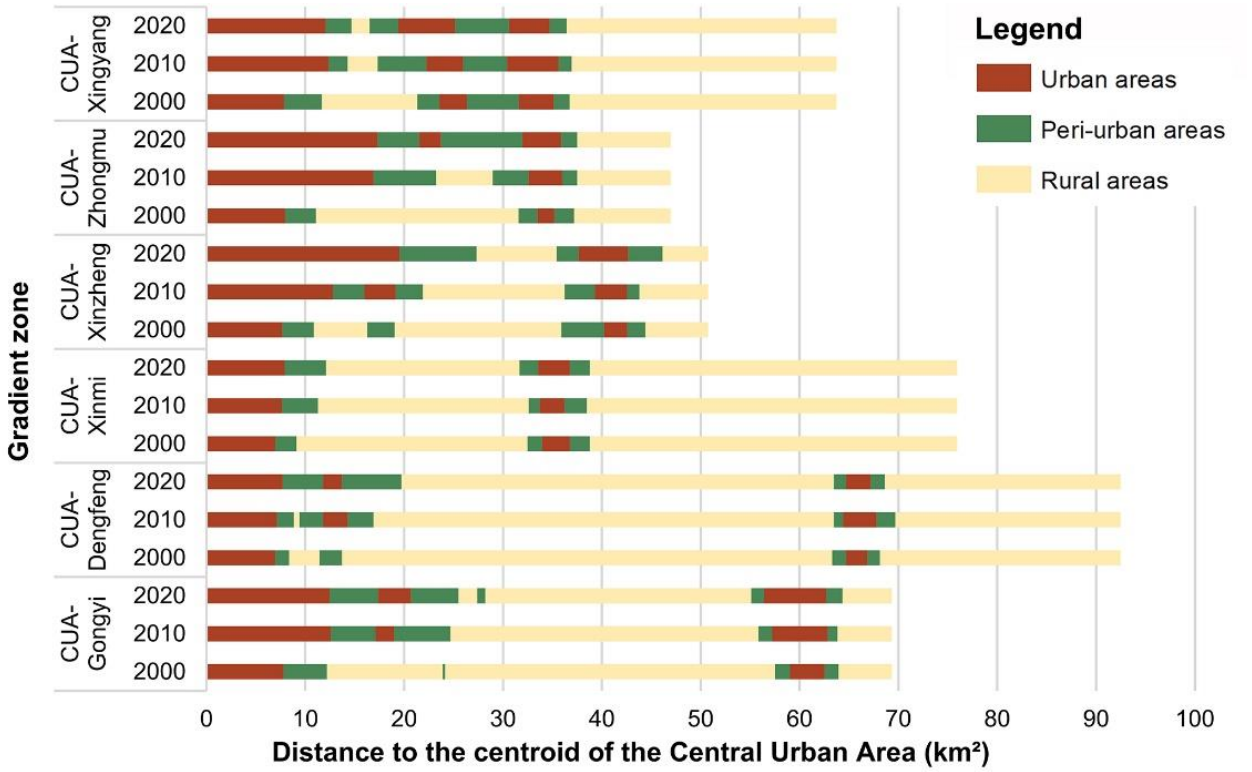

Figure 4.15: Spatial type evolution across the urban-rural gradient zones.

4.3.1 Spatiotemporal evolution of Imperviousness density (ID)

In the gradient zones, the ID shows a decreasing trend from urban to rural areas. As shown in ***Figure 4.16***, regions with high ID values are generally urban areas, with an average value of 0.8072 across the three years. Low ID regions correspond to rural areas, with an average value of 0.0856 over the three years. The ID of PUAs typically falls within a phase of transition, either from high to low or from low to high, with a three-year average value of 0.4656. According to the results of the one-way analysis of variance (ANOVA) and the post-hoc tests, the differences in the mean values of ID among urban, peri-urban, and rural areas were all significant (***Appendix 4***).

From a temporal perspective, the ID values showed an overall increasing trend from 2000 to 2020, with this trend being most pronounced in PUAs. The values for urban and rural areas changed little over time. These changes have led to a gradual narrowing of the gap between urban and PUAs, with the ID values of PUAs gradually shifting closer to those of urban areas. This indicates a significant increase in the construction intensity of PUAs. Among all the gradient zones, the CUA-Dengfeng and CUA-Xinmi gradient zones show the least change over time, while the CUA-Xinzheng and CUA-Zhongmu gradient zones exhibit the most significant changes.

After conducting a normality test on the ID values of PUAs across gradient zones, the data were found to largely follow a normal distribution. Based on this, an ANOVA was performed, revealing significant differences in ID values among the three location types of PUAs ($p = 0.035$). Specifically, Isolated PUAs had the lowest mean ID value, while Interurban PUAs exhibited the highest mean. The standard error of Transitional PUAs was relatively small, indicating a more concentrated distribution. Post hoc tests further revealed a significant difference in ID values between Interurban PUAs and Transitional PUAs, whereas differences among other categories did not reach statistical significance (***Table 4.4***).

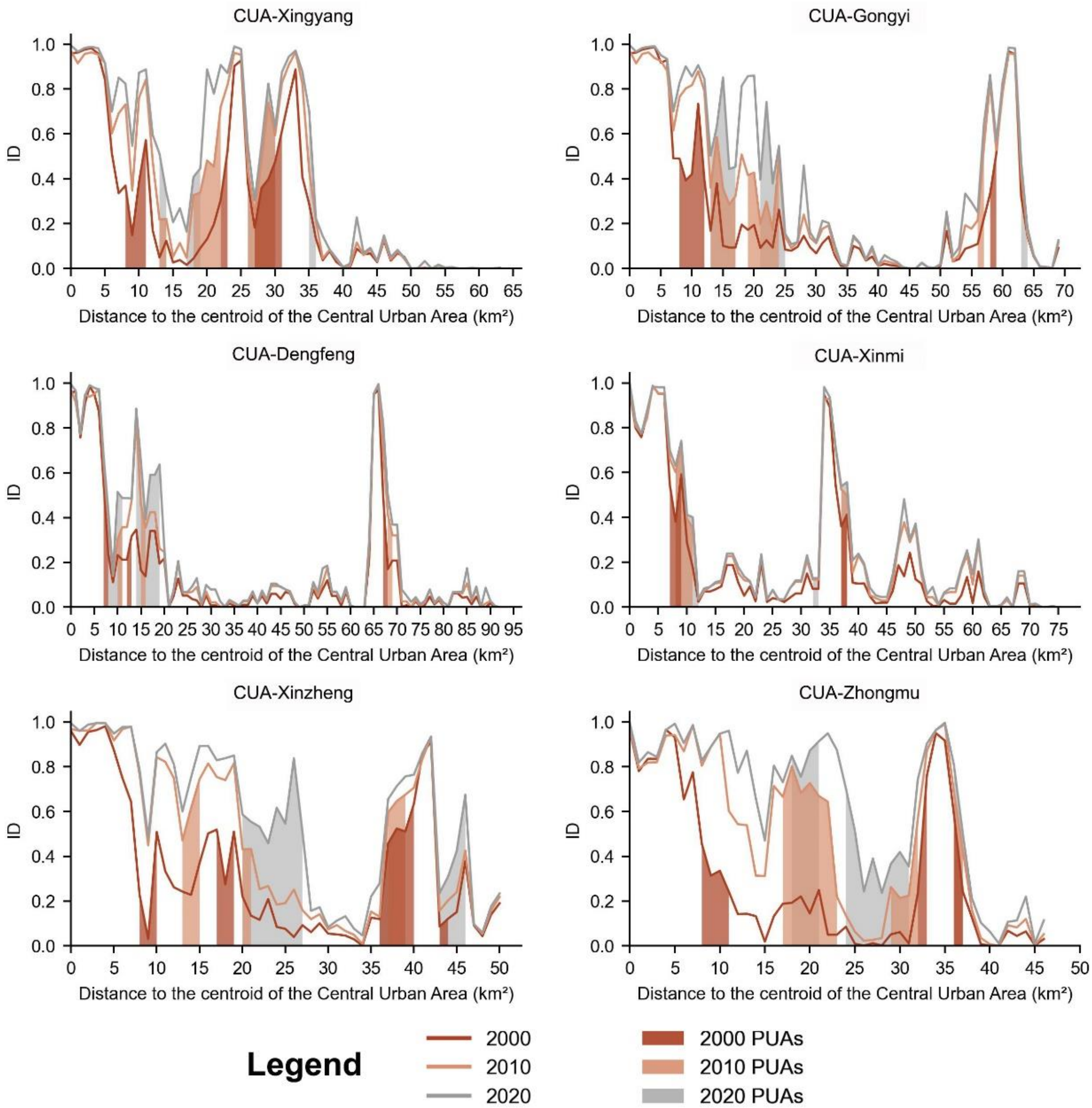

Figure 4.16: Line charts of ID along the gradient zones.

Table 4.4: Results of statistical tests in indicator values among the three locational types of PUAs across the gradient zones.

Indicator	Normality Test	Homogeneity of Variance Test	Parametric Test or Non-parametric Test	Post-hoc Test
ID	0.147	0.562	0.035*	Isolated PUAs *vs* Transitional PUAs: p=0.679 Isolated PUAs *vs* Interurban PUAs: p=0.171 Transitional PUAs *vs* Interurban PUAs: p=0.049*
NLI	0.000***	0.119	0.000***	Isolated PUAs *vs* Transitional PUAs: p=0.120 Isolated PUAs *vs* Interurban PUAs: p=0.034* Transitional PUAs *vs* Interurban PUAs: p=0.121
PNL	0.002**	0.928	0.068	
PCLA	0.000***	0.098	0.636	-

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

4.3.2 Spatiotemporal evolution of Nighttime Light Intensity (NLI)

The NLI in the gradient zones exhibits a decreasing trend from urban to rural areas (***Figure 4.17***). The three-year average NLI value for PUAs is 0.0667, lower than the three-year average NLI value for urban areas (0.2906) but higher than the three-year average NLI value for rural areas (0.0073). Through one-way ANOVA and post-hoc tests, it was found that the mean NLI in urban areas was significantly higher than that in other areas, while there was no significant difference in NLI between PUAs and rural areas (***Appendix 4***). In all the gradient zones, the CUA consistently has the highest NLI, with a significant gap between its highest NLI and those of other administrative regions. Additionally, more distinct breakpoints between urban and PUAs can be observed in the CUA compared to other regions.

Over time, both urban and PUAs show an increasing trend in NLI. For urban areas, two changes occur simultaneously: an increase in NLI values and a shift in the peak of NLI. These changes can be clearly observed in the CUA-Gongyi and CUA-Zhongmu gradient zones. The increase in NLI values for PUAs can be clearly observed in the CUA-Xinmi and CUA-Xinzheng gradient zones. Among all the gradient zones, the CUA-Dengfeng gradient zone exhibits the least temporal change, while the CUA-Zhongmu gradient zone shows the most significant changes.

After testing the NLI values of PUAs, it was found that the data did not follow a normal distribution. Therefore, a non-parametric method was used as an alternative to ANOVA. The results showed that Isolated PUAs had the lowest mean NLI value, while Interurban PUAs had the highest. The NLI values of PUAs in different location categories exhibited significant differences in both median and distribution. Post hoc tests further indicated that the NLI values of Interurban PUAs differed significantly from those of Isolated PUAs (***Table 4.4***).

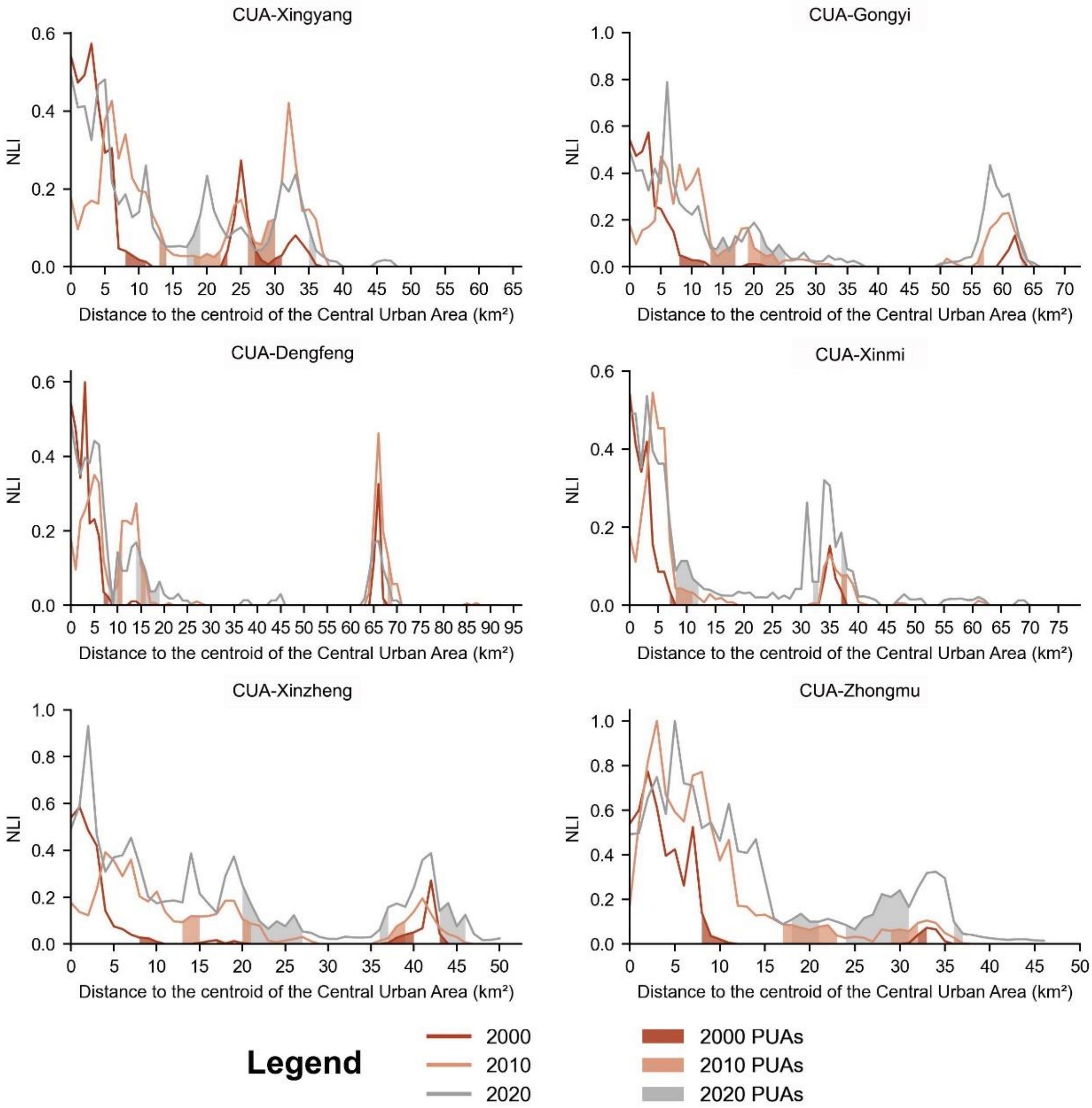

Figure 4.17: Line charts of NLI along the gradient zones.

4.3.3 Spatiotemporal evolution of Proportion of (semi-)natural land (PNL)

Although the PNL generally shows an increasing trend from urban to rural areas along the gradient zones, many exceptions make it difficult to distinguish the values of PNL across different spatial types (***Figure 4.18***). Rural areas have relatively high PNL values, with a three-year average of 0.8793. In contrast, the average PNL for urban areas is only 0.1111, but the range of PNL values in urban areas is quite large, and in some regions, the PNL even exceeds that of the PUAs. This phenomenon can be observed in the CUA-Zhongmu and CUA-Xingyang gradient zones. The average PNL for PUAs is 0.4893, and its range is also large. In gradient zones such as CUA-Xingyang, CUA-Xinmi, and CUA-Xinzheng, there are some PUAs with very high PNL values. The results of the one-way ANOVA showed that there were extremely significant differences in PNL among different regions ($p < 0.001$). Post-hoc tests indicated that there were significant differences in the mean values of PNL among the three regions (***Appendix 4***).

Over time, PNL in the gradient zones has shown a declining trend, which can be attributed to two main situations. The first situation is a slight decrease in PNL values without any change in spatial type. This can be observed in the PNL value changes in rural areas, especially during the 2000-2010 period, where the changes are more evident. The second situation involves a significant decline in PNL values due to changes in spatial types, which is also more pronounced during the 2000-2010 period. Whether it is the transformation of PUAs into urban areas (observed in the CUA-Xingyang and CUA-Dengfeng gradient zones) or the transition from rural to PUAs (observed in the CUA-Xinzheng gradient zone), the decline in PNL values is particularly notable.

Among PUAs, the mean PNL value was highest for Isolated PUAs and lowest for Interurban PUAs. However, the data did not exhibit a clear normal distribution. The Kruskal-Wallis H test indicated that differences in PNL among different location categories were not statistically significant in terms of either median or overall distribution (p = 0.068) (***Table 4.4***).

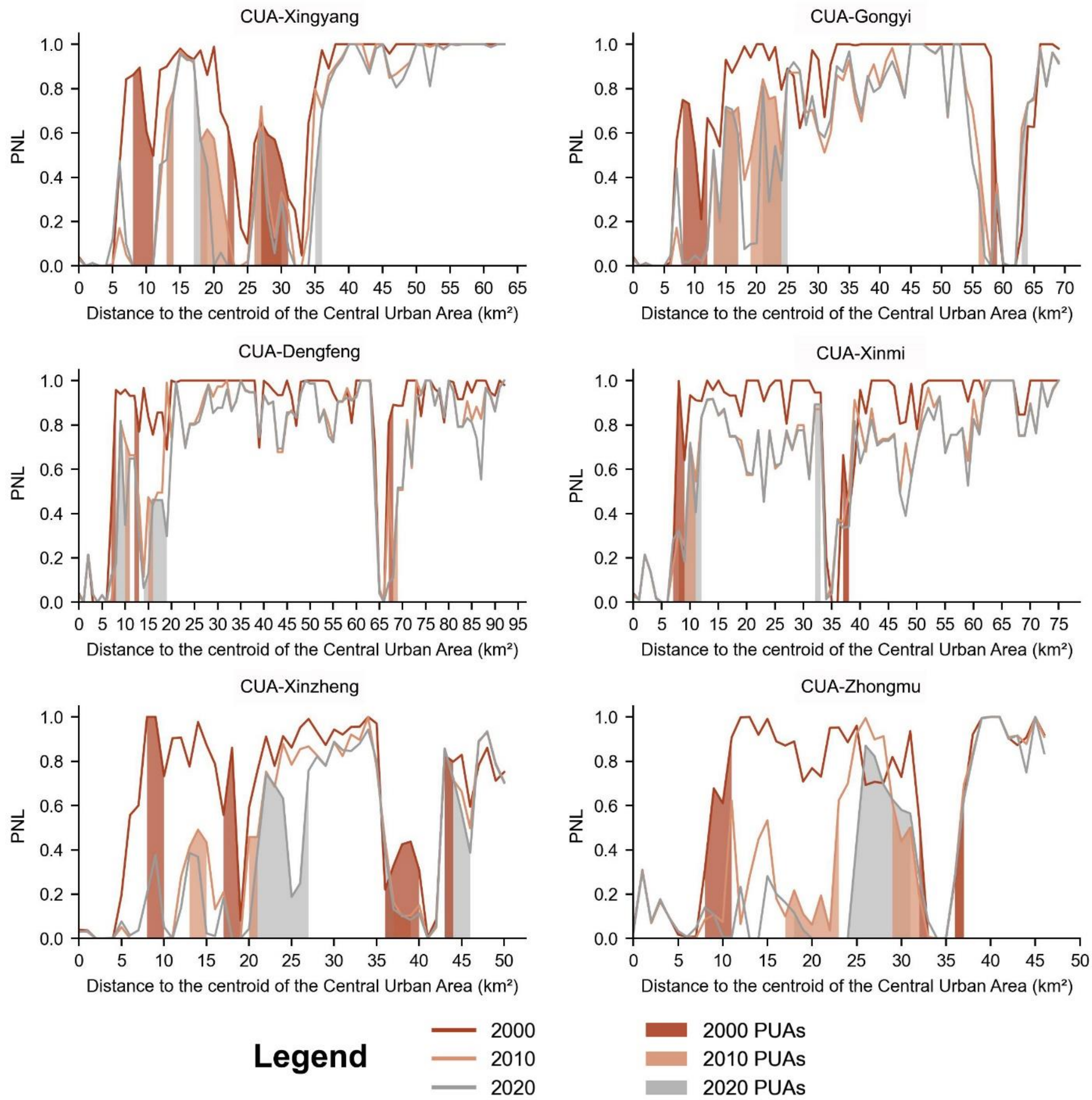

Figure 4.18: Line charts of PNL along the gradient zones.

4.3.4 Spatiotemporal evolution of Per Capita Land Area (PCLA)

The PCLA shows an increasing trend from urban to rural areas along the gradient zones. In ***Figure 4.19***, regions with higher PCLA values are mostly rural areas, with a three-year average of 0.0664. Urban areas, on the other hand, have lower PCLA values, with a three-year average of 0.0050. The average PCLA for PUAs is 0.0164. The results of the one-way ANOVA indicated that there were significant differences in PCLA among the three regions. Through post-hoc analysis, it was found that only the differences in PCLA between urban and rural areas reached a significant level.

The values of PCLA differ significantly across the gradient zones, as shown by the vertical axis. The CUA-Xinmi and CUA-Xingyang gradient zones exhibit very high peak values. These areas with peak values are characterized by natural or semi-natural land types with large patch sizes. In contrast, the CUA-Xinzheng and CUA-Zhongmu gradient zones generally have lower PCLA values, suggesting relatively higher population density in these areas.

In terms of temporal evolution, all these gradient zones show a trend of increase followed by a decrease. In 2010, PCLA reached its highest values in most areas. The decline in PCLA from 2010 to 2020 was quite noticeable, resulting in the PCLA values in 2020 being at their lowest across most gradient zones. The PCLA values of urban and PUAs are relatively close to each other, and over time, the gap between them has been narrowing. The variation in PCLA values also differs across regions: urban areas show the smallest variation, while rural areas exhibit the largest fluctuations.

The PCLA values of PUAs across different location types did not follow a normal distribution but met the assumption of homogeneity of variance. Non-parametric testing revealed no statistically significant differences in PCLA values among different location types (***Table 4.4***).

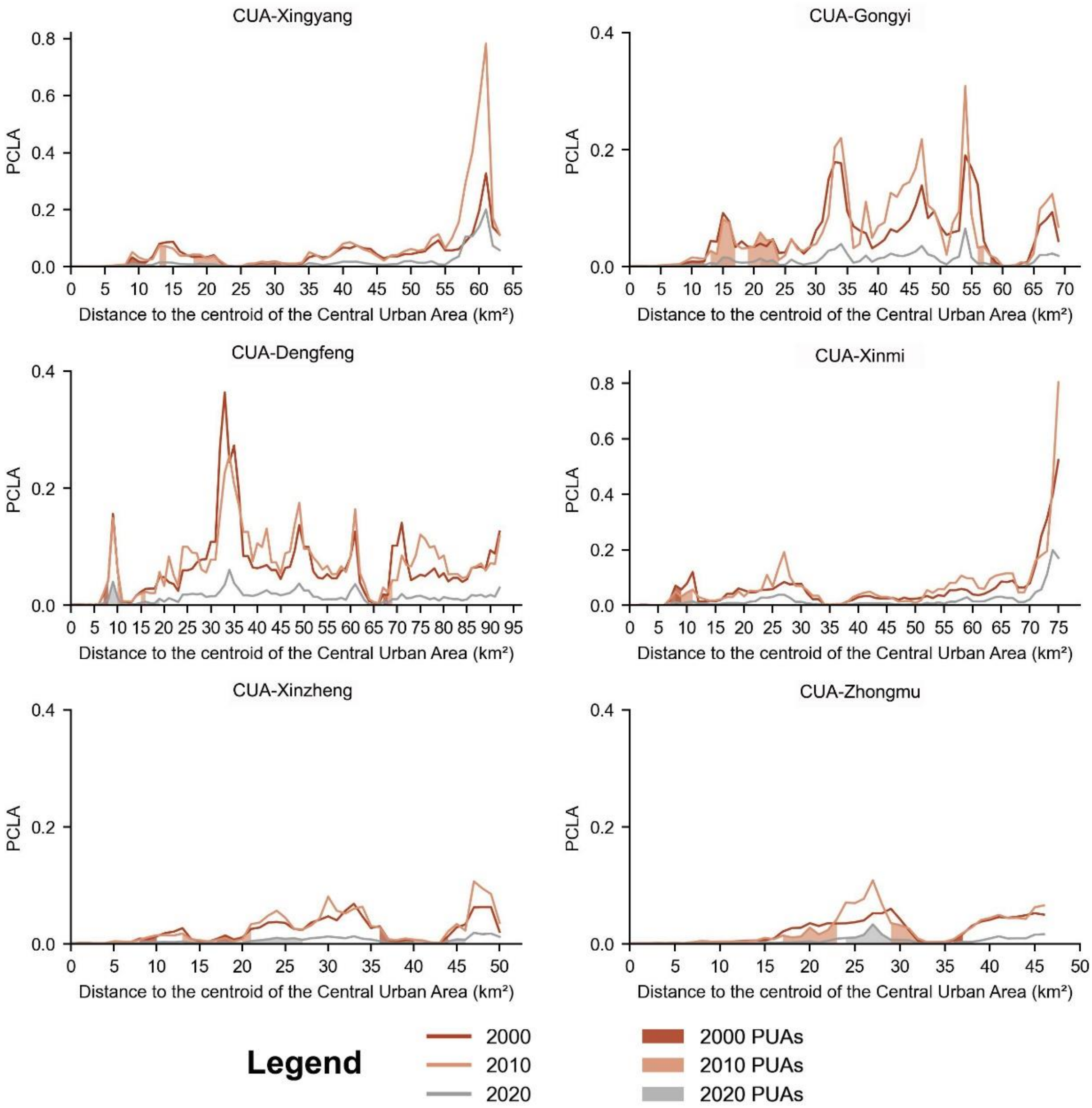

Figure 4.19: Line charts of PCLA along the gradient zones.

4.3.5 Summary and discussion

Through a comparative analysis of multidimensional indicators across urban-rural gradient zones, it was found that the previously hypothesized position of PUAs' indicator values, falling between those of urban and rural areas, holds true. This finding quantitatively supports the hybridity of PUAs. Additionally, the changes observed in PUAs over time clearly reflect their dynamic attributes. Although the dynamic trends of PUAs differ across various indicators, such as the ID and PCLA values of PUAs approaching those of urban areas over time, the NLI of PUAs grows in sync with that of urban areas, while the PNL of PUAs declines and consistently shows a blurred boundary with the PNL of rural areas.

There are also several conclusions in previous studies regarding the hybridity and dynamic nature of PUAs. Cattivelli (2021a) and Sylla et al. (2019) summarized the characteristics of PUAs as having lower population density compared to urban areas, dispersed housing development, fragmented communities, and being under pressure from neighboring urban centers, such as population migration. Zeng et al. (2022), using nighttime light data to identify PUAs, concluded that the nighttime light intensity in PUAs lies between that of urban and rural areas. Van Eupen et al. (2012) found that PUAs have a higher population density compared to rural areas. These characteristics are also corroborated by the distribution patterns of ID, NLI, and PCLA across gradient zones. Schulp et al. (2022) pointed out that the peri-urbanization process combines urban land expansion, farmland loss, and fragmentation, leading to a reduction in open spaces and threatening the supply of ecosystem services. I found that the PNL in PUAs indeed shows a gradual decline. These studies, along with my findings regarding the dynamics and hybridity exhibited by PUAs in multiple aspects, help to clarify the concept of PUAs further.

The differences observed between different location types of PUAs, especially in terms of ID and NLI, provide some explanations for the extent to which PUAs are influenced by geographic location. Specifically, Transitional PUAs and Interurban PUAs exhibit significant differences in ID. Interurban PUAs often serve as links connecting multiple urban areas, and under the collective influence of these urban regions, their construction intensity is evidently higher. Regarding NLI, the difference between Interurban PUAs and Isolated PUAs is even more pronounced. Shaw (2005) suggested that PUAs, as a new economic space, particularly in developing countries, provide opportunities for industrial investment. It can be speculated that urban areas exert a significant economic influence on Interurban PUAs, attracting numerous investors and facilitating the formation of large-scale industrial parks. In contrast, Isolated PUAs, being located farther from urban centers and having a fragmented, dispersed spatial distribution, struggle to leverage economic agglomeration effects.

4.4 Morphology of PUAs and PULs

4.4.1 Morphological spatial pattern of PUAs

From the perspective of overall spatial pattern, three distinct forms of PUAs were identified. A large number of PUAs are distributed in a circular pattern around urban areas, with this being most pronounced in the CUA, and smaller ring-shaped PUAs also appear around secondary urban centers. These PUAs can be considered products of urban radiative influence. They are primarily composed of Transitional PUAs and can be observed in all three years. Some PUAs are distributed in a belt-like pattern between neighboring urban areas. These PUAs emerged mainly after 2010, with the most pronounced presence in 2020, and can be found between the CUA and its surrounding administrative regions. These are mostly Interurban PUAs that gradually formed along roads, driven by the radiative influence of multiple urban areas, resulting in a networked, clustered distribution. A small portion of PUAs is distributed as small patches in rural areas across different regions, primarily composed of Isolated PUAs. The increase in this small patch form was most noticeable between 2000 and 2010. Between 2010 and 2020, this form mostly manifested as the expansion or merging of these small patches (***Figure 4.5***).

After conducting Morphological Spatial Pattern Analysis (MSPA) on the PUAs, it was found that the *Core* and *Edge* are the dominant morphological types in terms of area across all PUA categories. Among Isolated PUAs, the proportion of the *Core* is slightly higher compared to the other two types, whereas Transitional PUAs exhibit the lowest proportion of the *Core*. The large area of the *Edge* is primarily due to the relatively wide edge width setting in the MSPA analysis, which will not be discussed in detail in this study. For the remaining morphological types, the distribution across PUA categories is quite similar, with the proportion of the *Bridge* consistently slightly higher in Transitional PUAs than in the other two categories (***Figure 4.20***).

From a temporal perspective, the area of each morphological type within all categories of PUAs has shown an overall increasing trend. The most significant growth occurred in the *Core* of Transitional PUAs. In contrast, the morphological types within Isolated PUAs experienced slower and more stable growth. For Interurban PUAs, the *Core*, *Bridge*, and *Branch* types saw marked expansion during the 2000 - 2010 period but exhibited little change between 2010 and 2020. In terms of internal proportional distribution, all categories of PUAs displayed a declining share of the *Core*, accompanied by an increasing proportion of the *Bridge* and *Branch* (***Figure 4.20***).

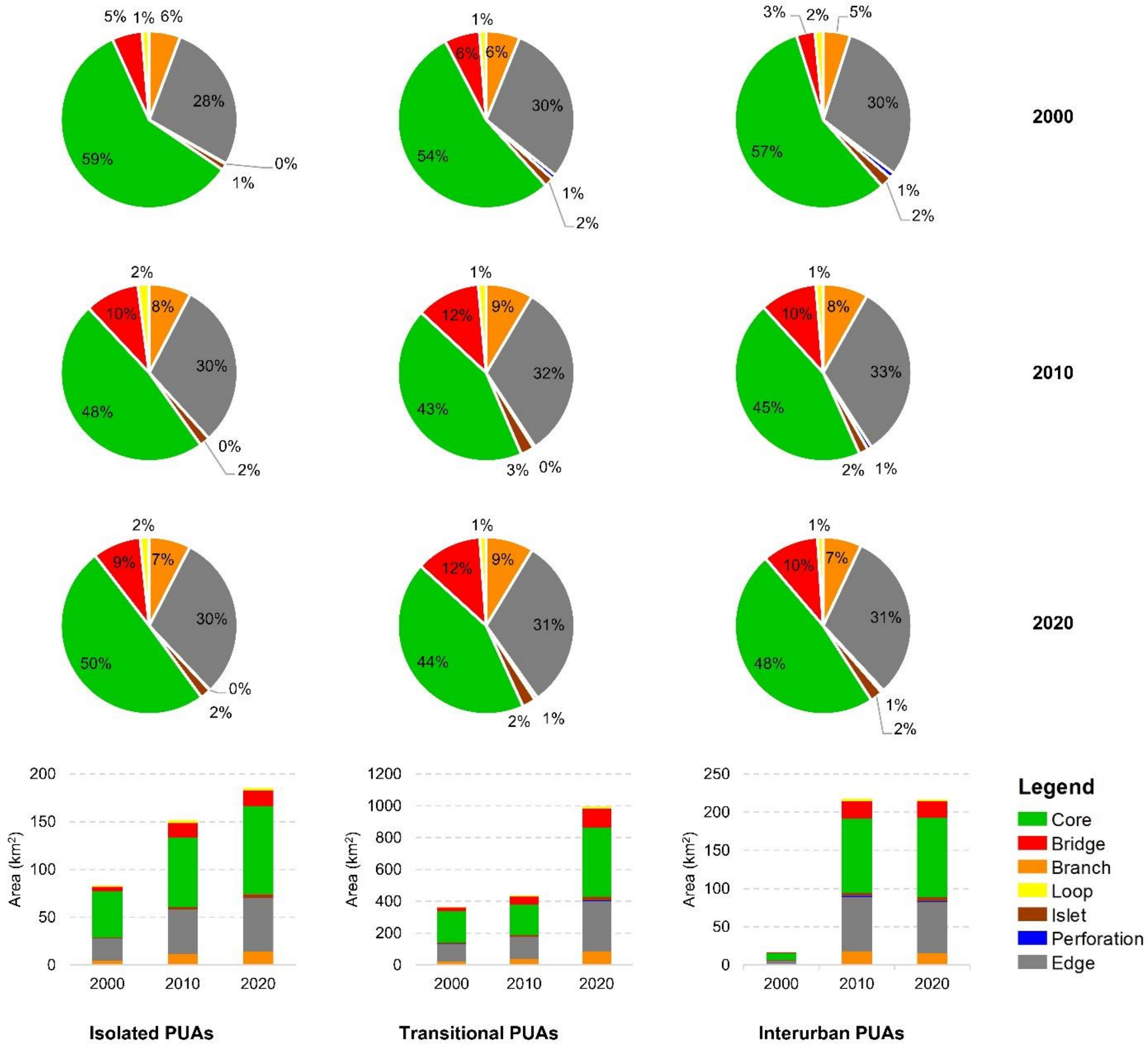

Figure 4.20: Proportion and area of seven morphological types in PUAs.

4.4.2 Morphological spatial pattern of PULs

Through MSPA, the morphological spatial pattern evolution characteristics of PULs were analyzed. In terms of agricultural PULs, the *Core* has consistently been the dominant morphological type, with its area continuously increasing. However, the proportion of the *Core* has been steadily declining, particularly during the period from 2000 to 2010. The overall area and individual patch size of the *Bridge* and *Loop*, which exhibit corridor-like properties, remain relatively small but show an increasing trend. As a linear and terminal structure, the *Branch* has also exhibited stable growth over time. The *Islet* and *Perforation* account for the smallest areas in the agricultural PULs. In 2000, the *Islet* had the smallest area, but by 2020, its area had increased to some extent. Overall, the morphological spatial pattern of agricultural PULs has shown a transition from the *Core* to more linear and fragmented structures (***Figures 4.21, Appendix 5***).

Figure 4.21: Proportion of morphological types of PULs.

In artificial PULs, the *Core* remains the dominant category. Among the corridor-like categories, the area of the *Bridge* has consistently been larger than that of the *Loop*. The *Bridge* exhibits a distinct linear structure and increasingly aligns with roads over time, whereas the *Loop* shows a less pronounced linear pattern. The *Islet* was initially concentrated in the CUA, with only a small presence in other administrative regions. However, the number of the *Islet* patches in other administrative regions gradually increased over time. The *Branch* is relatively evenly distributed across PUAs. The *Perforation* has maintained the smallest area among all categories across the three years. Notably, the *Perforation* was absent in 2000 and 2010 but appeared in small quantities in the CUA and Xingyang by 2020. Overall, the area proportions of different morphological types within the artificial PULs have remained relatively stable, with the *Bridge* showing a notable increase (***Figures 4.21, Appendix 6***).

In green PULs, the area proportions of different morphological types have gradually become more balanced. The area of the *Core* experienced minimal growth from 2000 to 2010 but expanded several times from 2010 to 2020, making it the dominant category in green PULs by 2020. This increase was primarily due to the emergence of two large patches in the CUA and Zhongmu. In 2000, the *Branch* accounted for a relatively large proportion, but its area proportion steadily declined in the following years. The area proportions of the *Bridge*, *Loop*, and *Islet* remained small, with the *Bridge* and *Islet* experiencing significant growth between 2010 and 2020 (***Figures 4.21, Appendix** 7*).

In water PULs, the morphological types also exhibit a relatively balanced distribution, with an overall dominance of linear forms. The area proportion of the *Core* is not particularly prominent, although it shows an increasing trend. Within the *Core*, there are three subdivided morphological forms: large patches, small patches, and linear patches. In 2000, the *Islet* had the highest area proportion, and its area has continued to grow over time, primarily in a linear form. The *Branch* is also a prominent category in water PULs, with significant growth from 2010 to 2020. Given its definition, most rivers and tributaries correspond to this morphological type. The *Bridge* and *Loop* have the smallest area proportions but show an increasing trend over time. These two types are mostly concentrated in the CUA and the surrounding PUAs, exhibiting distinct linear structures (***Figures 4.21, Appendix 8***).

To explore the differences in morphology between PULs and other landscapes, I also analyzed the urban landscapes as a comparison. The results indicate that, unlike the dominance of artificial landscapes in urban areas, agricultural landscapes and artificial landscapes coexist in a more balanced manner in PUAs. Moreover, the proportions of different morphologies in PULs are more balanced compared to urban landscapes, with the *Bridge* and *Branch* being more prominent in PULs. In contrast, urban landscapes are predominantly characterized by the *Core* morphology (***Figure 4.22***).

In terms of each landscape category, the morphological diversity in PULs is greater than in urban landscapes. Specifically, the agricultural urban landscapes are predominantly composed of the *Core*, whereas in PULs, the *Bridge* and *Branch* also account for a significant proportion alongside the *Core*. The green urban landscapes are relatively homogeneous, primarily characterized by the *Islet*. In contrast, the green PULs exhibit greater morphological diversity, with the *Core* and *Branch* being the dominant types in 2000 and 2010. By 2020, the *Core* became the largest morphological category, while the *Islet*, *Branch*, and *Bridge* also expanded, resulting in a highly diverse landscape structure. The composition of water landscape morphologies remains relatively balanced. The water urban landscapes are mainly characterized by the *Islet*, *Bridge*, and *Branch*, whereas in PULs, the proportion of the *Core* has significantly increased. Artificial urban landscapes are primarily composed of the *Core* and *Edge*, while in PULs, the *Core* remains dominant, with the *Bridge* and *Branch* showing noticeable growth (***Figure 4.22***).

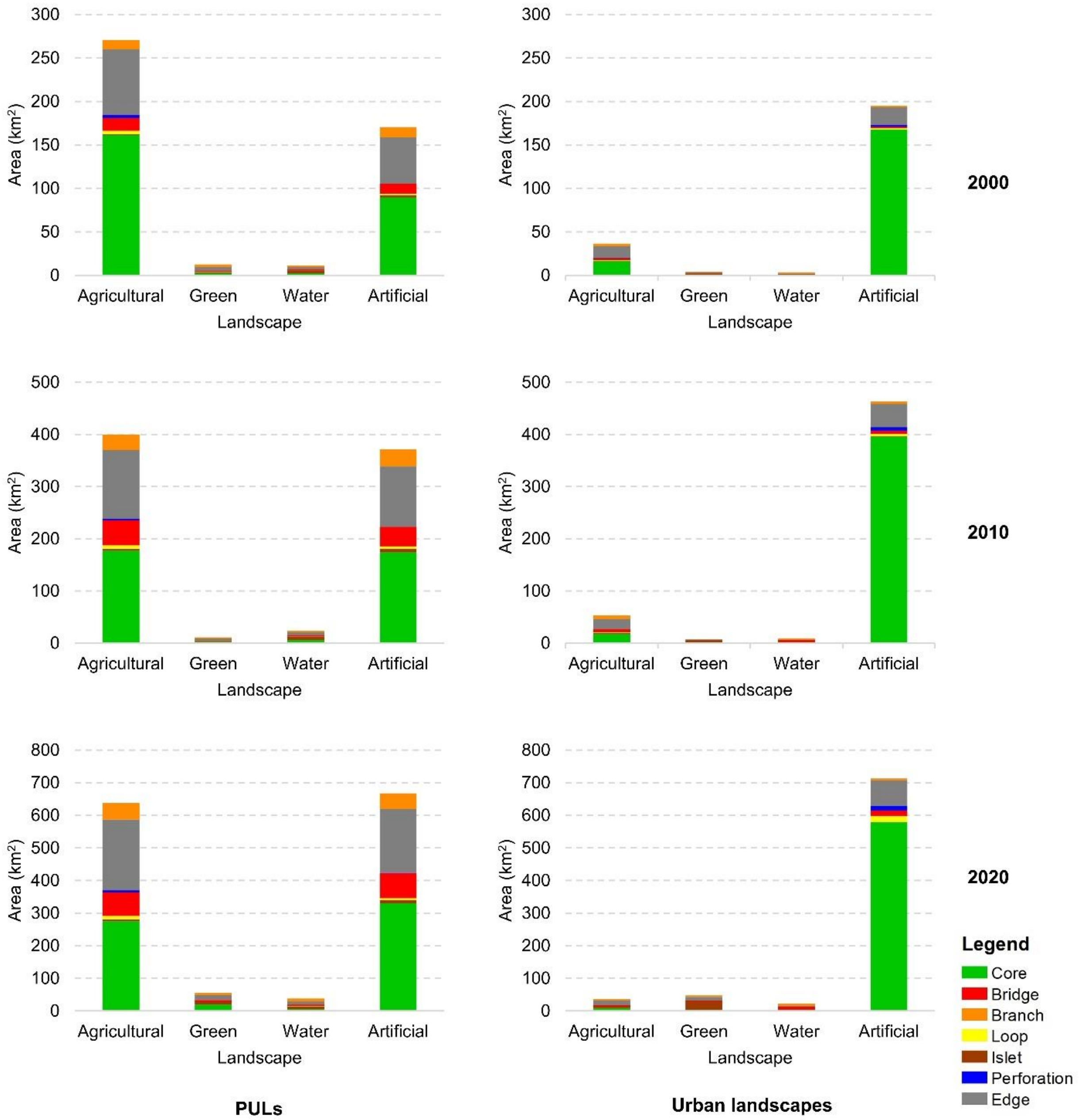

Figure 4.22: Comparison of the area of seven morphological types in PULs and urban landscapes.

4.4.3 Summary and discussion

Focusing on PUAs, I conducted a series of spatial analyses, which had different purposes. The expansion analysis of PUAs focuses on the dynamic change process and clarifying the direction and extent of expansion. Both location analysis and MSPA are based on the data of three years for analysis, and the results obtained are static. As for the relationship among these three analyses, first of all, the expansion of PUAs leads to the diversification of their location types. The infilling expansion mainly led to the increase of Transitional PUAs. Edge expansion has an impact on all three PUAs. Outlying expansion is mainly related to Isolated PUAs. As for MSPA, first of all, the expansion of PUAs may affect the diversity of forms, and through MSPA, it can help distinguish the three location types of PUAs (***Appendix 9***).

In this section, I found that the overall morphology of PUAs is primarily characterized by rings, belts, and small patches. Furthermore, distinct morphological differences are also observed among the various categories within both PUAs and PULs. In urban planning, the relationship between morphology and function is often closely interlinked. Morphology and function interact with each other, jointly shaping the spatial structure and living environment of a city. On one hand, morphology influences the realization of functions, while on the other hand, functions also drive the formation of morphology (***Figure 4.23***).

(1) Morphology Influences Function

The spatial morphology of PULs plays a critical role in shaping the functional performance of PUAs. For instance, in the context of ecological functions, the morphological classifications derived from MSPA exhibit considerable alignment with established theories in landscape ecology. For example, the *Core* corresponds to the *Source-Sink Theory*. In the spatial morphology of this study area, the *Core* is the most important morphological type. Both agricultural and artificial PULs dominate this category, occupying an overwhelming proportion. From the perspective of landscape ecology, the *Core* of agricultural PULs serves as a primary source for various ecological processes in PUAs, such as biodiversity conservation (Li et al., 2024) and food supply (Rolf et al., 2020). In general, the *Core* in artificial PULs tends to play a sink role, often relying on external resource inputs or ecological support. Based on ***Figure 4.22***, a rough estimation of the Source-Sink relationship in PUAs can be made: in 2000 and 2010, the area of ecological source regions was greater than that of sinks, indicating sufficient ecological supply from these natural or semi-natural landscapes. However, by 2020, the area of sinks exceeded that of sources, signaling a lack of ecological supply.

The *Bridge* and *Loop* correspond to the concept of the *Corridors* in *Landscape Ecological Patterns*. The *Corridors* play a crucial role in landscape ecology by facilitating the movement of species and the flow of ecological processes. The *Islet* and *Branch* overlap with the concept of the *Stepping stones* in *Landscape Ecological Patterns*. In this context, the *Stepping stones* provide critical temporary habitats for species migration or dispersion during ecological processes. By incorporating these concepts into the results of the MSPA, it is evident that the *Corridors* are most pronounced in agricultural and artificial PULs. The *Stepping stones* are primarily found in artificial, agricultural, and water PULs. Generally, artificial PULs tend to have lower ecological quality, which limits the ecological functions they can provide. The *Corridors* and *Stepping stones* within artificial PULs can enhance their ecological functions through measures such as increasing the amount of artificial green space and improving vegetation diversity. For example, in 2013, Zhengzhou proposed the construction of an ecological corridor network along two ring roads and thirty-one radial roads to improve urban greening. This policy effectively facilitated the development of corridor-shaped landscapes in both urban and PUAs.

(2) Function Drives Morphology

The functional demands of PUAs directly influence their spatial morphology. In Zhengzhou, the morphological evolution of PUAs corresponds to the process of urban areas radiating outward and rural areas experiencing bottom-up revitalization. Clearly, PUAs have absorbed a considerable portion of the functions of urban areas, resulting in the significant accumulation of artificial PULs. This accumulation manifests in core patches, such as industrial parks and university towns, which also drive the development of surrounding infrastructure, including roads. PUAs are strongly functionally dependent on urban areas, and as such, their morphological composition is primarily characterized by ring-shaped patterns surrounding urban areas and belt-shaped patterns connecting different urban areas. These morphologies facilitate the maintenance of connectivity with urban centers. Simultaneously, during this process, the *Core* areas of natural or semi-natural landscapes gradually degrade, and *Corridors* are interrupted. Joniak-Lüthi (2016) analyzed the spatial transformations induced by the expansion of road infrastructure in northwest China, arguing that contemporary urban and peri-urban spaces are characterized by uneven and dispersed morphological patterns. In addition, the bottom-up industrial revitalization in rural areas generates a demand for the aggregation of artificial PULs, leading to the formation of block-shaped Isolated PUAs.

The different morphological distributions within each location type of PUA also indicate that the morphological changes of these PUAs are influenced by the functional differences corresponding to their geographic locations. This phenomenon is similarly observed in other research areas. For instance, Bucharest, the capital of Romania and a highly complex economic city, has developed distinct types of PUAs on its outskirts, deepening its unbalanced development. In the northern part of Bucharest, there is an affluent PUA combining high-market real estate and high-value services, while the large PUAs in the eastern and southern parts of the city are dormitory zones for cheap labor, mainly engaged in construction, retail, and hospitality industries. Naturally, the differences between these two types of PUAs lead to disparities within them, such as differences in the built environment, transportation, and prices, resulting in an unbalanced and varied urban morphology (Petrovici and Poenaru, 2025).

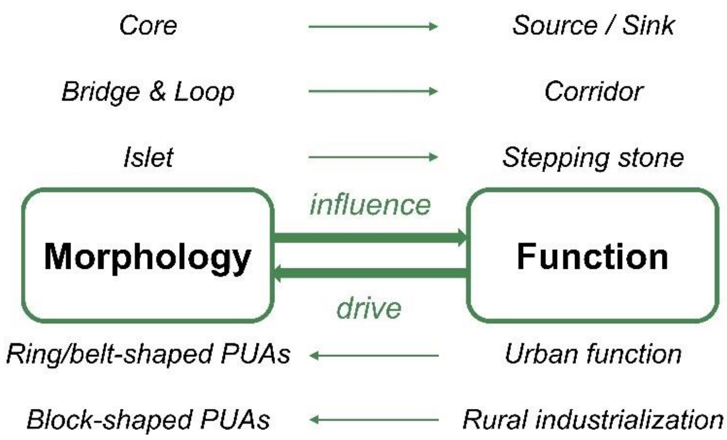

Figure 4.23: Morphology and function relationships in PUAs

4.5 Structure of PUAs and PULs

4.5.1 Landscape Metrics of PUAs

Figure 4.24 presents the Composition metrics of the three types of PUAs at the landscape level. It can be observed that, although the SHDI of Transitional PUAs consistently remains at the highest level, the PD and AREA_MN values are at intermediate levels. Isolated PUAs have the highest PD, which results in the lowest AREA_MN among the three types, and their SHDI shows minimal change. Interurban PUAs, on the other hand, generally exhibit the largest AREA_MN, with the lowest PD, and their SHDI shows an increasing trend. These characteristics suggest that Transitional PUAs have the highest landscape diversity, with Interurban PUAs having larger patches and increasing landscape diversity, while Isolated PUAs are dominated by smaller patches.

Generally, Interurban PUAs are influenced by the radiation of two or more urban areas, which would, in theory, result in a higher potential for landscape transformation. However, analysis of specific PULs reveals that Interurban PUAs were initially dominated by large-patch agricultural landscapes. Over time, the AREA_MN of artificial landscapes steadily increased and became the largest landscape type by 2020. In contrast, the numerous small agricultural patches in Isolated PUAs were the primary factor contributing to the increasing gap in AREA_MN compared to the other two types of PUAs.

Figure 4.25 represents the Configuration metrics. According to the data shown by PARA_MN, both Isolated PUAs and Transitional PUAs have remained relatively stable, while Interurban PUAs exhibit more significant fluctuations across the three years. In 2010, Interurban PUAs had the highest PARA_MN among the three types, indicating that the patch shape complexity was highest. However, in the other two years, its PARA_MN was the lowest. This phenomenon is largely associated with the high PARA_MN of water bodies in Interurban PUAs in 2010. In that year, most patches in Interurban PUAs contained water, primarily in the form of linear, natural rivers, which increased the overall complexity of patch shapes in Interurban PUAs.

The TECI values for all three types of PUAs show a slow-increasing trend, with Interurban PUAs and Transitional PUAs having very similar values. Isolated PUAs consistently had lower TECI values, indicating fewer high-contrast boundaries and slightly lower landscape heterogeneity.

In the PROX_MN, Isolated PUAs had the lowest value, reflecting the lowest proximity of similar patches. Transitional PUAs exhibited a complex trend with a decrease followed by a sharp increase, and by 2020, their PROX_MN became the highest, primarily due to the closer proximity and increased area of built-up patches. The PROX_MN in Interurban PUAs showed relatively minimal change, following a trend of increase followed by a decrease. Among the three types of PUAs, Interurban PUAs consistently maintained an intermediate level of proximity for similar patches.

Overall, the three types of PUAs exhibit distinct landscape structures in both composition metrics and configuration metrics. In terms of composition, Interurban PUAs are characterized by large patch sizes and low patch density, while Isolated PUAs are dominated by smaller patches and higher patch density. Regarding configuration, Interurban PUAs show greater variation in patch shape, while Isolated PUAs have lower landscape heterogeneity. Transitional PUAs exhibit stronger connectivity between similar patches, primarily due to the aggregation of built-up landscapes.

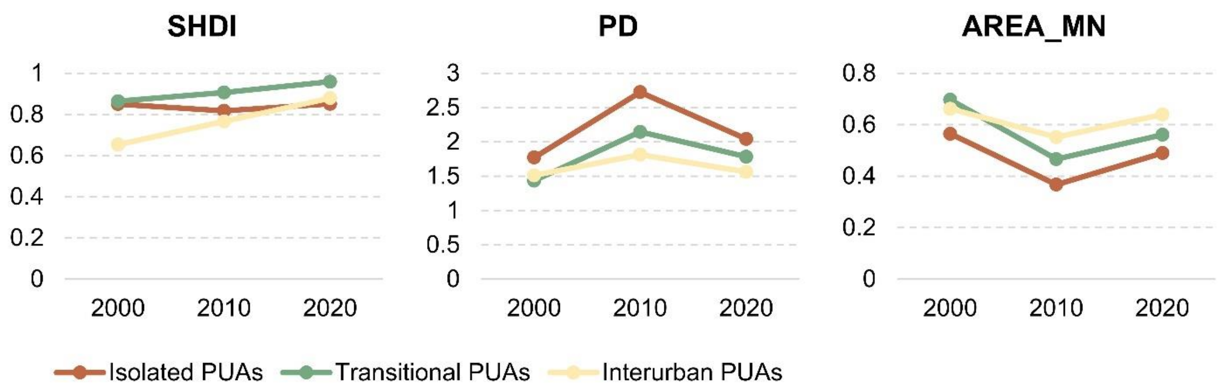

Figure 4.24: Composition metrics of PUAs at the landscape level.

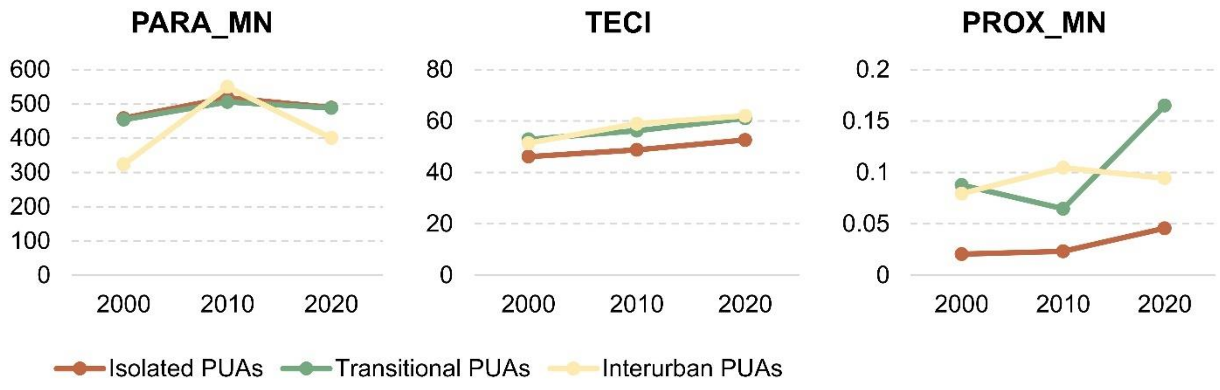

Figure 4.25: Configuration metrics of PUAs at the landscape level.

4.5.2 Landscape Metrics of PULs

(1) Composition metrics

In composition metrics, PLAND is a class-level metric, SHDI belongs to landscape-level metrics, while PD and AREA_MN belong to both class-level metrics and landscape-level metrics. ***Figure 4.26*** presents the calculation results of class-level metrics in the PULs. ***Table 4.5*** shows the calculation results for landscape-level metrics.

PLAND represents the proportion of each landscape type. Agricultural and artificial PULs dominate over the other two types. The PLAND of agricultural PULs exhibits a decreasing trend year by year, while that of artificial landscapes steadily increases, leading to a shift in the dominant PUL type from agricultural to artificial. As for green PULs, PLAND shows a slight decline followed by an increase, whereas the PLAND of water PULs remains relatively stable with minimal variation (***Figure 4.26***).

PD and AREA_MN, to some extent, reflect the degree of landscape fragmentation. At the landscape level, PD exhibited a trend of initial increase followed by a decrease from 2000 to 2020 (***Table 4.5***). During the period from 2000 to 2010, the overall increase in PD was primarily driven by the rising PD of agricultural and artificial PULs, despite a significant decline in the PD of green PULs. Conversely, from 2010 to 2020, the decrease in PD for agricultural and artificial PULs contributed to the overall decline in PD, while the green PULs continued to exhibit an opposite trend (***Figure 4.26***).

At the landscape level, AREA_MN exhibited a trend opposite to that of PD, showing an overall decline (***Table 4.5***). From 2000 to 2010, the increase in PD alongside the decrease in AREA_MN indicates that landscape fragmentation intensified during this period. However, from 2010 to 2020, the rise in AREA_MN and the decline in PD suggest a slowdown in the fragmentation process. At the class level, the AREA_MN of agricultural PULs was the largest in both 2000 and 2010, but by 2020, it was surpassed by artificial PULs. Both agricultural and artificial PULs experienced an initial decrease followed by an increase in AREA_MN between 2000 and 2020. Overall, the AREA_MN of agricultural PULs declined, whereas that of artificial PULs increased. Meanwhile, the AREA_MN of green PULs showed a slight upward trend, whereas that of water PULs exhibited a slight decrease (***Figure 4.26***).

SHDI reflects the PUL diversity. As shown in ***Table 4.5***, SHDI slightly decreased between 2000 and 2010 but increased during the period from 2010 to 2020. The overall trend of SHDI during the study period indicates an increase, suggesting that PUL types have become more diverse. This phenomenon aligns with previous studies that have concluded that land use in PUAs is characterized by a complex mix.

From 2000 to 2020, the PD of urban landscapes exhibited a continuous increase, while the AREA_MN consistently declined. These changes indicate a clear trend of fragmentation in urban landscapes, a trend that became more pronounced during the 2010 - 2020 period. In contrast, PULs demonstrated a trend toward reduced fragmentation over the same period (***Table 4.5***). At the class level, notable changes included an increase in PD for green urban landscapes and an increase in AREA_MN for artificial urban landscapes, both of which occurred primarily between 2010 and 2020 (***Figure 4.27***). The SHDI for urban landscapes was significantly lower than that of PULs, indicating lower landscape diversity (***Table 4.5***). Combined with the PLAND, the dominance of artificial urban landscapes suggests that most urban areas are characterized by a homogeneous landscape structure dominated by artificial landscapes (***Figure 4.27***).

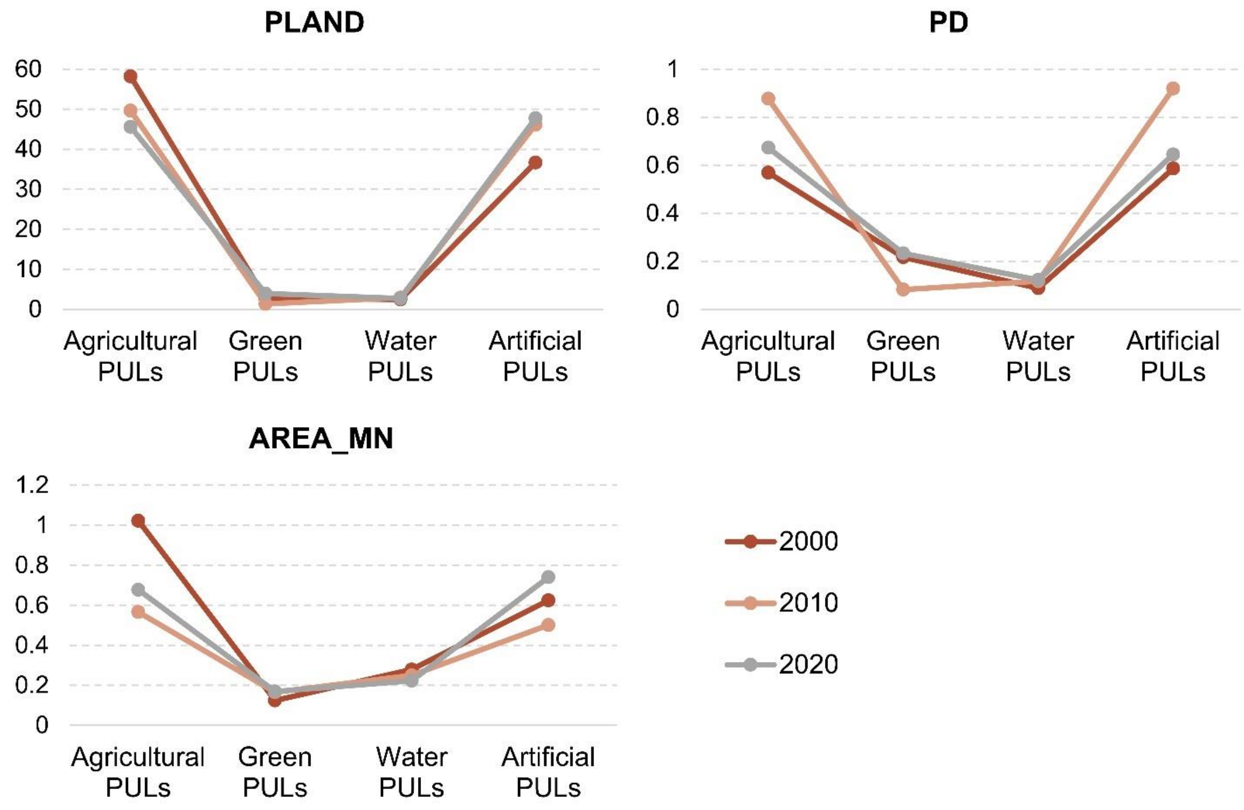

Figure 4.26: Class-level Composition metrics in PULs.

Table 4.5: Landscape-level Composition metrics in PULs and urban landscapes.

	PULs			Urban landscapes		
Composition metrics	**2000**	**2010**	**2020**	**2000**	**2010**	**2020**
PD	1.4612	1.9954	1.6735	1.212	1.2562	1.7756
AREA_MN	0.6844	0.5011	0.5976	0.8251	0.7960	0.5632
SHDI	0.8714	0.8662	0.9367	0.5842	0.4757	0.5242

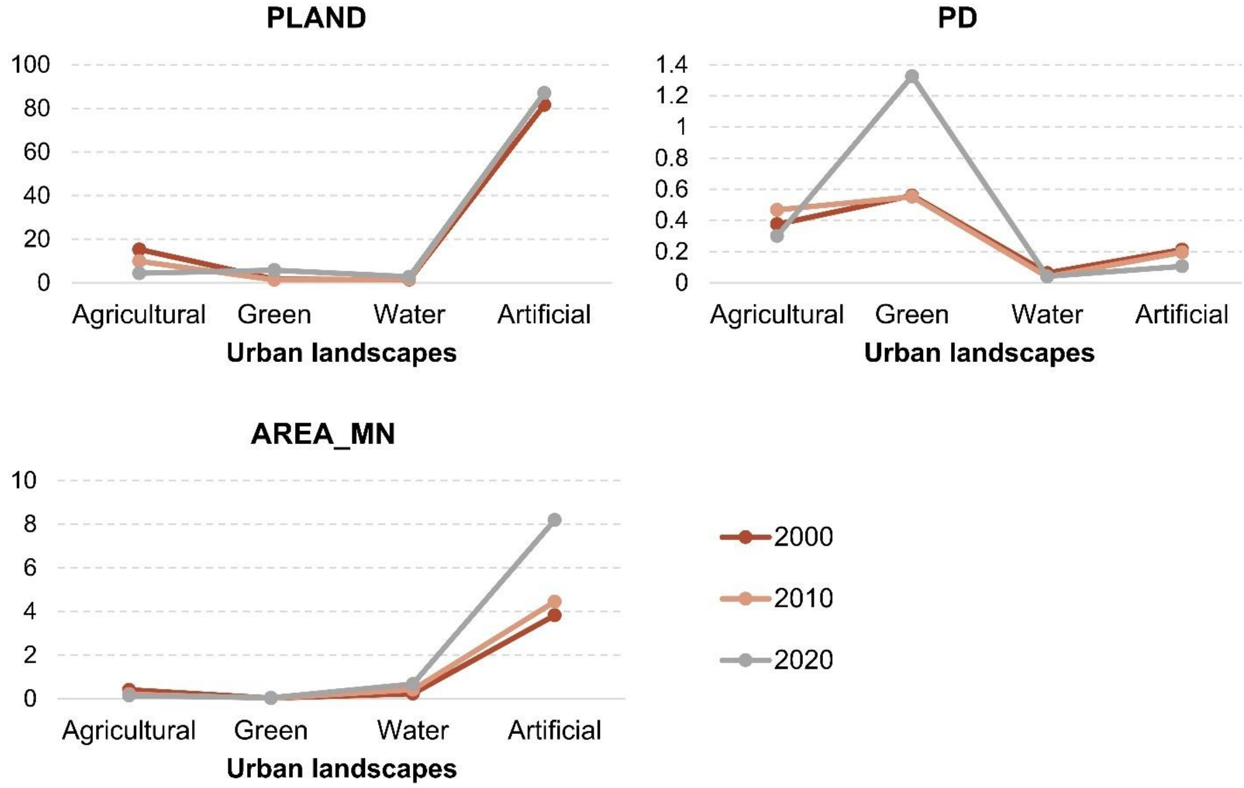

Figure 4.27: Class-level Composition metrics in urban landscapes.

(2) Configuration metrics

Among the Configuration metrics, only CONTAG is a landscape-level metric, while the other metrics apply to both class and landscape levels. The CONTAG of PULs experienced a slight decline from 2000 to 2020, indicating a decrease in the relative aggregation of different PUL types (***Table 4.6***). This suggests that landscape types became more dispersed, and individual patches became increasingly fragmented. Furthermore, this process also reflects an increase in the heterogeneity of PULs.

Table 4.6: Landscape-level Configuration metrics in PULs and urban landscapes.

Configuration metrics	PULs			Urban landscapes		
	2000	**2010**	**2020**	**2000**	**2010**	**2020**
PARA_MN	449.4351	504.8489	470.6326	819.8294	796.4909	707.1565
TECI	52.1633	57.0871	61.4966	53.3828	57.0433	59.0934
PROX_MN	0.0802	0.0868	0.1891	0.1926	0.7071	0.2292
CONTAG	65.3926	64.9592	62.2445	76.9827	80.9089	78.5820

PARA_MN measures the complexity of patch shapes within a landscape. At the landscape level, PARA_MN in PULs followed a trend of initial increase followed by a decrease, reaching its highest value in 2010. This highest value indicates that patch shapes were the most irregular, with more complex boundaries that might have been more susceptible to external disturbances. In contrast, the lowest PARA_MN value was observed in 2000, suggesting that patch shapes were overall more regular (***Table 4.6***). At the class level, the PARA_MN of agricultural PULs exhibited a trend consistent with the landscape-level pattern, showing an overall tendency toward more regular patch shapes. Meanwhile, green PULs exhibited a trend completely opposite to that at the landscape level. Both water and artificial PULs displayed a steadily increasing PARA_MN trend, indicating that patch shapes in these landscapes became increasingly complex. Among them, water PULs showed the most significant increase, with the highest PARA_MN values recorded in 2010 and 2020 (***Figure 4.28***).

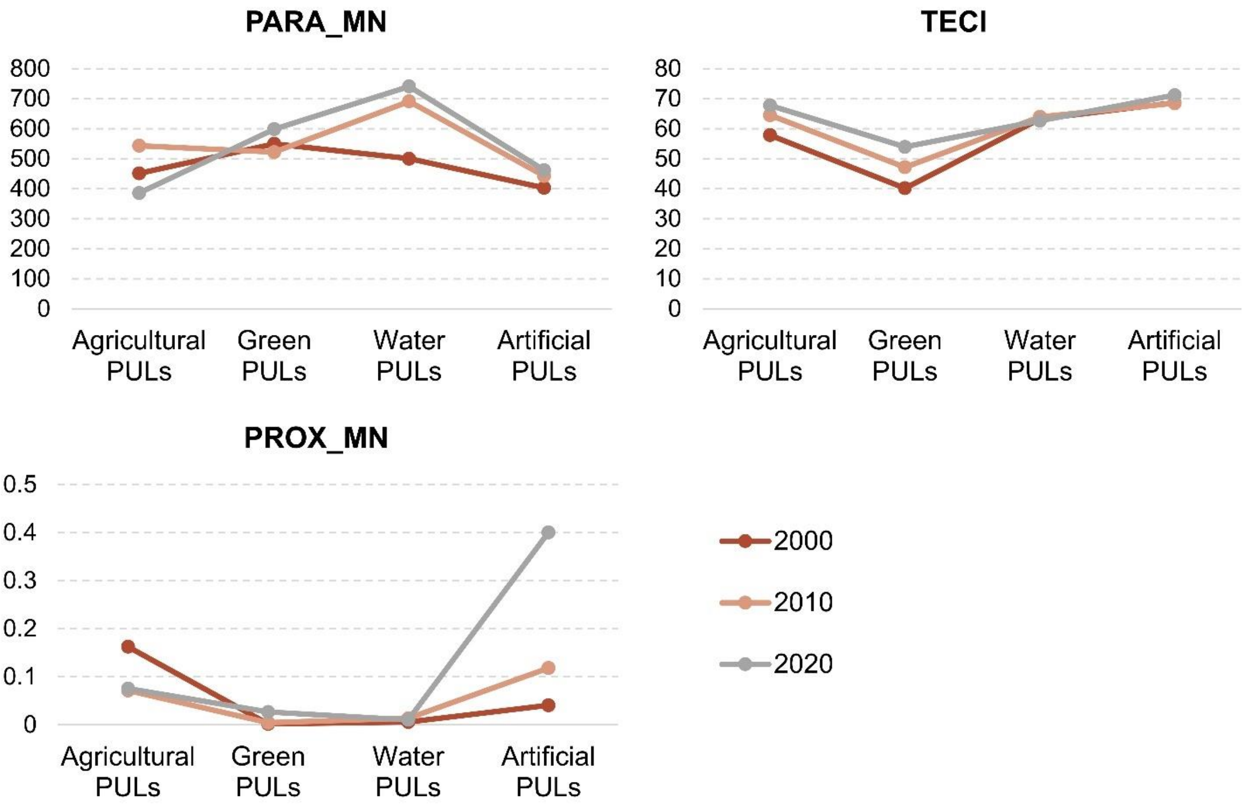

Figure 4.28: Class-level Configuration metrics in PULs.

TECI exhibited an increasing trend at the landscape level, indicating a growing number of high-contrast boundaries in PULs, such as those between green and artificial PULs (***Table 4.6***). This phenomenon suggests an increase in landscape heterogeneity. Landscapes with high TECI values typically feature more complex ecological interactions but are also more susceptible to human disturbances. At the class level, TECI highlights the contrast intensity at the boundaries between a specific landscape type and other landscapes. The most significant TECI changes occurred in agricultural and green PULs, both of which showed a clear increasing trend. Since agricultural and green PULs have the highest boundary contrast with artificial PULs in this study, this trend reflects an expansion of their contact areas. Meanwhile, the TECI of artificial PULs remained the highest among all landscape types throughout the study period, with no significant temporal variation (***Figure 4.28***).

PROX_MN reflects the spatial proximity and connectivity of patches of the same type within PULs. At the landscape level, PROX_MN exhibited an increasing trend over time, with a more rapid increase during the period from 2010 to 2020 (***Table 4.6***). This indicates that spatial connectivity within the landscape gradually strengthened, which, to some extent, benefits species dispersal and the continuity of ecological processes, thereby promoting sustainable development. At the class level, artificial PULs followed this increasing trend, gradually becoming the dominant landscape type. By 2020, the PROX_MN value of artificial PULs far exceeded that of other landscape types, reflecting the increasing spatial connectivity over time. In contrast, agricultural PULs exhibited an opposite trend. As PUAs became increasingly connected by roads, infrastructure, and built environments, formerly large agricultural patches were fragmented into smaller, scattered patches, leading to reduced connectivity. Green PULs showed a slight increase in PROX_MN, particularly between 2010 and 2020, while the PROX_MN value of water PULs remained largely unchanged over time (***Figure 4.28***).

There are some similarities between urban landscapes and PULs. For instance, the TECI values and growth trends of both urban and PULs are quite similar, with increased landscape heterogeneity observed in both (***Table 4.6***). However, at the class level, water landscapes exhibit different characteristics. While the TECI of water PULs showed little significant change over time, water urban landscapes exhibited a trend of initial increase followed by a decrease, reflecting the process of hardening and ecological restoration (***Figure 4.29***). During the early stages of urban development, most riverbanks within urban areas were transformed into impermeable surfaces to provide space for urban expansion. In 2013, Zhengzhou was approved as a national pilot city for water ecological civilization construction, beginning the development of ecological parks along several rivers within the city. This initiative led to the restoration of most hardened riverbanks to green riverbanks, promoting greater integration between water and green landscapes and reducing the contrast at the boundaries.

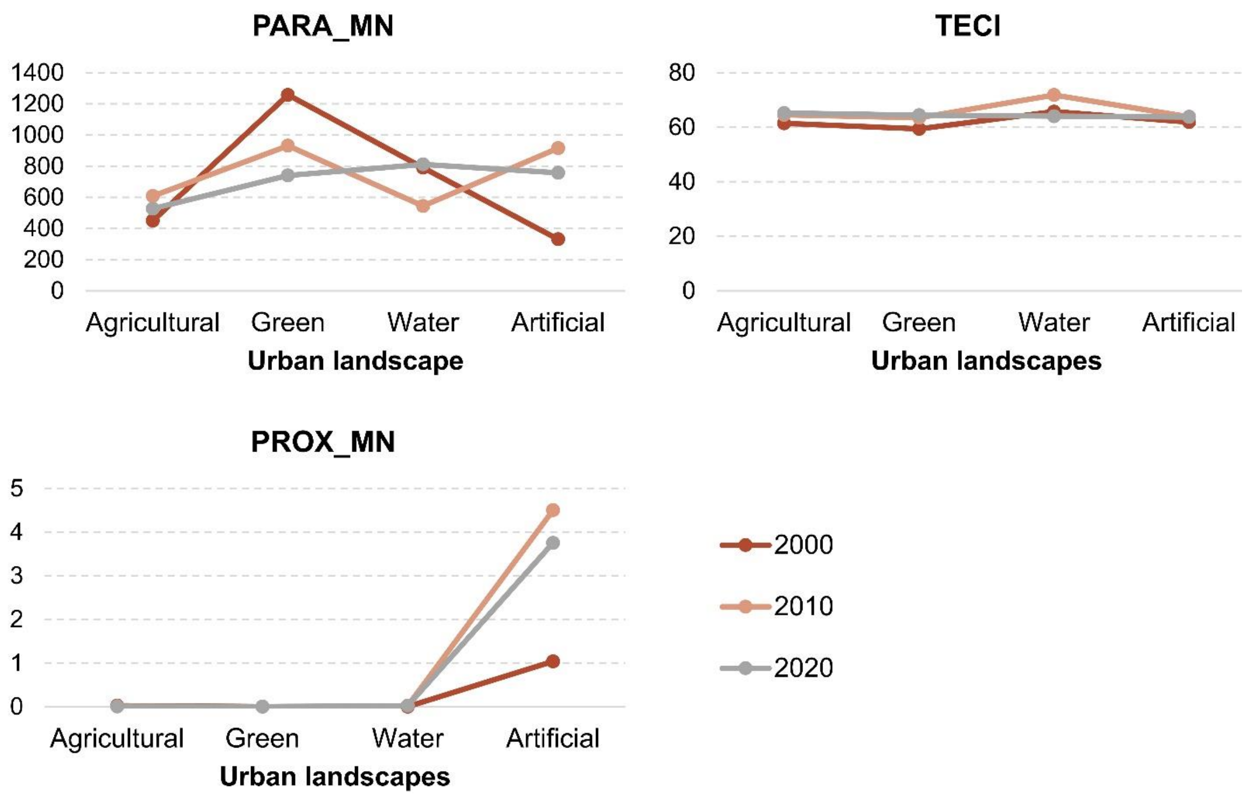

Figure 4.29: Class-level Configuration metrics in urban landscapes.

In other configuration metrics, PULs exhibit characteristics that are quite different from urban landscapes. For instance, compared to PULs, urban landscapes generally have higher PARA_MN values, meaning that the patch shapes in urban landscapes are more complex than those in PULs. Over time, the PARA_MN of urban landscapes has decreased year by year (***Table 4.6***), primarily driven by the increasing regularity of green urban landscapes due to human influence ***(Figure 4.28).*** Green urban landscapes are most likely parks, ecological corridors, and other areas that are actively planned and managed by humans, which is why they tend to have more regular boundaries.

Regarding PROX_MN, urban landscapes exhibit significantly higher values than PULs, reflecting a greater spatial proximity and connectivity of similar landscape types. However, this value is primarily driven by artificial landscapes, especially in 2010. Urban landscapes also show slightly higher CONTAG values compared to PULs, with an overall growth trend that is opposite to that of PULs (***Table 4.6, Figure 4.29***). These characteristics suggest that urban areas have a higher relative aggregation of different landscape types, with a trend of increasing spatial clustering.

4.5.3 Summary and discussion

In this study, the use of Landscape Metrics quantitatively presents the fragmentation of natural and semi-natural landscapes and the connectivity and aggregation characteristics of artificial landscapes in PULs. Landscape fragmentation refers to the process of converting large or continuous areas into smaller, more isolated spaces that lack physical connectivity, often due to rural land being fragmented by urban land use. Landscape fragmentation affects both ecosystems and human activities (Zambrano et al., 2019). It not only increases the number of patches but also increases the total length of edges associated with these patches. The increase in total edge length is common in PULs (Hardt et al., 2013, Recanatesi, 2015), often associated with anthropogenic modifications such as road and infrastructure development, residential expansion, and other human-driven activities (Lebrasseur, 2024). These human modifications have also led to the increase and aggregation of artificial landscapes.

Therefore, many studies have emphasized the phenomenon of landscape fragmentation caused by urban expansion. Salem and Tsurusaki (2024) found that over time, the degree of landscape fragmentation increased due to rapid urban expansion. These findings are consistent with the study by Magidi and Ahmed (2019), which indicated that the degree of landscape fragmentation in Tshwane, South Africa, was positively correlated with urban sprawl. Similarly, research by Fenta et al. (2017) and Abedini and Khalili (2019) conducted in the cities of Mekelle in Ethiopia and Urmia in Iran also reached similar conclusions. In this study, the fragmentation phenomenon in PULs was more pronounced during the 2000-2010 period, whereas the fragmentation rate significantly slowed down during the 2010-2020 period. This phenomenon can, to some extent, reflect the development intensity in PUAs transitioning from rapid to slow. In contrast, the fragmentation of urban landscapes intensified during the 2010-2020 period, which may be associated with the implementation of urban renewal policies in Zhengzhou, particularly the introduction of pocket park initiatives. This is supported by the marked increase in PD observed in green urban landscapes during this period.

The fragmentation of agricultural PULs during urban expansion has been particularly significant and has attracted increasing attention in recent years (Cheng et al., 2015, Pribadi and Pauleit, 2015, Zheng et al., 2024a). Many cases describe the development of urban land at the cost of agricultural land and the resulting landscape fragmentation (Bartels et al., 2020). The urban expansion process not only reduces the area of agricultural land but also alters the composition of different types of agricultural land, leading to intensified fragmentation of agricultural PULs (Yu et al., 2018). In China, the implementation of the strictest farmland protection policies in 1998 has been shown to have a positive impact on the protection of farmland areas (Huang et al., 2019, Zheng et al., 2024a).

However, with the acceleration of urbanization and the implementation of policies such as returning farmland to forests, agricultural land in peri-urban and rural areas has still faced significant loss. In response, China proposed the *Permanent Basic Farmland* policy in 2016 to further strengthen protection efforts. The rational planning and protection of agricultural PULs remains a critical issue that requires continued attention in the future.

4.6 Driving factors of the spatiotemporal evolution of PUAs

Since urban planning and management are typically based on administrative regions, this section statistically analyzes the evolution of PUAs in each administrative region to identify their regional differences and explore the driving factors behind these changes.

The statistical results of the evolution of PUAs in each administrative region show that PUAs in all regions have exhibited varying degrees of growth over time (***Figure 4.30***). The PUAs in the CUA have shown an increasing trend over the past two decades. Among them, the PUAs in the CUA were the largest in both 2000 and 2010 but were surpassed by Zhongmu in 2020. ***Figure 4.9*** clearly shows the outward expansion of the CUA's PUAs. By 2020, the PUAs surrounding the CUA had crossed administrative boundaries, extending into neighboring regions, especially Zhongmu. This is one of the reasons for the rapid growth of PUAs in Zhongmu. However, as early as 2000, the PUAs in Zhongmu ranked among the lowest in Zhengzhou. It was only during the 2010-2020 period that the PUAs in Zhongmu experienced rapid growth.

Xinzheng is also one of the regions where PUAs have grown rapidly. In 2000, Xinzheng already had three distinct PUAs, located respectively on the periphery of the old urban area, Zhengzhou Airport, and Longhu Town. With the development of urbanization and peri-urbanization, these three areas gradually expanded in size and connected through a linear structure to form a cohesive whole. Furthermore, the PUAs in Xinzheng have merged with the large PUAs of the CUA and Zhongmu, while also integrating the smaller PUAs from Xinmi, thereby forming a clear network structure.

In contrast, Gongyi, Xingyang, and Xinmi exhibit moderate PUA growth rates. The growth of Xingyang's PUAs primarily relies on the formation and expansion of Interurban PUAs and Transitional PUAs, which eventually integrated into the PUA network dominated by the CUA; while in Gongyi and Xinmi, the growth of PUA is mainly driven by the growth of Transitional PUAs and Isolated PUAs. Dengfeng is the region with the slowest PUA growth in Zhengzhou, primarily relying on the gradual expansion of Transitional PUAs and Isolated PUAs.

Overall, the various administrative regions of Zhengzhou have shown differentiated PUA evolution trends. The next step is to explore the driving factors that contribute to these differences, which will help predict future development trends and facilitate early planning and management to guide the sustainable development of PUAs. It can also help to understand the conflicts between urban and rural areas and determine how to address these conflicts (Dadashpoor & Ahani, 2021). The discussion of driving factors in this section primarily focuses on urban-rural influences, location and topography, and city planning. In addition, the growth of PUAs is also influenced by other factors such as economic and social conditions (Colantoni et al., 2016).

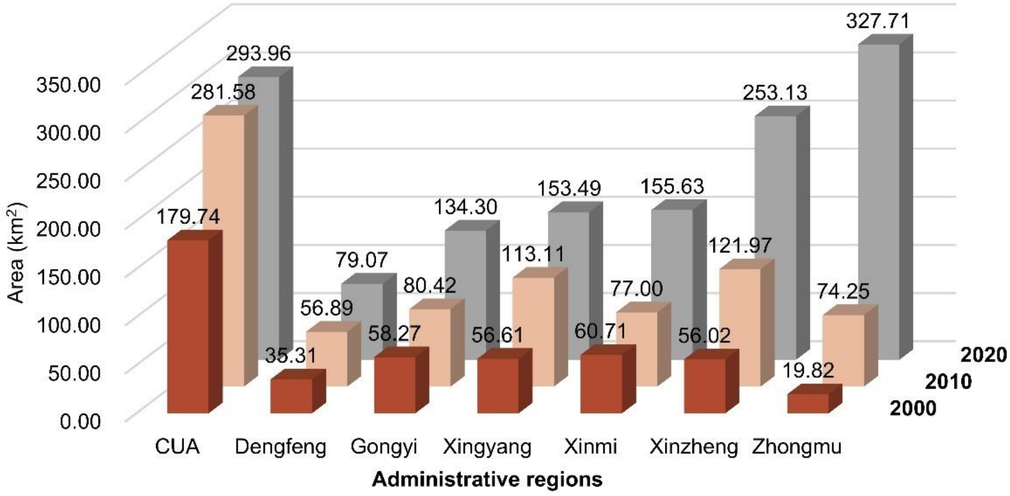

Figure 4.30: Area of PUAs by administrative region.

4.6.1 Multi-center urban radiation and rural industrialization

Moissidis and Duquenne (1997) proposed that PUAs are influenced by both urban and rural factors. Similarly, Tian et al. (2017a) found that the formation of PUAs in Shanghai was driven by both urban radiation and rural industrialization. Examining the spatial evolution of PUAs in Zhengzhou, it is evident that PUAs generated by the radiation effect of multi-center urban areas cover a significantly larger area than those formed through rural industrial transformation. The radiation effect of the CUA is particularly pronounced.

Early perspectives regarded PUAs as a product of urbanization (Antrop, 2004). Urban expansion has facilitated the formation of PUAs, driving the gradual transition of land use within PUAs from rural to urban functions, a phenomenon observed in many megacities. This process also triggers a series of transformations within PUAs, including demographic, economic, and social changes, making them prime locations for regional and cross-regional infrastructure and industrial investments, such as industrial parks, logistics hubs, and real estate developments (Ban and Adascalitei, 2022, Castellani et al., 2022, Petrovici and Poenaru, 2025). Over time, the expansion of ring-shaped PUAs on the urban periphery may reduce the distance between adjacent PUAs, eventually leading to their integration into a continuous urbanized pattern. This trend is particularly evident in the areas surrounding Zhengzhou's CUA, including Xingyang, Xinzheng, and Zhongmu, where PUAs are not only driven by their respective urban centers but also influenced by the radiation effects of the CUA (***Appendix 3***). A similar phenomenon has been observed in Lombardy and Emilia-Romagna, Italy, where urbanization has led to a high degree of integration between metropolitan areas and small to mid-sized towns, forming a polycentric PUA continuum.

The radiation effect of multi-center urban areas on PUAs not only promotes the contiguous development of PUAs but also enables their expansion beyond administrative boundaries. In this study, the phenomenon of PUAs crossing administrative borders is clearly observed in the CUA and its surrounding cities and counties, where these areas had already merged into an indistinguishable whole by 2020. Furthermore, similar cross-border development of PUAs has also been documented in Lombardy and Emilia-Romagna, Italy (Cattivelli, 2021b).

China's dual urban-rural system has significantly constrained balanced development between urban and rural areas. The concentration of resources and population in urban regions has exacerbated the urban-rural divide. As rural populations migrate to cities, the phenomenon of rural hollowing has become increasingly common in China. One major consequence of this trend is land abandonment, as farmland is no longer the primary livelihood for rural residents, making land conversion more likely. The 1978 Reform and Opening-up policy allowed the establishment of township and village enterprises (TVEs), encouraging farmers to engage in industrial production and accelerating rural industrialization. Under this policy, TVEs rapidly emerged as the dominant form of rural industrialization in the 1980s and 1990s, particularly in Jiangsu Province, Zhejiang Province, and Guangdong Province, where they developed into the TVE economic model. With the introduction of the Three Rural Issues policy in 2000, rural industrialization and urbanization were promoted simultaneously, leading to the gradual relocation of township industries to county seats and development zones. The 2014 New Urbanization Strategy further emphasized a county-based economic development model, facilitating the concentration of rural industries in county seats and small cities. This shift has driven the transformation of rural industrialization from TVEs to industrial parks and modern manufacturing sectors.

Under the guidance of these policies, some rural areas have transitioned from being predominantly agricultural to becoming more industrialized and commercialized, accompanied by the reallocation of land and population, which has driven rural development. Over time, this process has led to the emergence of PUAs. However, PUAs influenced by rural industrialization tend to develop spontaneously from the bottom up, with limited expansion potential. Their spatial distribution varies, with some located far from other PUAs, making it difficult to generate large-scale agglomeration effects. Many township enterprises with growth potential have relocated to industrial parks in response to policy directives, facilitating the transition from Isolated PUAs to Transitional PUAs or Interurban PUAs. As a result, Isolated PUAs tend to account for a relatively small proportion of all PUAs (Tian et al., 2017a).

4.6.2 Location and topography

Location and topography also play a significant role in the evolution of PUAs. Observing the transformation of PUAs across different administrative regions within the study area, it is evident that PUAs in Zhongmu, Xinzheng, Xingyang, and Xinmi, neighboring the CUA, have experienced rapid growth.

Among these four areas, Zhongmu, characterized by a predominantly flat terrain typical of plain regions, has the most favorable conditions for construction activities, leading to the fastest PUA expansion. Xinzheng and Xingyang, consisting of both hilly and plain areas, have seen slower PUA growth compared to Zhongmu. Xinmi, with its predominantly mountainous and hilly landscape, features a transitional plain area in the east but has experienced the slowest PUA expansion among the four cities.

Gongyi and Dengfeng, both located on the western side of Zhengzhou and farther from the CUA, have the slowest PUA growth among all regions. Gongyi features a diverse topography, with mountainous and hilly terrain in the west, plains in the east, and the Yellow River flowing through its territory. Dengfeng, on the other hand, is characterized by a typical mountainous landscape centered around Mount Song, with significant elevation variations. Comparatively, Gongyi has experienced slightly faster PUA growth than Dengfeng.

Overall, administrative regions adjacent to the CUA within the study area have more favorable conditions for PUA development. Additionally, the evolution of PUAs is influenced by topography, with faster growth observed in the northeastern plain region compared to the southwestern mountainous and hilly areas. These two driving factors have also been confirmed in other study areas. For instance, Haldar et al. (2024) proposed in their study on the peri-urbanization expansion and influencing factors of Durgapur that the determining factor for the development of the built-up area is the distance from the city core. Guan et al. (2022) found that in their study on green space fragmentation in the urban fringe of Ganjingzi District, Dalian, urban construction land expanded more slowly in hilly and mountainous terrains.

4.6.3 City planning

City planning plays a key role in the spatial evolution of PUAs. In the Zhengzhou Master Plan (1995-2010), a *multi-center, cluster-based* layout structure centered around the CUA was proposed. In the Master Plan for Zhengzhou Metropolitan Area (2012-2030), the city was divided into three main functional zones. The CUA is designated as the primary city zone, focusing on the expansion and improvement of modern service functions. Zhongmu, Xingyang, and the northern parts of Xinzheng are categorized as the new urban functional zone, with an emphasis on developing air transport-related industries, manufacturing, logistics, and other modern industries. Xinmi, Gongyi, Dengfeng and the southern part of Xinzheng are classified as sub-regional functional zones, primarily focusing on natural conservation and cultural tourism.

On one hand, the decentralization of functions requires stronger connections between the various centers, and PUAs effectively serve as bridges linking these urban centers. In the PUA identification results for Zhengzhou, it is evident that regions located between urban centers are more likely to transition from rural areas to PUAs. On the other hand, different functional orientations have led to the differentiated development of PUAs. In administrative regions focused on the development of modern industries, the expansion of PUAs is significantly larger than in areas focused on ecological protection and cultural tourism. Zhongmu, Xinzheng, and Dengfeng are typical examples of this trend.

Relying on the initially spontaneous development of small-scale industrial zones and the support of the Master Plan, Zhongmu has gathered a large number of industries, such as automotive equipment manufacturing and logistics, to form large-scale industrial parks. This has driven economic growth, employment opportunities, and infrastructure development in the surrounding areas. On the other hand, the establishment of large-scale cultural and tourism projects, such as the Fantawild Amusement Park and Film Town, has attracted a significant number of tourists and commercial establishments, creating new hubs of economic activity.

In Xinzheng, the establishment of the Airport Economy Zone in the eastern part of the city has driven the improvement of infrastructure in surrounding areas, leading to the conversion of some agricultural land into urban land. As a result, PUAs gradually emerged around these urban areas. On the other hand, the university town, located at the junction between Xinzheng and the CUA, has attracted new populations and businesses to the originally rural areas, accelerating the urbanization and peri-urbanization processes in the region. Combined with the presence of the old town, these factors have contributed to a polycentric urban pattern in Xinzheng. The PUAs surrounding these centers have also gradually expanded and connected.

Dengfeng is characterized by its abundant natural resources, which have led to many areas being designated as construction-restricted zones. This has, to some extent, hindered connectivity between regions and affected the development of PUAs.

The spatial evolution of PUAs is mainly driven by the above-mentioned factors. Consequently, PUAs can quickly reflect the dynamics of urban development. Focusing on these areas can provide timely feedback to governments and planners, allowing them to better guide urban planning, improve land use efficiency, and promote sustainable development.

4.7 Planning guidelines for PUAs and PULs

4.7.1 Peri-urbanization challenges in Zhengzhou

(1) Lack of planning and management

The Built-up Areas of Zhengzhou in 2020 are 1,284.89 km^2. The overlay analysis between the Built-up Areas and PUAs revealed that the Built-up Areas primarily overlap with the urban areas in Zhengzhou. Additionally, it also overlaps with some PUAs and a small portion of rural areas (***Figure 4.31***). Approximately 35% of PUAs (489.37 km^2) are located within the Built-up Areas, which indicates that only these PUAs were subject to urban planning and regulation, while nearly 65% of PUAs remain in an unregulated state of development. ***Figure 4.31*** also highlights the newly designated Built-up Areas in 2020, which are largely concentrated in the CUA, demonstrating a trend of outward expansion. However, data from a single year is insufficient to fully capture the relationship between PUAs and Built-up areas. Future research incorporating data from multiple years could help analyze their spatial dynamics, providing insights into the evolution of planning and regulation in PUAs.

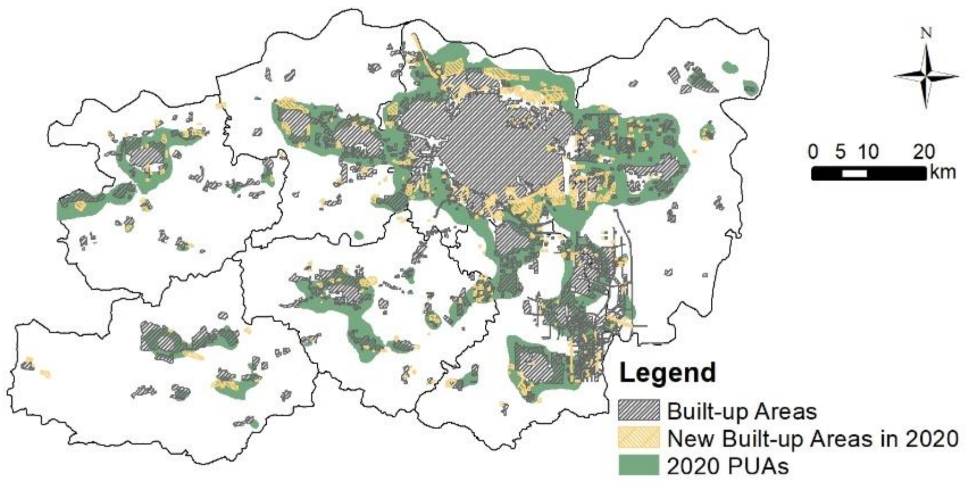

Figure 4.31: Overlay map of Built-up Areas and PUAs in Zhengzhou.

(2) Dual effects of the polycentric development pattern

The PUAs in Zhengzhou exhibited a trend of networked and contiguous development during the study period. The formation of this spatial pattern is closely related to the '*multi-center networked urban system*' proposed in The Master Plan for Zhengzhou Metropolitan Area (2012-2030). This kind of multi-center network layout has precedents in many cities. A notable precedent can be found in Dutch planning from the 1970s, where the official concept of *clustered deconcentration (gebundelde deconcentratie)* was introduced, aiming at "a designed development of towns in the direct sphere of influence of an urban area". The interrelationships between towns in polycentric regions, and even between different urban regions, are further explored within the concept of *urban networks* (Zonneveld and Verwest, 2005, Westerink et al., 2013). Similarly, since the 1990s, several Mediterranean cities in Southern Europe, such as Rome, Athens, and Lisbon, have undergone a transition from compact to expansion-oriented urban forms, gradually evolving into polycentric spatial structures (Salvati et al., 2016b, Di Feliciantonio and Salvati, 2015, Nickayin et al., 2021).

The polycentric spatial structure has facilitated a shift from compact expansion to dispersed, low-density development (Follmann, 2022, Webster and Muller, 2009). This transformation is particularly pronounced in PUAs, where studies suggest that it imposes significant pressure on already fragile natural resources and landscapes (Kim et al., 2012, Kontgis et al., 2014). However, from a human-centered perspective, the polycentric development model has been shown to offer several benefits, particularly in terms of functionality and economic foundations. By distributing urban functions across multiple sub-centers, this networked system helps alleviate population and industrial pressures on the primary urban core. Additionally, some consequences of urbanization, such as the fragmentation of green spaces, can also yield certain human benefits, for example, enhancing social interactions (leBrasseur, 2022) and increasing accessibility to green areas (Wandl and Magoni, 2017).

(3) Homogenization of morphology and structure

Through the previous analysis of PULs, it was found that PULs in Zhengzhou exhibit a morphological pattern of cross-administrative networking development. The expansion of artificial landscape core areas has led to their surpassing the gradually diminishing core areas of natural and semi-natural landscapes. Structurally, the PULs in Zhengzhou show a trend of fragmentation of natural and semi-natural landscapes alongside the aggregation of artificial landscapes. The agricultural landscape, which originally served as the matrix, has been gradually diminishing in the process of peri-urbanization, giving way to increasingly large-scale artificial landscapes. This expansion of artificial landscapes has further constrained the development of green spaces and water bodies, making their preservation and growth more challenging.

4.7.2 Global experiences

Given the numerous sustainable planning challenges present in PUAs, scholars worldwide have explored the possibilities for promoting sustainable planning from various perspectives. Some scholars emphasize the crucial role of clear policy planning and effective governance structures in steering urban expansion toward sustainable development (Gupta et al., 2015). These have thus become fundamental tools for guiding the development and management of PUAs, especially in addressing the competition for limited land resources (Sumbo et al., 2023, Salem and Tsurusaki, 2024). They also represent specific measures that governments can employ to achieve their policy objectives (Howlett, 1991).

In this section, I summarized the spatial planning and regulatory tools used in global PUA research cases and presented ten case studies (***Appendix 10***). These tools and cases provide insights for developing sustainable planning guidelines for PUAs in Zhengzhou. The main spatial planning and regulatory tools include:

(1) Urban Growth Management Policies (UGMPs)

UGMPS are used to limit urban growth, such as through strict construction control regulations, spatial management, and the establishment of urban growth boundaries (UGBs). Research in the US and Europe has shown that some PUAs under UGMPs have experienced significant land use conflicts, often due to changes in landscape characteristics, population migration, as well as conflicts between different interest groups (Shaw et al., 2020). The creation or existence of UGMPs may exacerbate these issues (Kirby and Scott, 2023). UGBs are one common form of UGMPs. They are typically simple boundary lines that mark the extent to which development is allowed and are often complemented by other protected areas or different land-use zones (Woo and Guldmann, 2011). Additionally, UGBs are often regularly adjusted for phased development, rather than serving as a permanent barrier (Nelson and Moore, 1993). Examples include Oregon's UGBs (Seltzer, 2009) and Chinese UGBs (Sun et al., 2021). UGBs are widely used in the US, with over 150 UGBs in place (Kirby and Scott, 2023).

(2) Spatial Planning and Zoning

These are important tools for managing urban development and shaping the urban environment. Globally, these tools aim to optimize land use and align development with environmental sustainability. Research indicates that effective spatial planning is crucial for reducing urban sprawl, supporting green infrastructure, and promoting socio-economic inclusivity (Domingo et al., 2021, Karakus et al., 2015). In regions experiencing rapid urbanization, such as South Asia, zoning is essential for controlling urban expansion, minimizing environmental impact, and improving land use efficiency (Hossain and Huggins, 2021). Furthermore, zoning practices are increasingly aligned with global sustainable development goals, influencing policy-making and urban management. This alignment helps manage urban expansion in a way that promotes sustainable development goals and improves community well-being (Ma et al., 2024, Oliveira et al., 2018), which is particularly important for PUAs, where land use changes frequently occur (Mamun et al., 2024).

(3) Natural and Landscape Conservation Planning

This includes planning for green infrastructure, greenways, green belts, green wedges, and the designation of regional ecological corridors (Filepné Kovács et al., 2018, Filepne Kovacs et al., 2024). Recent studies on green belts in Europe have shown that, in the 21st century, green belts are effective in preventing urban expansion, particularly around large cities (Pourtaherian and Jaeger, 2022). Green belts tend to surround urban and PUAs, protecting open spaces. A green belt spanning over 12,500 km and crossing 24 countries was planned along the former Iron Curtain in Europe, aimed at protecting natural and cultural landscapes and serving as a cornerstone of the pan-European ecological network[4]. More specific examples include the London Green Belt (Abercrombie, 1944), Seoul's Green Belt (Bengston and Youn, 2006), and the Greater Golden Horseshoe Green Belt in Ontario (Macdonald et al., 2021). Green wedges, on the other hand, are narrow corridors extending outward between urban and PUAs (Hedblom et al., 2017). Examples of Green Wedges include those in Northern European cities like Copenhagen, Stockholm, and Helsinki (Vejre, 2017), as well as Melbourne's Urban Wedge (Buxton and Goodman, 2016).

(4) Other individual plans

Individual planning can be optimized and regulated for specific sectors, promoting sustainable regional development, such as in public transportation planning, infrastructure planning, and environmental sanitation planning. For example, in Luxembourg, urban planners and land managers designed a public transportation network and integrated it with the strategic spatial

[4] https://www.europeangreenbelt.org/

planning implemented in urban planning documents. This has made Luxembourg a prime example of sustainable spatial planning (Gerber et al., 2018, Lord et al., 2015, Grabowska et al., 2024). In Delhi, the extension of the metro system to PUAs has improved their accessibility, reduced local residents' reliance on minibuses and motorcycles, and contributed to better air quality. Additionally, Transit-Oriented Development (TOD) can help guide population and industrial agglomeration to a certain extent.

4.7.3 Context-specific planning guidelines

To address the challenges currently faced by PUAs and PULs in Zhengzhou, I have proposed corresponding planning guidelines from both the regional and local levels.

(1) Regional level

a) Conducting spatial and land monitoring to predict future development.

The quantitative identification and spatiotemporal evolution analysis of PUAs that I provided in this study offer theoretical support for government-led spatial monitoring of PUAs. By tracking the spatial evolution trends of PUAs, it is possible to anticipate the direction of urban development and intervene in advance, guiding urbanization and peri-urbanization toward an efficient and sustainable trajectory while curbing disorderly urban sprawl.

Land use change is one of the most significant transformations within PUAs. In many countries, monitoring land use is even a mandatory and priority goal in policies (Cegielska et al., 2024, Noszczyk, 2018, Sapena and Ruiz, 2019). In recent years, China has advanced the construction of a *Territorial Spatial Planning System*, emphasizing dynamic monitoring and refined management. The *Farmland Protection Redline Policy* ensures that the area of basic farmland does not decrease. These initiatives provide policy support for land monitoring in PUAs. National strategies such as *Smart Cities* and *Digital Villages* also offer technical and financial support for land monitoring in PUAs. By monitoring the current situation, it is possible to predict potential land conflicts in PUAs, enabling early intervention and resolution.

b) Coordinating compact settlements and low-density development in spatial patterns.

A compact settlement structure emphasizes high-density development, mixed land use, and the containment of unregulated land expansion. While commonly associated with urban areas, this approach should also be advocated in PUAs to mitigate the current trend of edge expansion (Shi et al., 2024). Herold et al. (2003) highlighted that well-defined planning tools are the most effective means of achieving urban compactness. By implementing rational land planning, improving infrastructure, and enhancing ecological networks within PUAs, compact settlement structures can be fostered, leading to efficient land use, dense spatial organization, and shared infrastructure.

However, it is crucial to distinguish this compact structure from the urbanization process. Instead, it should be adapted to local characteristics, with high-density layouts in core areas of PUAs while maintaining lower-density development in peripheral regions. Additionally, public green spaces should be expanded, and the functional distribution of commercial and office areas should be carefully planned to enhance both living quality and convenience. In lower-density areas, rural characteristics should be preserved, with a development approach that integrates modern agriculture with cultural tourism. For polycentric cities, a compact settlement layout can be primarily implemented in the core area of Interurban PUAs and Transitional PUAs. While in Isolated PUAs, low-density development can be the main approach.

Regarding how to choose high-density development PUAs, it is necessary to combine the existing plans and policies to avoid conflicts. Zhengzhou released the latest master plan in 2025, demarcating permanent basic farmland, ecological protection areas, and urban growth boundaries in the map (***Appendix 11***). This map can be combined with the map of PUAs, and then high-density development PUAs can be selected from these urban growth areas. For permanent basic farmland and ecological protected areas, they provide strong policy support for the preservation of rural characteristics within PUAs, thereby slowing down urban sprawl.

c) **Maintaining the morphological diversity of PULs.**
Given that the morphological diversity of various landscapes in PULs is greater than that in urban areas, efforts should be made to preserve this characteristic. Landscape diversity not only contributes to the healthy functioning of ecosystems but also enhances their resilience to environmental changes, supporting biodiversity conservation. From a human perspective, a diverse landscape creates a more attractive living environment, improving quality of life while also providing valuable opportunities for environmental education, research, tourism, and recreation. Therefore, landscape planning and ecological conservation should fully consider the integration of different landscape forms to achieve both ecological and social benefits. By coordinating natural landscape conservation planning with infrastructure planning, the morphological coexistence of natural, semi-natural, and artificial landscapes in PUAs can be ensured. This approach allows for the presence of core areas of natural and semi-natural landscapes, which provide ecosystem services, alongside core areas of artificial landscapes, which serve human needs. These two types of landscapes can be interconnected through corridor landscapes, maintaining both internal and external connectivity while also preserving linkages between smaller landscape patches.

d) **Enhancing the connectivity of natural and semi-natural landscapes.**
In planning, highly fragmented natural and semi-natural PULs can be integrated through land consolidation policies, merging small landscape patches into larger, more continuous units. Additionally, forecasting the impact of unregulated artificial landscape expansion on the overall heterogeneity and connectivity of PULs can help guide timely adjustments in development strategies. To reshape the structure of natural and semi-natural landscapes and improve network systems, green space planning and wetland conservation planning should be incorporated.

(2) Local level

At the local level, the selected PUAs exhibit more detailed regional characteristics, and detailed planning goals and policy implementation tools were proposed based on these characteristics. The policy implementation tools include legal and regulatory tools, economic tools, information and incentive tools, government public investment tools, administrative and organizational management tools, planning and research tools, monitoring and evaluation tools, and public-private partnership and collaborative governance tools (Spyra et al., 2021, Filepne Kovacs et al., 2024, Filepné Kovács et al., 2018). These tools are used to guide, regulate, and control regional development in order to support the achievement of planning goals.

Case A: Mazhai Town, CUA

This case is located at the southwest edge of the CUA, at the intersection of the CUA, Xingyang, and Xinmi, with a total area of approximately 30.10 km^2. According to the Seventh National Census, as of 2020, the total population of Mazhai Town was 80,089. By the end of 2018, there were 314 industrial enterprises in Mazhai Town. In recent years, there have been significant changes in land use, particularly the conversion of agricultural land into urban and industrial land (***Appendix 12***).

In 2000, the Mazhai Town Industrial Park was established just two years earlier. Led by local enterprises such as the Mazhai Eastern Noodle Machine Factory and Tianfang Instant Noodle Factory, these township enterprises rapidly emerged, driving the development of the town center. As a result, an Isolated PUA began to form in the town center. However, the surrounding areas remained distinctly rural.

By 2010, the Mazhai Town Industrial Park had gradually expanded and formed agglomeration effects, attracting a large number of small and medium-sized enterprises. This also led to improvements in infrastructure, such as roads. The expansion of three universities further attracted a large student population and commercial development, significantly increasing the level of urbanization in the town center, which was eventually recognized as an urban area (***Figure 4.32a***). However, this urban area remained separated from the CUA by Interurban and Transitional PUAs, which filled the gap between the two.

By 2020, with further development of the town center and the interlinking of urban patches, the Interurban PUA between the Mazhai Town urban area and the CUA continued to expand, forming a connected urban block (***Figure 4.32b***). The surrounding PUAs had also fully transformed into Transitional PUAs. Notably, with the implementation of Zhengzhou's *Village Consolidation and Urban Integration* project in 2013, under the government's leadership, most rural self-built houses near the town center were demolished and replaced by higher-rise buildings with more urban characteristics. Around these high-rise buildings, some farmland and undeveloped land still remain (***Figure 4.32c***).

In the Master Plan 2012-2030, due to the presence of the Jiayu River and the Jialu River (***Figure 4.32d***), the areas around these rivers in this region have been designated as ecological forest land, while the remaining areas are designated as suitable for construction. In the land use layout plan, most of the land in this area is planned for industrial use, and in the industrial layout plan, the area is specifically designated for traditional food-related industries based on the actual situation, thus promoting industrial development. The three existing universities have been allocated land for educational and research purposes. These plans have played a policy-driven role in promoting the development of the PUAs.

From the development history and planning of the PUAs in Mazhai Town, it is evident that the early-stage PUA was clearly driven by rural industrialization. Due to its location on the edge of the CUA, it gradually became influenced by the urban radiation, transitioning from PUAs to full urbanization over time. The dual driving forces of rural industrialization and urban radiation have led to rapid development in the region over the past two decades. This region has undergone the transformation from PUAs to urban areas and from rural areas to PUAs, encompassing all location types of PUAs' evolution, making it highly representative.

Figure 4.32: Henan Technical College of Construction (a), urban areas (b), PUAs (c), and Jialu River (d) in Mazhai Town.

At the same time, the issues exhibited in this town reflect common drawbacks in the processes of peri-urbanization and urbanization. Firstly, the compact settlement structure has led to land abandonment. Although the intention behind the compact settlement structure was to improve land use efficiency, after the rural independent houses were demolished and replaced by dense residential communities, the land saved in the process has not been well utilized. Most of it remains unused, and in many areas, this state has persisted for over a decade, exacerbating land waste (***Figure 4.33a***). Furthermore, the residents who once lived off farming moved into apartment buildings with urban lifestyles, gradually causing a shift in their way of life. They abandoned farming as a livelihood and turned to factory work in the increasingly numerous factories in the area. As a result, the original farmland has been left fallow (***Figure 4.33b***).

In addition, with the construction of the residential buildings, the government planned a series of supporting facilities, including roads, parks, and commercial streets. These projects were initially well-promoted, but due to a lack of financial support and oversight from relevant departments in the later stages, many of them became unfinished projects. Roads that were nearly completed remained closed or semi-closed for years due to the absence of final construction steps (***Figure 4.33c***). Parks that were completed were initially popular among nearby residents and even residents from farther areas, thriving for a time. However, without proper management in the later stages, these parks gradually fell into disrepair and were eventually abandoned. The various facilities within the parks were also damaged, leading to resource waste (***Figure 4.33d***). Commercial streets, once built, failed to attract many shops due to limited foot traffic, and their operation times heavily relied on the nearby university students, who are a transient population.

Figure 4.33: Field survey images of Mazhai Town.

Based on the existing issues, planning goals, corresponding recommendations and policy implementation tools are proposed (***Table 4.7***).

Table 4.7: The issues observed in Mazhai Town and the corresponding policy implementation tools.

Issue	Goal	Recommendation	Tools
Land abandonment	Improve land use efficiency	Evaluate, plan and reuse abandoned land	Planning and research tools; Government public investment tools
Idle farmland	Restore the productivity of farmland	Encourage farmland contracting	Economic tools
		Develop agricultural parks	Public-private partnership and cooperative governance tools
		Develop specialized agricultural activities	Informational and motivational tools
Lack of infrastructure management	Improve construction and management of infrastructure	Complete unfinished construction projects	Administrative and organizational management tools
		Revitalize and regulate abandoned facilities	Legal and regulatory tools; Government public investment tools
		Improve the usage rate of	Informational and motivational tools;

Issue	Goal	Recommendation	Tools
		existing infrastructure	Economic tools

Case B: Baisha Town, Zhongmu

This case is located at the border between the CUA and Zhongmou, with a total area of approximately 41.48 km^2 (***Appendix 13***). In 2000, the entire area was classified as a rural region, characterized by an agricultural landscape with scattered rural settlements. The Jialu River flows through the eastern and northern parts of the town.

By 2010, with the increase in artificial landscapes, large areas of Transitional PUAs had emerged. Among these PUAs, building material markets and storage facilities occupied significant portions of the land (***Figure 4. 34a***), while nearby farmland was primarily used for greenhouse strawberry cultivation and sales (***Figure 4. 34b***), attracting people from both near and far. In 2015, Baisha Town underwent a comprehensive demolition and reconstruction process, and by 2017, villagers began relocating back in phases. This process accelerated the urbanization and peri-urbanization of the area.

Figure 4.34: The building materials market (a), strawberry greenhouse farms (b), urban areas (c), and Xianghu Ecological Culture Park (d) in Baisha Town.

By 2020, the western part of the area, bordering the CUA, had been transformed into part of the CUA, and a small urban patch had formed in the center of Baisha Town, though it had not yet connected with the CUA (***Figure 4. 34c***). A linear park and the Xianghu Ecological Culture Park were established along the Jialu River (***Figure 4. 34d***), enhancing the environmental quality of the region. During this period, rural areas no longer existed, and the entire surrounding area of the urban district had transformed into Interurban and Transitional PUAs.

The transformation from a completely rural area to PUAs and eventually urban areas demonstrates Baisha Town's rapid development. In the Master Plan 2012-2030, the area was strategically planned to leverage its transportation and locational advantages, positioning it as a regional service center to accommodate the transfer of industries and population from the CUA. The area was also designated to focus on the development of vocational education, modern services, and high-tech industries. With the expansion of the CUA, Baisha Town gradually integrated into the urban framework of the CUA.

During field research, several issues in Baisha Town were identified. Similar to Mazhai Town, Baisha also has some idle land following the demolition process (***Figure 4. 35a***). The conversion of farmland into artificial land is occurring rapidly, with rural characteristics nearly disappearing and being replaced by clusters of high-rise residential buildings (***Figure 4. 35b***). These buildings attract an influx of population due to their geographic advantage near the CUA and relatively low prices. Despite the large number of residential projects developed in this area, the lack of supporting industries raises concerns about the emergence of a commuter town phenomenon. Additionally, insufficient public transportation coverage forces commuters to rely more on private vehicles, leading to traffic congestion. These deficiencies in infrastructure negatively impact residents' quality of life (***Figure 4. 35c, d***). To address these challenges, I have proposed planning objectives, recommendations, and relevant policy implementation tools (***Table 4.8***).

Figure 4.35: Field survey images of Baisha Town.

Table 4.8: The issues observed in Baisha Town and the corresponding policy implementation tools.

Issue	Goal	Recommendations	Tools
Land abandonment	Improve land use efficiency	Evaluate, plan and reuse abandoned land	Planning and research tools; government public investment tools
Farmland loss	Development of urban agriculture	Develop urban agriculture based on the existing greenhouse cultivation foundation	Economic tools; Informational and motivational tools; public-private partnership and collaborative governance tools
Insufficient infrastructure support	Optimize the transportation system	Improve public transportation and promote the Transit-Oriented Development (TOD) model	Government public investment tools
	Strengthen public services	Coordinate population growth with the enhancement of public services	Government public investment tools; planning and research tools

Case C: Chengguan Town, Xingyang

Chengguan Town is located between the urban areas of Xingyang and Shangjie District, with a total area of approximately 51.80 km² (***Appendix 14***). Due to its unique geographic location, the central area of Chengguan Town has consistently exhibited characteristics of Interurban PUAs, influenced by the dual radiating effects of the two adjacent urban centers (***Figure 4.36a***). The extent of these Interurban PUAs has continued to expand over time, primarily along the north-south axis, with a more pronounced expansion trend toward the north. A small number of Transitional PUAs exist on the periphery of the Interurban PUAs, which are influenced by only one of the neighboring urban areas (***Figure 4.36b***). All PUAs in the region consist of a mix of agricultural landscapes and built-up landscapes.

In the northern and southern parts of Chengguan Town, there are two areas that have consistently remained rural. In the north, the Suo River flows through the area, with extensive farmland and rural settlements distributed along both banks (***Figure 4.36c***). The southern area features a hilly and mountainous landscape, characterized by large patches of green space.

In the Master Plan 2012－2030, the majority of Chengguan Town was designated for green space and industrial land use (***Figure 4.36d***). This planning framework explains why the Interurban PUAs in this area have expanded in spatial extent over the past two decades but have not transformed into fully urbanized areas.

On one hand, the area's water bodies and green landscapes serve as an important ecological green core, and planning efforts aimed at their protection have hindered the integrated development of the two adjacent urban centers. On the other hand, the urban areas of Xingyang and Shangjie are managed by separate administrative authorities, resulting in a lack of coordinated planning in areas such as infrastructure development, land use, and industrial distribution. From the perspective of Xingyang's urban development, the CUA to the east exerts a stronger integrative influence, which has led to a greater focus on eastward development to achieve connectivity with the CUA. As a result, Chengguan Town, located in the western part of Xingyang's urban area, has experienced a relatively slow transformation.

Figure 4.36: The Interurban PUAs (a), Transitional PUAs (b), water landscape (c), and industrial land (d) in Chengguan Town.

Unlike the other two cases, Chengguan Town did not undergo demolition or redevelopment between 2000 and 2020. Field surveys and street view imagery reveal that the PUAs in Chengguan Town contain relatively few urbanized structures and are primarily composed of rural-style residential buildings. Many of these houses have been extended vertically using corrugated metal sheets, which pose safety risks and negatively impact the streetscape (***Figure 4.37a***). Although wide roads have been constructed, many large transport vehicles and private cars are parked along the roadside, contributing to a poor road environment (***Figure 4.37b***). Other infrastructure is also underdeveloped, resulting in a generally disordered landscape (***Figure 4.37c***).

Additionally, Chengguan Town's PUAs host numerous construction machinery manufacturing enterprises, many of which had significant pollution issues in the past. In response, the local government initiated reforms and implemented a system of classified management for these enterprises. Dispersed businesses were guided to relocate into designated industrial parks, resulting in the establishment of the Wulong Industrial Cluster and the New Materials Industrial Cluster (***Figure 4.37d***). Moving forward, the environmental impacts of these enterprises on the PUAs will require continuous and proactive monitoring (***Table 4.10***).

Figure 4.37: Field survey images of Chengguan Town.

Table 4.9: The issues observed in Chengguan Town and the corresponding policy implementation tools.

Issue	**Goal**	**Main recommendations**	**Tools**
Fragmentation due to different administrative divisions	Achieve coordinated planning and development	Strengthen communication and cooperation between planning departments in layout planning	Administrative and organizational management tools
Conflicts between natural and artificial landscape development	Balance the relationship between protection and development	Strengthen the protection of water systems and ecological forests to prevent land loss	Planning and research tools; Direct public investment tools
		Develop the cultural and recreational value of natural landscapes	Informational and motivational tools; Public-private partnerships and cooperative governance tools
Disordered environment	Regulate and manage buildings and infrastructure	Demolish illegal and non-compliant structures	Legal and regulatory tools; Administrative and organizational management tools
		Regulate roadside vehicle parking	Administrative and organizational management tools; Economic tools
		Improve sanitation and facilities in public spaces	Government public investment tools; Planning and research tools

Issue	Goal	Main recommendations	Tools
Potential environmental pollution from enterprises	Maintain green, low-pollution development of enterprises	Conduct timely pollution monitoring and management for factories	Legal and regulatory tools; Administrative and organizational management tools

5. NEW SCIENTIFIC RESULTS

The new scientific findings from the present dissertation results are summarized in the following eight theses:

Thesis 1: Progress and limitations of peri-urban area (PUA) research at the global and Chinese levels.

Through a review of the literature, I found that research on PUAs is widespread globally. However, despite shared popular themes, there are regional differences that result in context-specific interpretations of the concept and characteristics of PUAs, lacking a unified standard. Consequently, current studies face limitations in the delineation, quantitative analysis, and landscape planning of these areas.

The study of PUAs originates from early 20th-century European research on urban morphology. A bibliometric analysis of global PUA research literature reveals that the highest volume of research output comes from Asia, led by China; North America, represented by the USA; and Europe, with Italy as a key contributor. In terms of research chronology, North America, Australia, and Europe were the earliest regions to initiate studies on PUAs. The most prominent research topics worldwide include ecological and environmental research, policy and conflict research, spatial morphology research, and land use studies.

In China, research on PUAs began in 1989. These researches were first initiated in major cities, led by Beijing, as well as in the economically developed eastern coastal regions, which have also produced the most extensive research outcomes. Chinese PUA research has primarily focused on four key themes: land use research, land governance research, ecological and environmental research, and spatial morphology research.

Currently, there is no unified standard or method for identifying PUAs. However, previous research has introduced numerous qualitative and quantitative identification approaches, which vary depending on regional and socio-spatial scales. Consequently, there is a notable lack of literature offering direct comparisons among these approaches. Moreover, studies that use identification results to conduct spatiotemporal analyses are also relatively limited.

Furthermore, a review of the literature on peri-urban landscapes (PULs) reveals a set of common characteristics, particularly their dynamic, disordered, and fragmented nature. Regional variations are also evident; for instance, in China, PULs often feature agricultural landscapes as the basic landscape and factory landscapes as the dominant landscape. However, there is a notable lack of case studies focusing on the future sustainable planning and practical implementation of PULs, limiting the availability of references for applied research and policy-making.

Thesis 2: Differences in accuracy and applicability of three quantitative PUA identification methods.

Based on the literature review, I selected three quantitative methods for identifying PUAs: the Threshold method, Breakpoint Clustering, and the Multilayer Perceptron model. Using a unified study area and set of indicators, I conducted a direct comparison of their identification

performance and discussed the applicability of each method.

In selecting the identification methods for comparison, I first chose the Threshold method, which has been widely applied across multiple case studies with consistently effective results. Then, I creatively combined two commonly used approaches, the breakpoint detection and the clustering method, into a hybrid method termed Breakpoint Clustering, aiming to address the limitations of each individual technique. Finally, I introduced the currently popular machine learning techniques by selecting the Multilayer Perceptron model for the identification of PUAs. The main comparative findings include:

a) Based on the criteria of accessibility and wide applicability, I constructed a multi-source indicator system, which includes Imperviousness Density (ID), Nighttime Light Intensity (NLI), Proportion of (semi-) natural land (PNL), and Per Capita Land Area (PCLA). The values of these indicators can represent different regional characteristics, and thus have performed very well in the identification of PUAs.
b) Using the data from 2020, these three methods yielded similar PUA identification results in Zhengzhou. Among them, the Threshold method showed lower accuracy, while both the Breakpoint Clustering and Multilayer Perceptron model demonstrated higher consistency and accuracy in their identification results.
c) In terms of operation and application, the Threshold method is widely used due to its simplicity, making it suitable for macro-scale applications such as overall planning and policy formulation. The Breakpoint Clustering and the Multilayer Perceptron model involve more complex procedures, but they are better at accurately capturing the complex boundaries of PUAs. Therefore, they can be used not only to define the boundaries of PUAs at the macro level but also to play a role in more detailed design and management processes.

<u>Thesis 3: Spatiotemporal evolution of PUAs in multiple dimensions.</u>

After identifying the PUAs of Zhengzhou in 2000, 2010, and 2020 using the Multilayer Perceptron model, I summarized the spatiotemporal trends of PUAs from the perspectives of spatial transition, expansion patterns, land use changes, and locational types.

Spatial transition: Both urban and PUAs in the study region exhibit a growth trend in the area. The expansion of urban areas primarily results from the conversion of PUAs, while the growth of PUAs mainly depends on the transformation of rural areas. Notably, the rate of conversion of rural areas to PUAs accelerated during the period from 2010 to 2020.

Expansion patterns: The spatial extent of PUAs has gradually expanded over time, with edge expansion being the dominant pattern. This has led to an overall expansion-driven rather than compact development trend across all administrative regions of Zhengzhou.

Land use change: Agricultural land and built-up land are the dominant land types within PUAs. Through the Land Cross Transfer Matrix calculations, I found that the spatiotemporal evolution of PUAs is marked by significant agricultural land encroachment by built-up land.

Location types: Along with the expansion of PUAs, three types of PUAs have emerged in Zhengzhou: Interurban PUAs are located between urban areas, exhibiting relatively stable changes and serving as a bridge connecting different urban centers; Transitional PUAs are situated between urban and rural areas, accounting for the largest proportion of PUAs and most accurately reflecting urban expansion; Isolated PUAs are surrounded by rural areas, characterized by smaller average sizes and more scattered spatial distribution. Isolated PUAs primarily result from bottom-up rural industrialization.

Thesis 4: Quantification of the hybrid and dynamic attributes of PUAs.

By plotting line graphs of the indicators along the urban-rural gradient zones and conducting statistical analysis, I validated the hypothesis that PUAs exhibit indicator values, specifically in ID, NLI, PNL, and PCLA, that fall between those of urban and rural areas. This finding quantitatively demonstrates the hybridity of PUAs, which integrate both urban and rural characteristics in terms of construction, economy, naturalness, and population. It also reveals their dynamic nature over time.

The indicator values along the gradient zones confirm a transitional pattern from urban to peri-urban to rural areas: both ID and NLI exhibit a decreasing trend, while PNL and PCLA show an increasing trend. Among these indicators, ID displays pronounced differences among these areas. In contrast, NLI and PNL reveal blurred boundaries between rural and PUAs, indicating less distinct transitions. PCLA values vary across different gradient zones; for instance, the CUA-Xinzheng and CUA-Zhongmu gradients exhibit notably lower PCLA values compared to other zones, suggesting relatively higher overall population densities in these two gradients.

In addition, the direction of dynamic changes in PUAs varies across different indicators. For example, both ID and PCLA of PUAs tend to approach the values of urban areas over time, urban and PUAs show synchronized growth in NLI, while the PNL of PUAs continues to decline, remaining blurred at the boundary between the PNL of rural areas.

Within PUAs, there are certain differences between different location types of PUAs in terms of ID and NLI. The difference in ID between Transitional PUAs and Interurban PUAs is significant. As for NLI, the difference between Interurban PUAs and Isolated PUAs is even more pronounced. In terms of PNL and PCLA, there are no significant differences in indicator values of all location types of PUAs.

Thesis 5: The morphological evolution of PUAs and PULs and their comparison with urban landscapes

In Zhengzhou, I identified ring-shaped, belt-shaped, and patch-shaped PUAs. Based on the Morphological Spatial Pattern Analysis (MSPA), I found both similarities and differences in the morphological evolution of PUAs across the three location types. For PULs, not only do the morphological evolutions among different categories within them vary, but their distinctions from urban landscapes are also quite evident. The morphology of PULs influences regional functions, while the functional demands of PUAs directly impact their spatial morphology.

In PUAs, the ring-shaped morphology is the most typical, often occurring on the outskirts of urban areas, mostly classified as Transitional PUAs. Isolated PUAs are primarily patch-shaped, small in area, and scattered. Belt-shaped PUAs emerged later and are primarily found between adjacent urban areas.

Within PUAs, the area of each morphological type in all categories shows an increasing trend. The *Core* remains the largest morphological type, although its proportion has decreased. In contrast, the proportion of *Bridges* and *Branches* has gradually increased. In comparison, the growth rates of each morphological type in Isolated PUAs are slower and more stable, with Core slightly outperforming the other two types in terms of proportion. In Transitional PUAs, the proportion of Core is the smallest, but the proportion of Bridge consistently remains slightly higher than the other two types of PUAs. In Interurban PUAs, the growth of *Core*, *Bridge*, and *Branch* types was particularly evident between 2000 and 2010.

In PULs, agricultural PULs show a trend of transitioning from *Core* to linear and even fragmented forms. In artificial PULs, the area proportions of each morphological type remain relatively stable, with a notable increase in the proportion of *Bridges*. In green PULs, the area proportions of each morphological type are gradually becoming more evenly distributed. In water PULs, there is also a relatively balanced distribution of the proportions of each morphological type, with a general dominance of linear forms.

A comparison between the morphologies of PULs and urban landscapes reveals that the morphology of PULs is more balanced and diverse than that of urban landscapes, with linear *Bridges* and *Branches* occupying a larger proportion.

<u>Thesis 6: Structural quantification of PUAs and PULs and their distinction from urban landscapes.</u>

I selected Landscape Metrics related to both composition and configuration to quantify the spatial structure of PUAs and PULs. The results revealed structural differences among various locational categories within PUAs, as well as a distinct pattern in PULs characterized by fragmentation of natural and semi-natural landscapes and aggregation of artificial landscapes. These structural patterns exhibit both similarities and differences compared to those observed in urban landscapes.

From the composition metrics, I selected Percentage of Landscape (PLAND), Patch Density (PD), Mean Patch Area (AREA_MN), and Shannon’s Diversity Index (SHDI), while from the configuration metrics, I used Mean Perimeter-Area Ratio (PARA_MN), Total Edge Contrast Index (TECI), Mean Proximity Index (PROX_MN), and Contagion (CONTAG). The analysis based on these metrics revealed that:

In PUAs, Interurban PUAs are characterized by large patch areas and low patch density, with a clear increasing trend in patch diversity and significant temporal changes in patch shapes. Isolated PUAs primarily consist of small patches with high patch density and low landscape heterogeneity. Transitional PUAs exhibit the highest landscape diversity, with strong connectivity among similar patches, mainly due to the clustering of artificial landscapes.

In composition metrics, agricultural and artificial PULs exhibit more prominent composition characteristics, specifically reflected in higher PLAND, PD, and AREA_MN. At the landscape level, the dominant PUL type shifted from agricultural to artificial PULs, accompanied by a fragmentation process that first accelerated and then slowed down over time. Meanwhile, the SHDI gradually increased. In contrast, urban landscapes exhibited lower diversity, with a notable intensification of fragmentation during the 2010-2020 period.

In configuration metrics, the patch shapes of PULs tend to become more complex, and the landscape exhibits increasing heterogeneity. These trends are primarily driven by changes in water and green PULs. Meanwhile, artificial PULs contribute to enhanced spatial connectivity; however, the overall aggregation of PULs shows a declining trend due to human activity disturbances. Similarly, the heterogeneity of urban landscapes also increased; however, the shape of patches in urban landscapes tended to be more regular compared to those in PULs, and the overall landscape exhibited a higher degree of spatial aggregation.

Thesis 7: The spatiotemporal evolution of PUAs is mainly driven by urban-rural driving forces, location and topography, and city planning.

Based on the preceding analysis, I found that the spatiotemporal evolution of PUAs exhibits regional disparities. In the case of Zhengzhou, the northeastern region shows both a larger extent and a faster growth rate of PUAs compared to the southwestern region. To explain these spatial differences, I identified three main driving factors.

Urban-rural driving forces: The radiative influence of urban areas has facilitated the formation of Transitional PUAs. In polycentric cities, the radiation of multiple urban centers has further promoted the emergence of Interurban PUAs and also enhanced the connectivity between PUAs, leading to the formation of continuous networks. Rural industrialization has led to the creation of Isolated PUAs, which, over time, have transitioned into Transitional PUAs and even Interurban PUAs.

Location and topography: The administrative regions located close to the CUA with flat terrain experience faster growth in PUAs. In contrast, administrative regions that are farther from the CUA and situated in more mountainous terrains face certain limitations in the development of PUAs.

City planning: The administrative regions within the study area are assigned different functional roles in urban planning, which influence their peri-urban development. For example, the CUA, as the primary functional zone, has significantly higher construction intensity and density compared to other administrative regions. This has accelerated the expansion of PUAs in the CUA.

The spatial evolution of PUAs is influenced by the aforementioned multiple factors. Conversely, it can quickly reflect the dynamic development of the city. Focusing on these areas can provide timely feedback to governments and planners, enabling them to better control the direction of urban planning, improve land use efficiency, and promote sustainable development.

Thesis 8: Context-specific planning guidelines for PUAs and PULs at the regional and local levels.

Drawing on planning experiences from other cases, I applied these insights to the challenges currently faced by Zhengzhou's PULs. At the regional level, I proposed planning guidelines centered on spatial planning and regulatory tools. At the local scale, I selected three towns as case studies to develop detailed planning recommendations and policy implementation tools.

I examined the current peri-urbanization challenges faced by Zhengzhou, which include a lack of comprehensive planning and management, the dual effects of a polycentric urban structure, and increasing homogenization in spatial form and structure. Subsequently, I identified four main types of spatial planning and regulatory tools based on ten case studies: (a) urban growth management policies; (b) spatial planning and zoning; (c) nature and landscape conservation planning; and (d) other individual plans.

Building on the assessment of current conditions in the study area and global planning experiences, I propose the use of spatial planning and regulatory tools at the regional scale to address existing problems within the PUAs. These proposals include:

a) Conducting spatial and land monitoring to predict future development.
b) Coordinating compact settlements and low-density development in spatial patterns.
c) Maintain the morphological diversity of PULs.
d) Enhancing the connectivity of natural and semi-natural landscapes.

At the local scale, I selected three representative towns and addressed specific issues that emerged during the evolution of PUAs in these areas, such as the abandonment of arable land and the lack of infrastructure management. For each case, I proposed detailed planning objectives, guidelines, and policy implementation tools. This analytical framework provides a theoretical foundation for the optimization practices of PUAs.

6. CONCLUSION AND PROSPECTS

6.1 Summary of the dissertation

The global emergence of peri-urbanization has driven both theoretical and practical research in recent years. Building on these studies, I use Zhengzhou as a case study to demonstrate an analytical framework for examining the spatiotemporal evolution of peri-urban areas (PUAs) within a polycentric urban context, as well as to propose sustainable planning guidance for peri-urban landscapes (PULs). This section aims to address the research questions posed at the beginning of the dissertation and to present the corresponding conclusions.

Question 1: What are the global research trends and hotspots related to PUAs? What advancements and gaps exist in the identification of PUAs and the planning of PULs?

In terms of research output, China, the United States, and Italy have contributed the most to studies on PUAs. Chronologically, research on PUAs began earlier in North America, Australia, and Europe. At the global level, the major research themes on PUAs include ecological and environmental studies, policy and conflict studies, spatial morphology studies, and land use studies. Within China, research on PUAs initially emerged in major cities, particularly Beijing, and the economically developed coastal regions in the east, where the most substantial body of research has been produced. Chinese studies on PUAs primarily focus on four key themes: land use research, land governance research, ecological and environmental research, and spatial morphology research.

Previous studies have introduced numerous qualitative and quantitative methods for identifying PUAs; however, a standardized approach has yet to be established. Moreover, there is a lack of literature that provides a clear comparative overview of quantitative identification approaches. In terms of the spatiotemporal evolution of PUAs, quantitative analyses remain limited. Research on PULs is largely based on case studies combined with spatial pattern analysis, which has helped summarize both common and region-specific characteristics of PULs. However, literature on future planning and practical applications of PULs remains relatively scarce.

Question 2: Given the same multi-source indicator system and study area, how do the accuracy and applicability of the three quantitative methods, Threshold method, Breakpoint Clustering, and Multilayer Perceptron model, compare in identifying PUAs?

Through comparison, I found that the Threshold method has the lowest accuracy and is only suitable for large-scale studies. Breakpoint Clustering demonstrates relatively high accuracy and provides more refined identification results. The Multilayer Perceptron model achieves the highest accuracy and has a broader applicability. Therefore, the Multilayer Perceptron model was ultimately selected for the multi-year identification of PUAs.

Question 3: From a spatiotemporal perspective, what are the characteristics of PUAs in polycentric cities in terms of spatial transition, expansion patterns, land use changes, and locational types?

The identification results of PUAs in Zhengzhou for the years 2000, 2010, and 2020 reveal that PUAs primarily evolve from rural areas while simultaneously transitioning toward urban areas. Edge expansion is the dominant type of PUA growth. Land use within PUAs exhibits a clear trend of conversion from agricultural land to built-up land. During spatiotemporal evolution, three distinct locational types of PUAs have emerged (Isolated PUAs, Interurban PUAs, and Transitional PUAs).

Question 4: How do PUAs differ from urban and rural areas in terms of construction, economy, naturalness, and population? Are there significant differences in these characteristics among PUAs of different locational types?

PUAs align with the hypothesis that their indicator values fall between those of urban and rural areas across four indicators: Imperviousness Density (ID), Nighttime Light Intensity (NLI), Proportion of (semi-) natural land (PNL), and Per Capita Land Area (PCLA). These indicators also exhibit temporal fluctuations. Notably, a trend toward convergence between PUA values and urban area values is particularly evident in ID and PCLA. Statistical analysis reveals significant internal differences within PUAs. Specifically, there is a significant difference in ID between Transitional PUAs and Interurban PUAs. Additionally, Interurban PUAs and Isolated PUAs exhibit a significant difference in NLI.

Question 5: How do the morphological evolutions of PUAs and PULs manifest?

PUAs primarily exhibit ring-shaped, belt-shaped, and block-shaped forms, with the belt-shaped pattern becoming more pronounced in later years. Among PUAs, Transitional PUAs display the most diverse morphological characteristics. PULs are characterized by large *Cores*, belt-shaped *Corridors*, and block-shaped *Stepping stones*. Compared to urban landscapes, PULs exhibit greater morphological diversity, particularly with a higher prevalence of belt-like structures such as *Bridges* and *Branches*.

Question 6: What structural characteristics do PUAs and PULs exhibit in terms of composition and configuration?

In PUAs, Interurban PUAs are characterized by large patch sizes and low patch density, whereas Isolated PUAs primarily consist of small patches with high patch density and low landscape heterogeneity. Transitional PUAs exhibit the highest landscape diversity and strong connectivity. From the perspective of composition, PULs show a fragmentation trend dominated by the fragmentation of natural and semi-natural landscapes. In terms of configuration, PULs exhibit increasing patch-shape complexity and enhanced heterogeneity, along with a significant trend of increased connectivity in artificial PULs.

Question 7: What factors influence the evolution of PUAs and PULs in polycentric cities?

The development of PUAs is primarily influenced by factors such as multi-center urban radiation, rural industrialization, location and topography, and urban planning. Specifically, PUAs that are located closer to the Central Urban Area (CUA), have flat terrain, and are influenced by the radiation of multiple urban centers develop more rapidly, especially in areas characterized by the development of modern industries like manufacturing in urban planning. In contrast, PUAs driven by rural industrialization, located farther from the CUA, and situated in mountainous or hilly landscapes, tend to develop more slowly. These areas are often designated for ecological protection in urban planning, which restricts the development of PUAs.

Question 8: Based on the existing peri-urbanization challenges, what PUL planning guidelines can be derived from global experiences?

Based on the existing challenges in the study area and the relevant experiences from ten PUL planning cases, the following recommendations are made:

At the regional level, the focus should be on: conducting spatial and land monitoring to predict future development; coordinating compact settlements and low-density development; maintaining the morphological diversity of PULs; and enhancing the connectivity of natural and semi-natural landscapes. At the local level, in response to issues such as idle farmland and inadequate infrastructure in three case towns, targeted planning guidance and policy implementation tools are proposed, for example, legal and regulatory tools, economic tools, information and incentive tools.

6.2 Limitations and recommendations for future research

The study of PUA identification and evolution not only aids in the rational planning and management of PUAs but also provides theoretical support for controlling urban sprawl, enhancing urban-rural integration, and promoting sustainable development. While PUAs are currently planned in China's urban planning primarily in the form of administrative regions such as townships, emphasizing the importance of PUAs in urban planning will elevate their status among policymakers and planners. In the future, the introduction of specialized planning could break administrative boundaries and facilitate unified planning and management.

However, some limitations should be noted. Firstly, due to the large study area in this research, I used 1 km^2 square grids for sampling when spatializing the indicator data. This process reduced the precision of some data. Additionally, there was a lack of multi-scale comparative analysis when choosing the grid size. In future research, the size of the grids can be appropriately adjusted according to the area of the research region, and the appropriate analysis scale can be selected through the method of multi-scale comparison.

Secondly, the selection of indicators has a significant impact on the identification results. Although I selected indicators from different dimensions and used different data to calculate them to avoid multicollinearity, it was still difficult to comprehensively characterize the characteristics that distinguish PUAs from other regions. The subsequent gradient zone analysis also indicated that in some indicators, PUAs did not show significant differences from other regions. In recent years, some big data represented by Point of Interest (POI) have also begun to be applied in the identification of PUAs, but due to the inability to obtain long-term time series data, it was not applied in this study.

While I presented three commonly used or novel methods for PUA identification, many quantitative identification methods have not been explored. Additionally, the identification methods were applied using data from only a single year, lacking a temporal comparison across multiple years. This may weaken the persuasive power of the results. Future studies could consider using multi-year data to compare the accuracy and applicability of PUA identification methods. Future research could explore more PUA identification methods based on the specific characteristics of the study area and attempt to incorporate more interdisciplinary theories and techniques for precise identification, thus laying the groundwork for cross-regional studies and in-depth longitudinal analysis of PUAs.

Furthermore, when formulating the sustainable planning guidelines for PULs in Zhengzhou, the cases I referred to were limited, and the proposed guidelines were relatively general, lacking discussions on the governance structure of the study area and their integration with policy tools. Throughout the entire research, I only discussed the case of PUAs in a polycentric city and lacked comparisons with other urban form cases. Future research could selectively compare various cases with different urban forms, which will help gain a more detailed understanding of how the formation of PUAs is influenced by urban forms.

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LIST OF FIGURES

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ACKNOWLEDGEMENT

Four years ago, I embarked on the journey of pursuing a PhD at the Hungarian University of Agriculture and Life Sciences (MATE). At the outset, I regarded doctoral study as something both romantic and rare, for it offered the opportunity to devote several years wholeheartedly to a single subject. Over the past four years, I have gone through the challenges and transformations brought by differences in culture, language, research, and lifestyle, gradually growing into who I am today. All in all, this has been one of the most unforgettable experiences of my life. Now, as I stand at the end of this journey, I would first like to congratulate myself on nearly completed this romantic and rare endeavor—every effort will eventually be rewarded.

I would like to express my deepest gratitude to my supervisor, Dr. Krisztina Filepné Kovács. Throughout my entire academic journey, she has always been by my side, guiding my research and dissertation with professionalism and dedication, while providing me with the most meticulous support and the warmest encouragement. I am particularly grateful for her patient guidance in helping me prepare and rehearse for important occasions. Beyond academics, she also showed me great kindness in life and introduced me to the culture of Hungary. I feel truly fortunate to have had such a supervisor.

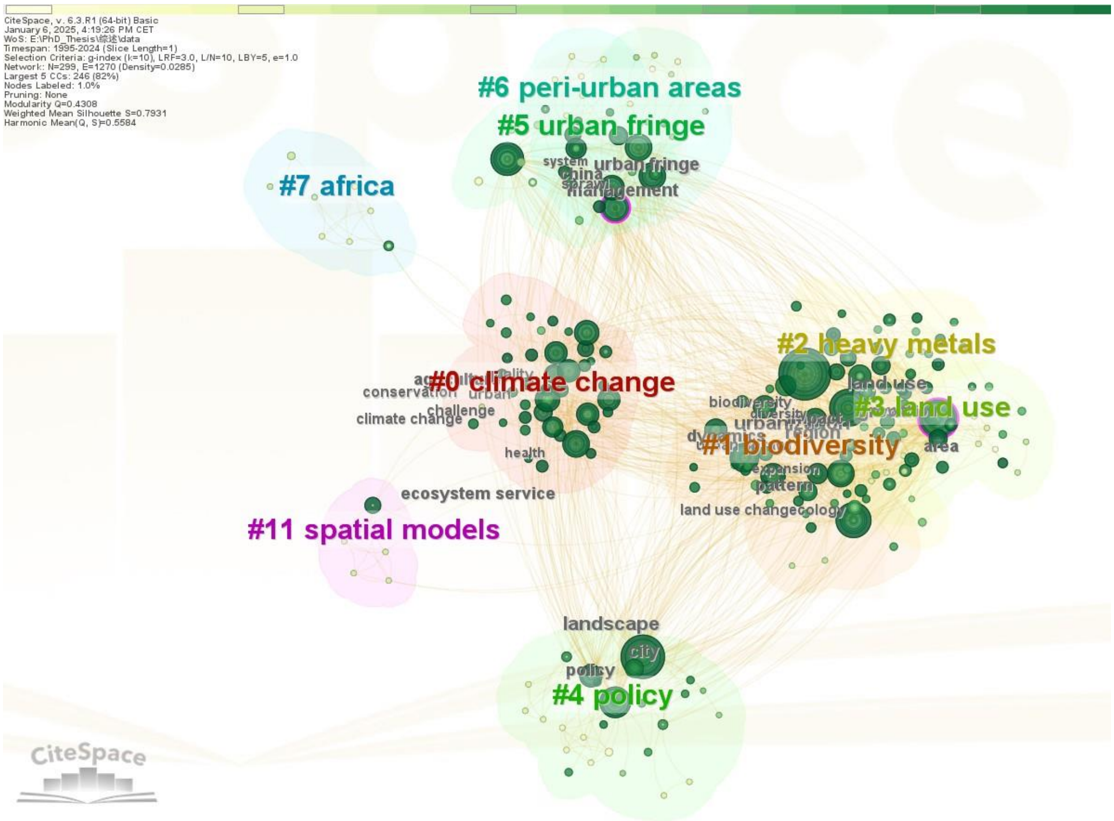
I would also like to thank the professors and colleagues at MATE who provided me with guidance in coursework, research, and academic exchange: Prof. Dr. László Bozó, Prof. Dr. Albert Fekete, Dr. László Kollányi, Dr. Vera Iváncsics, Dr. Sándor Jombach, Prof. Dr. Ágnes Sallay, Dr. István Valánszki, Dr. Zsófia Földi, Dr. László Zoltán Nádasy, Dr. Martin van den Toorn, Dr. Edina Klára Dancsokné Fóris, Dr. Éva Erdélyi, Hassan Yaseen Nasradeen, Rahaf Yousef, Ansam Bzour, Seloua Benkaid Kasbah, and Anas Tuffaha. I am also grateful to Ms. Edit Simáné Dolányi for her patient assistance with many administrative matters at the university. In addition, I would like to extend my sincere thanks to Prof. Guohang Tian, Prof. Ruizhen He, Dr. Huawei Li, and Dr. Shumei Zhang from Henan Agricultural University for their valuable guidance in my academic research.

I would like to express my heartfelt thanks to my friends for their companionship and support over the past four years: Manshu Liu, Xiaoyan Zhang, Dr. Yang Yang, Dr. Xinyu Wang, Dr. Yuchen Guo, Dr. Guifang Wang, Dr. Tian Bai, Kun Wang, Chenyu Du. May our friendship continue to accompany us in the years to come.

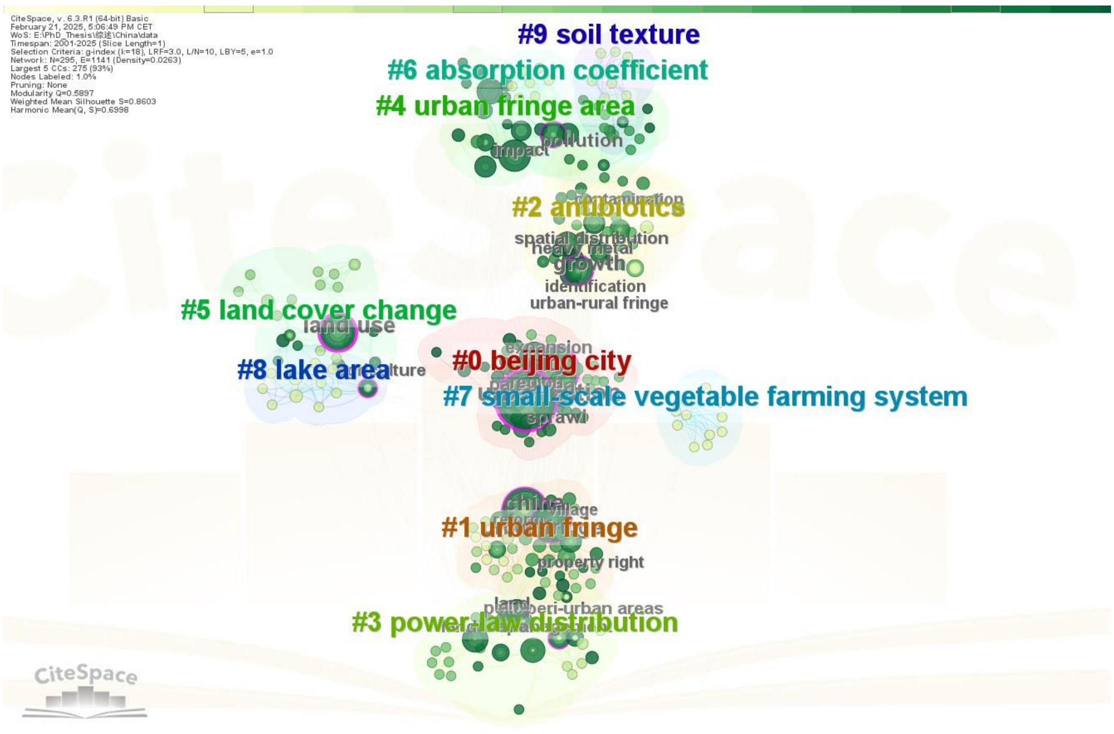
I would like to express my sincere gratitude to the China Scholarship Council and the Stipendium Hungaricum Programme for their financial support over the past four years, which made my studies and life possible.

Finally, I would like to express my heartfelt gratitude to my family in China for their constant emotional support and encouragement while I was studying abroad, which gave me the reassurance to focus on completing my studies.

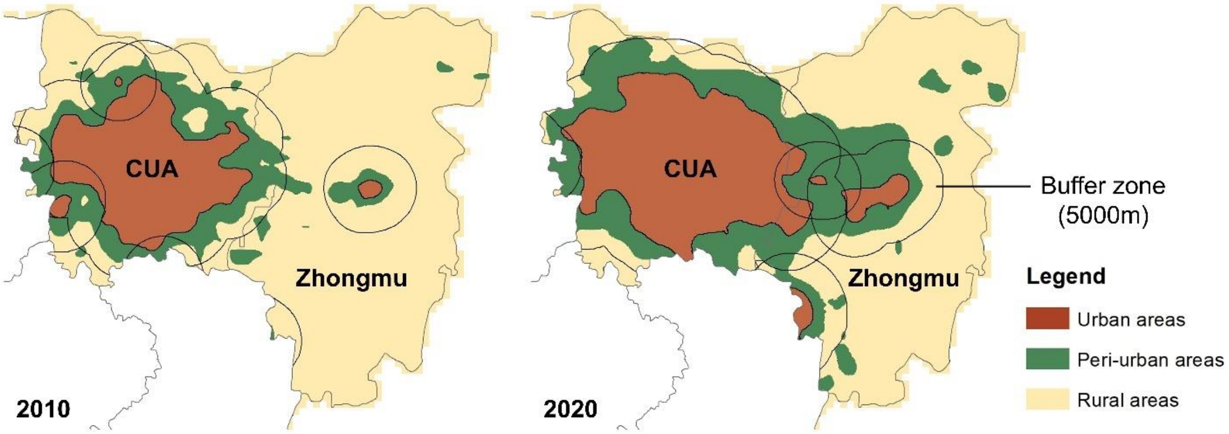
APPENDICES



Appendix 1: Keyword cluster of the Global Database.



Appendix 2: Keyword cluster of the Chinese Database.

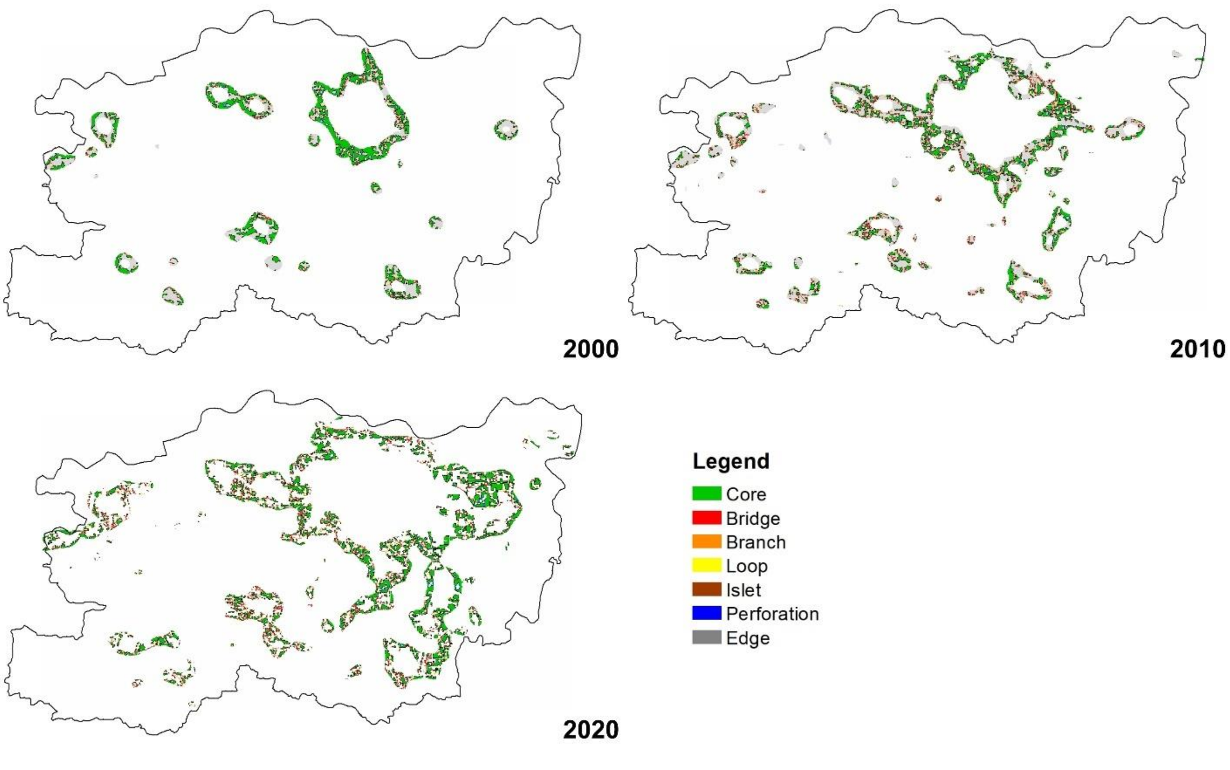


Appendix 3: Example of the urban radiation area (buffer zone).

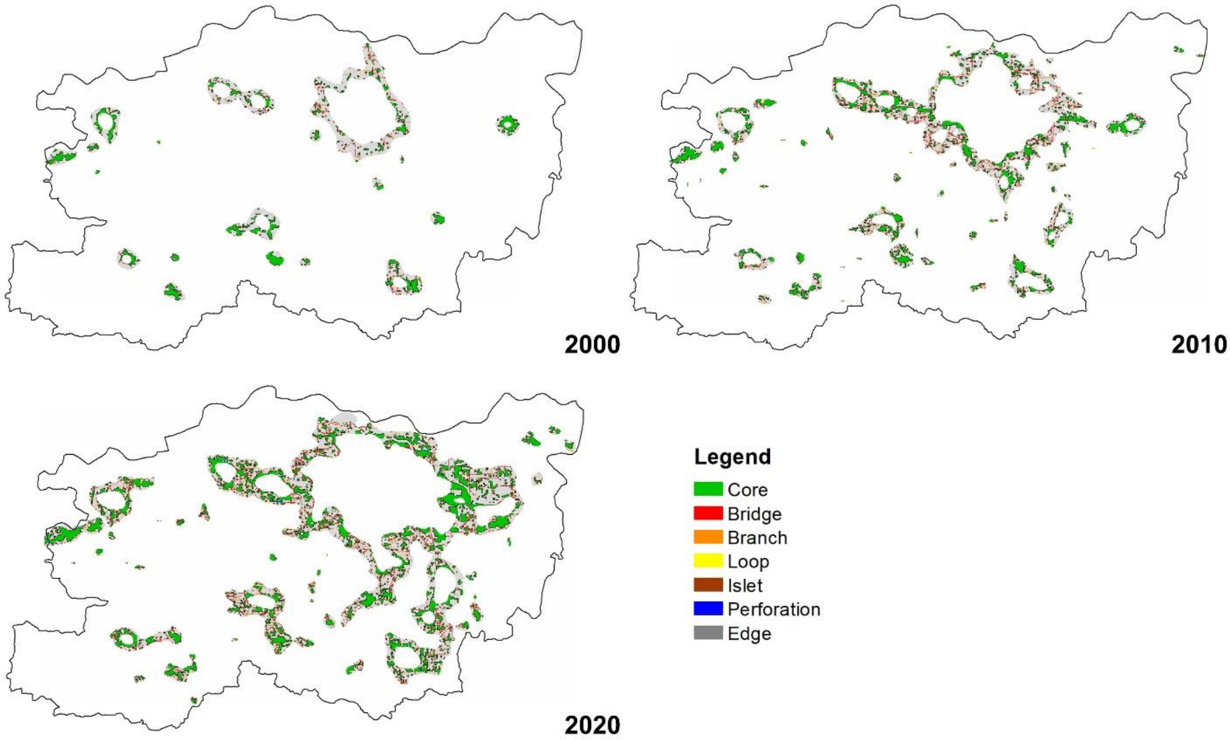
Appendix 4: Statistical test results of indicator values among the gradient zones for urban, peri-urban and rural areas.

Indicator	F	p-value	Post-hoc Test
ID	328.992	.000***	Urban areas > PUAs > Rural areas, all pairwise differences significant
NLI	70.456	.000***	Urban areas > PUAs, Urban areas > Rural areas (significant); PUAs ≈ Rural areas
PNL	254.388	.000***	Rural areas > PUAs > Urban areas, all pairwise differences significant
PCLA	5.959	.038*	Rural areas > Urban areas (significant); PUAs ≈ Urban areas, PUAs ≈ Rural areas

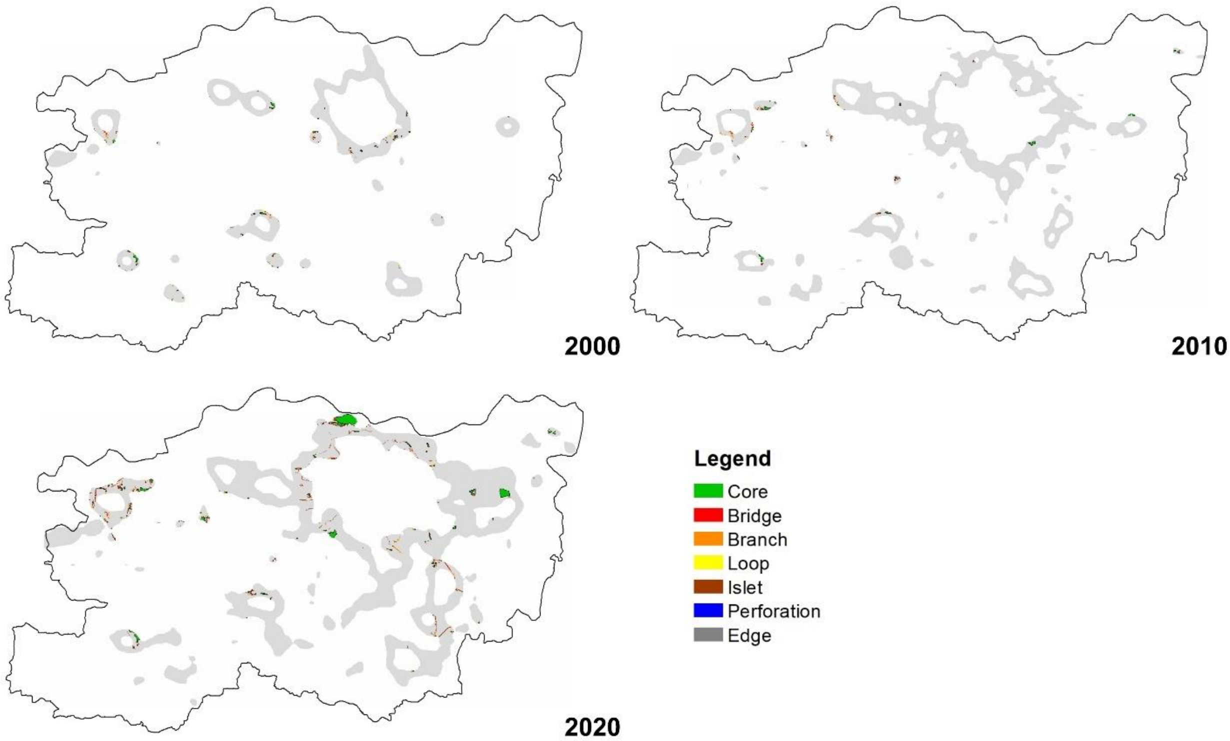
***p < 0.05, **p < 0.01, ***p < 0.001**



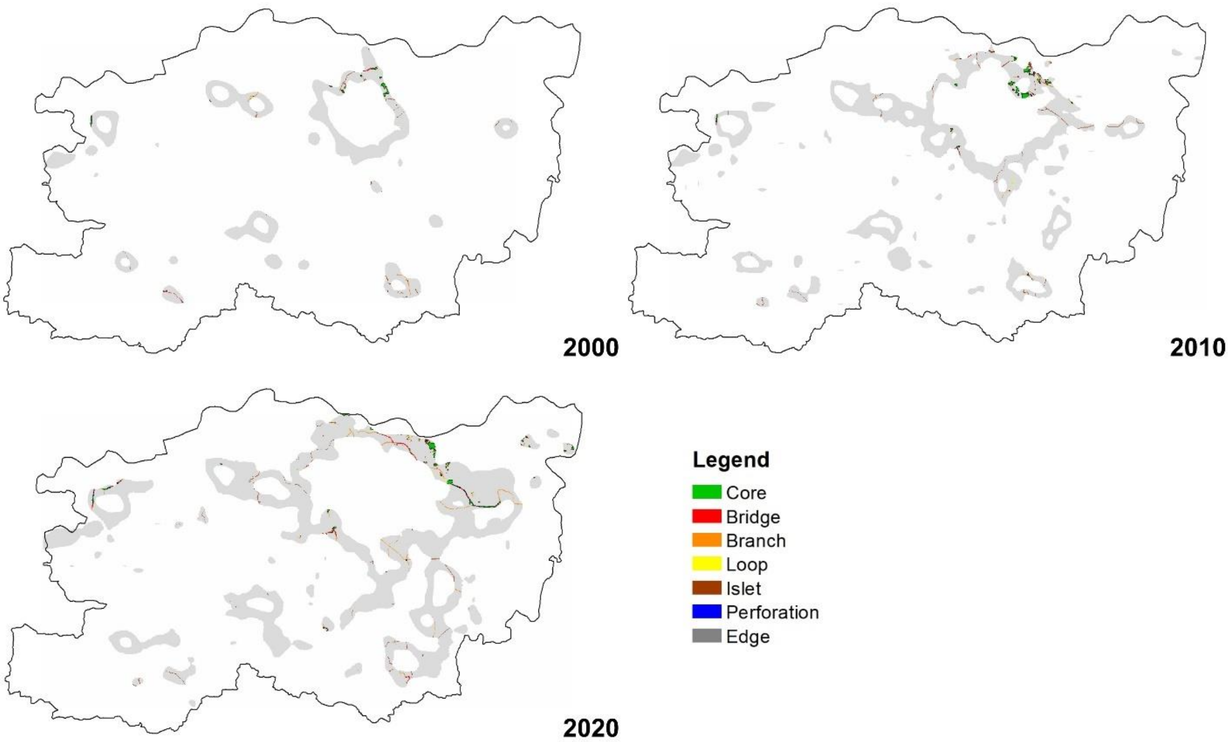
Appendix 5: Spatial distribution of morphological types of Agricultural PULs.



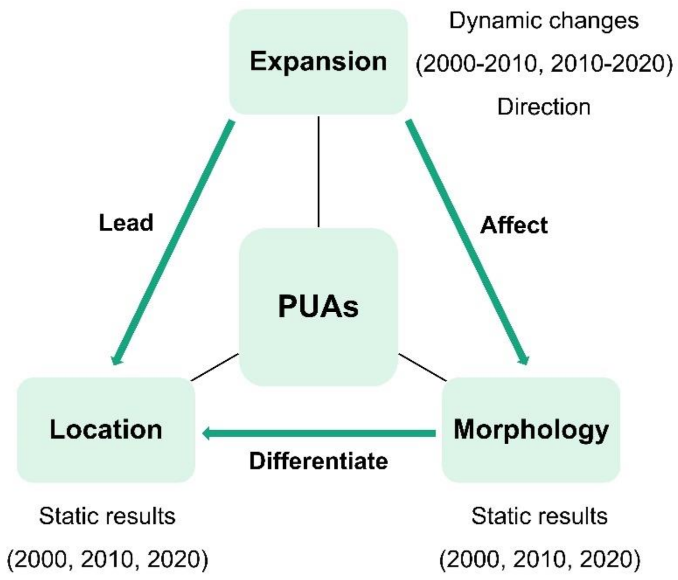
Appendix 6: Spatial distribution of morphological types of Artificial PULs.



Appendix 7: Spatial distribution of morphological types of Green PULs.



Appendix 8: Spatial distribution of morphological types of Water PULs.



Appendix 9: correlation of expansion analysis, location analysis, and morphological spatial pattern analysis of PUAs.

Appendix 10: Case studies on spatial planning and regulatory tools for PUAs.

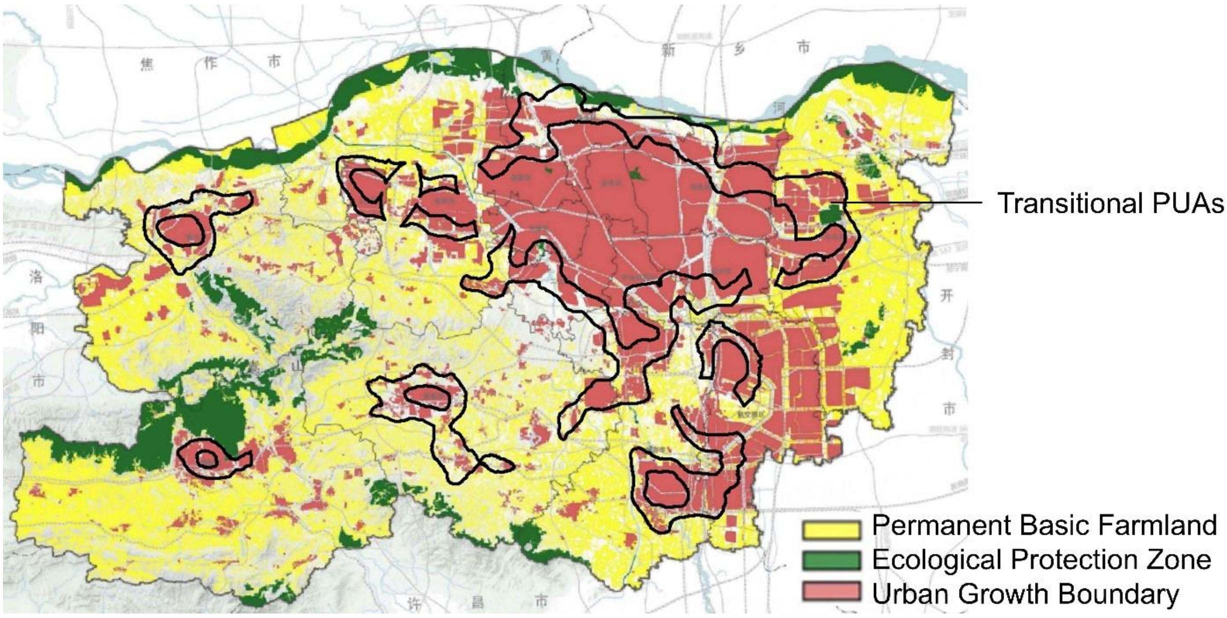
Case 1	**Romania** (Petrovici and Poenaru, 2025)
Challenges	PUAs exhibit significant heterogeneity compared to urban areas, characterized by uneven and dispersed spatial patterns.
Tools	1) Urban policies are implemented at regulatory, planning, financial, and institutional levels, aiming to achieve four key objectives: promoting spatial sustainability by managing rapid urban expansion, leveraging urban assets,

	and enhancing connectivity both within and between urban and PUAs. 2) The metropolitan areas are categorized into three types: growth, static, and shrinking cities.
Recommendations	A more refined classification of regional types should be established, with tailored planning strategies based on the characteristics of each area. For PUAs, sustainable land-use planning, smart infrastructure, and enhanced transportation connectivity are recommended. Strengthened institutional cooperation is also necessary.
Case 2	**Greater Cairo, Egypt** (Salem and Tsurusaki, 2024, Youssef et al., 2020)
Challenges	PUAs in Greater Cairo face a range of environmental, social, and economic challenges, including landscape fragmentation, resource depletion, and inadequate infrastructure. Urban expansion has resulted in the loss of agricultural land in PUAs.
Tools	Several laws and legislative measures regulate urban expansion and protect agricultural land, including: *Unified Building Law No. 119/2008; Urban Planning Law No. 3/1982; Agricultural Land Protection Law No. 116/1983*.
Results	The effectiveness of these laws in addressing the challenges of rapid urban expansion has been inadequate. This shortcoming is primarily due to the authorities' failure to fully enforce these regulations.
Recommendations	A comprehensive land management strategy should be implemented, including the establishment of green belts, the protection of agricultural reserves, and the promotion of compact urban forms to minimize land consumption in urban areas.
Case 3	**Chattogram Metropolitan Area, Bangladesh** (Mamun et al., 2024)
Challenges	Peri-urbanization has led to severe deforestation and urban encroachment into previously untouched areas, significantly altering the landscape.
Tools	2) *Detailed Area Plan (DAP) 2007/2008*: established strategic open spaces and no-development zones; 3) *Chattogram Metropolitan Master Plan (CMMP) 2009–2015*; 4) *Foundational Structure Plan (1995–2015)*; 5) *Urban Development Master Plan (1995–2005)*: proposed land use in coastal zones was designated as a *No Development Zone* to prevent large-scale industrial expansion and to encourage only temporary settlements and light industrial development;
Results	1) The spatial zoning plan led to more rural-to-urban migration. This resulted in large-scale peripheral expansion, encompassing both housing projects and industrial development. 2) Despite the restrictions imposed by the DAP, many industrial activities continued to take place without legal authorization or thorough environmental assessments. 3) Despite afforestation and reforestation efforts aimed at rectifying illegal land use practices, their impact has remained limited.
Case 4	**Greater Helsinki Region, Finland** (Lebrasseur, 2024, Söderström et al., 2015)
Challenges	The geographical expansion has led to the fragmentation and isolation of green spaces from the larger regional rural green areas, resulting in a fragmented green spatial structure and pattern within PUAs.

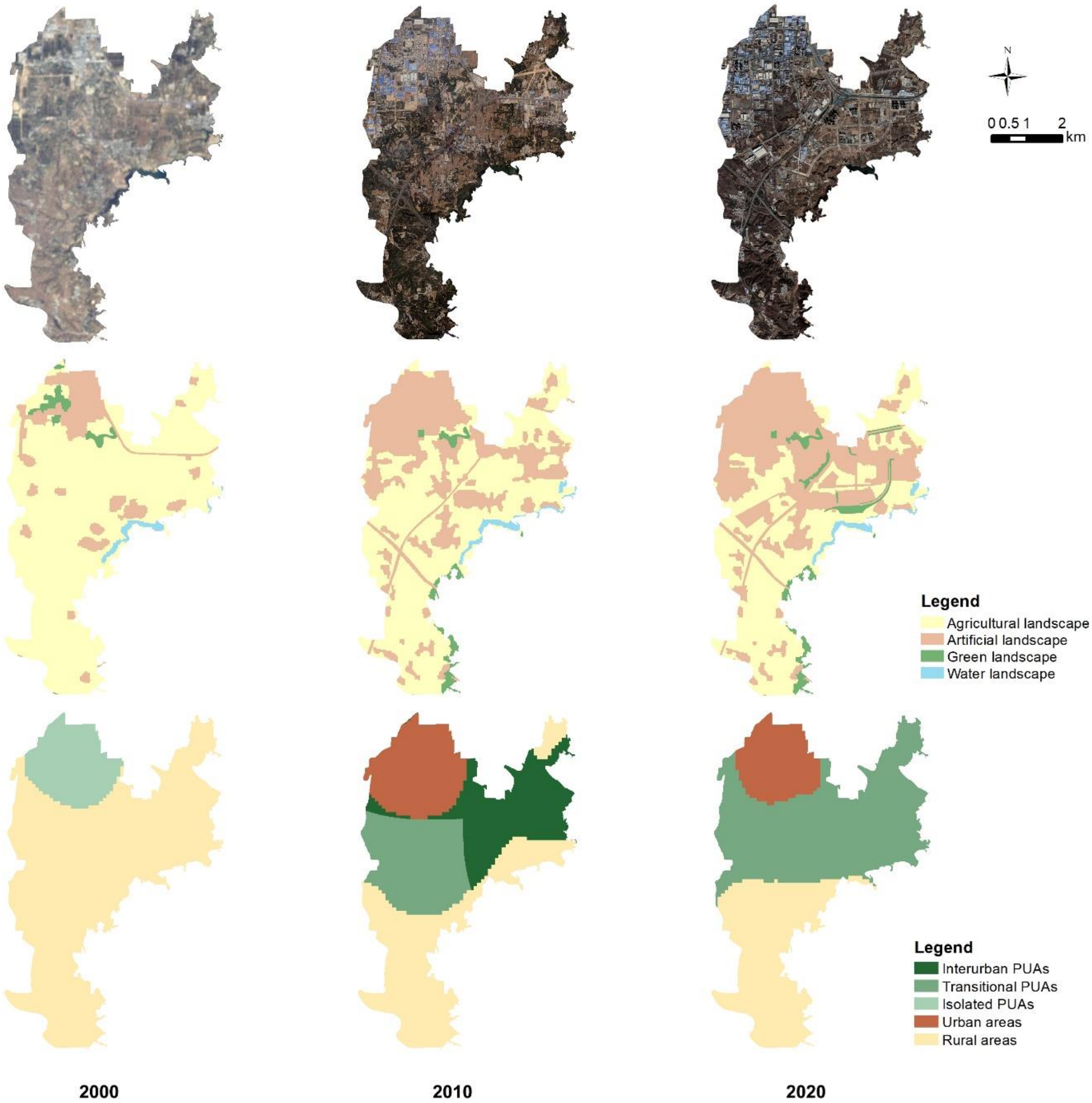
Tools	The *Land Use and Building Act* by the Ministry of the Environment only encourages sustainable development.
Results	The current planning lacks clear policies or approaches to protect the core areas of existing public green spaces.
Case 5	**Stockholm, Sweden** (Schmitt et al., 2015, Xiu et al., 2016, Lebrasseur, 2024)
Tools	1) Urban planning (Översiktsplan för Stockholm) considers green spaces and how to meet the demands for ecosystem services based on the planning directions and strategies of the city's urban and environmental plans. 2) The city's unique polycentric urban form includes green wedges and green connections, with policy goals focused on protecting public urban green spaces and enhancing biodiversity and green network connectivity.
Recommendations	The future polycentric development approach, based on the current green structure and land cover, should focus on meeting ecological and social requirements.
Case 6	**Krakow, Poland** (Busko and Szafranska, 2018, Cegielska et al., 2018a, Kukulska-Kozieł, 2023, Pluta, 2016, Cegielska et al., 2024)
Challenges	An inadequate spatial planning system makes it difficult to address the balance between developable, natural, and typical agricultural land in PUAs.
Tools	1）*Act on the protection of agricultural and forest land*； 2）*Polish Act on spatial planning and development*: regulates national spatial policy; 3）The local zoning plan is the only legally binding spatial planning document in Poland, but it is not mandatory.
Results	1) The spatial planning system has failed to ensure the stability of land use, with agricultural land continuously being converted to non-agricultural uses, the majority of which are residential areas. 2) In 2021, only 32% of the country's territory was covered by local zoning plans. The spatial management of the remaining areas is controlled by administrative decisions.
Recommendations	Using legal and regulatory tools to anticipate and resolve conflicts; establishing an effective spatial planning system and enhancing public participation; diagnosing land use conflicts to balance diverse interests.
Case 7	**Mexico** (Aguilar et al., 2022, Lebrasseur, 2024)
Challenges	The phenomenon of illegal occupation of land in informal settlements continues to be significant, leading to urban expansion. Urban expansion has caused environmental deterioration in some areas, resulting in the gradual disappearance of large Conservation Areas.
Tools	The local government has given great attention to the Conservation Areas and even provided economic incentives to improve the environment. However, no comprehensive protection policy with strict zoning has been formulated for the entire Conservation Areas.
Results	The urban planning regulations have not been effectively implemented, and the illegal land occupation in the Conservation Areas and the deterioration of the environment continue to occur.
Case 8	**Rome, Italy** (Grabowska et al., 2024)

Tools	A new master plan for Rome was implemented in 2000. The document aims to promote polycentric growth to address the spontaneous spread of artificial surfaces in PUAs.
Results	The expansion of Rome's functional urban area has slowed down as a result of the policy.
Case 9	**Turin, Italy** (Gottero et al., 2023)
Tools	1) *Regional territorial plan RLP 2011*; 2) *Regional landscape plan RLP 2017*; 3) *Green Crown Project*: defining urban edges and gateways; ecological de-fragmentation; promoting multifunctional agriculture; enhancing landscape heritage and local identity. 4) *Provincial Territorial Plan PTCP2 2011*: defined the green system and ecological network of the metropolitan area; 5) *General Territorial Plan PTCM Draft Version 2021*: includes rules (Art. 44) and guidelines for open spaces in the PUAs: preventing land take and soil sealing; reclaiming brownfield and degraded areas; fostering multifunctional and social agriculture; improving naturality and environmental quality; protecting traditional rural landscape features; removing or mitigating visual impacts; qualifying urban edges; strengthening recreational networks.
Case 10	**Budapest, Hungary** (Nowak et al., 2022, Filepne Kovacs et al., 2024)
Challenges	The spatial planning system has ineffective control over land cover changes; the spatial planning framework appears fragmented due to the lack of strategic guidelines.
Tools	1) The *Budapest 2030 Long-Term Urban Development Concept (2013)*: a municipal policy document established in accordance with *Act LXXVIII* of 1997 on the formation and conservation of the built environment, concerning the future form of Budapest. The document divides Budapest into five functional zones, including the inner zone, the transitional zone, the suburban zone, the hilly zone, and the Danube zone; 1) The *National Spatial Plan and the Budapest 2030 Strategy* introduced the concept of a compact residential structure to mitigate urban sprawl; 2) The *Budapest Strategy 2030* and the *Budapest Green Infrastructure Strategy* emphasize the importance of protecting the *Green Wedges*, which include open spaces, green corridors, forests, waterways, and agricultural land systems; 3) The *Act on Nature Conservation (No. LIII of 1996)* defined the national ecological network areas. These areas are incorporated into national-level land use plans; 4) The *National Development and Territorial Development Concept 2014–2020*: This concept foresaw the development of a polycentric settlement system, whose decentralized and network-based spatial structure would alleviate the excessive burden on Budapest. 5) The *Act No. CXXII of 2013* concerning agricultural and forestry land trade; 6) The *Act No. LXIV. of 2005. on Land use plan of Budapest agglomeration* was the first national-level legislation in Hungary to establish a unified spatial plan

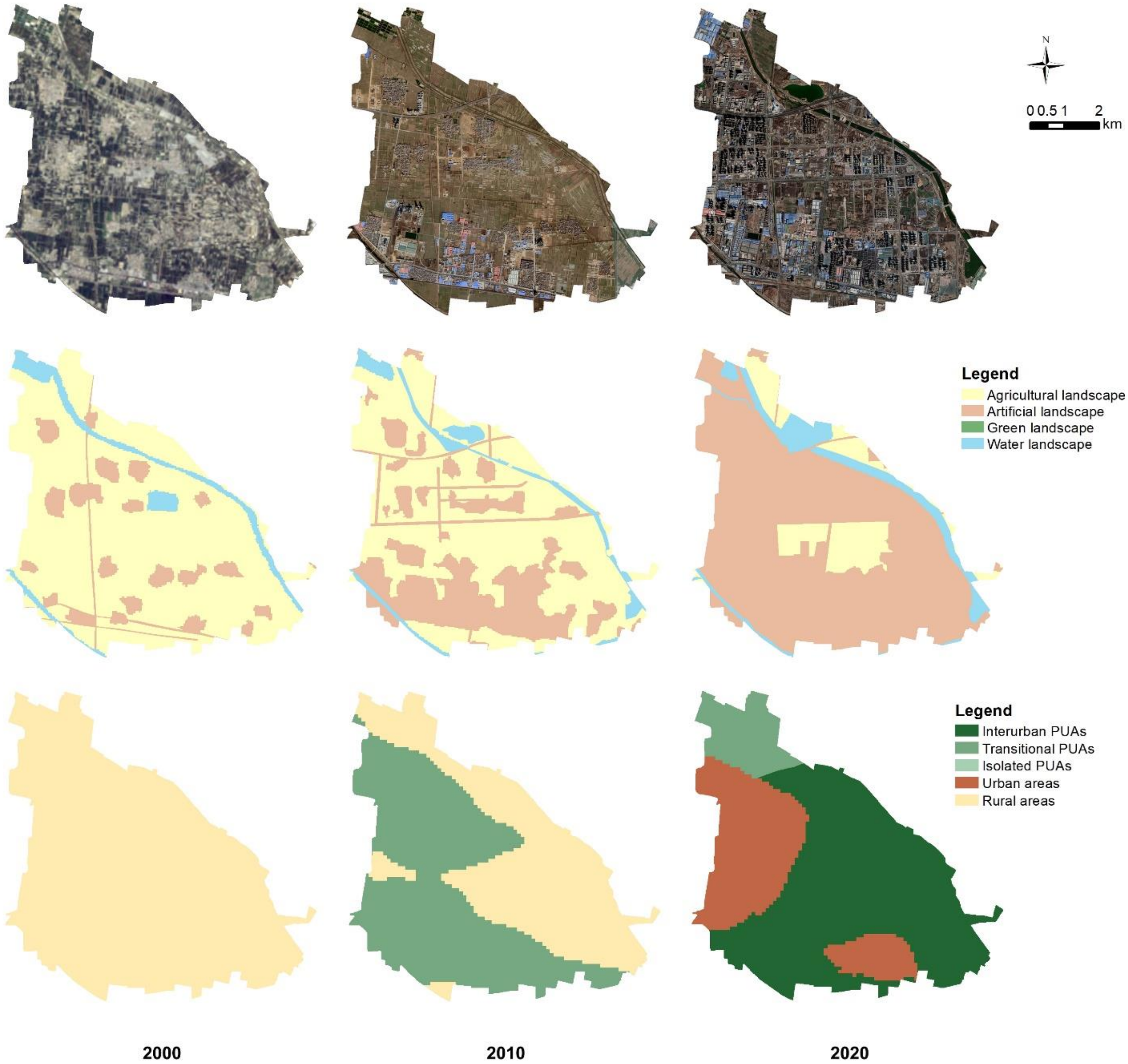
for a major metropolitan area. It has now become part of the *Act No. CXXXIX of 2018* on the Land Use Framework Plan of Hungary and Priority Regions.



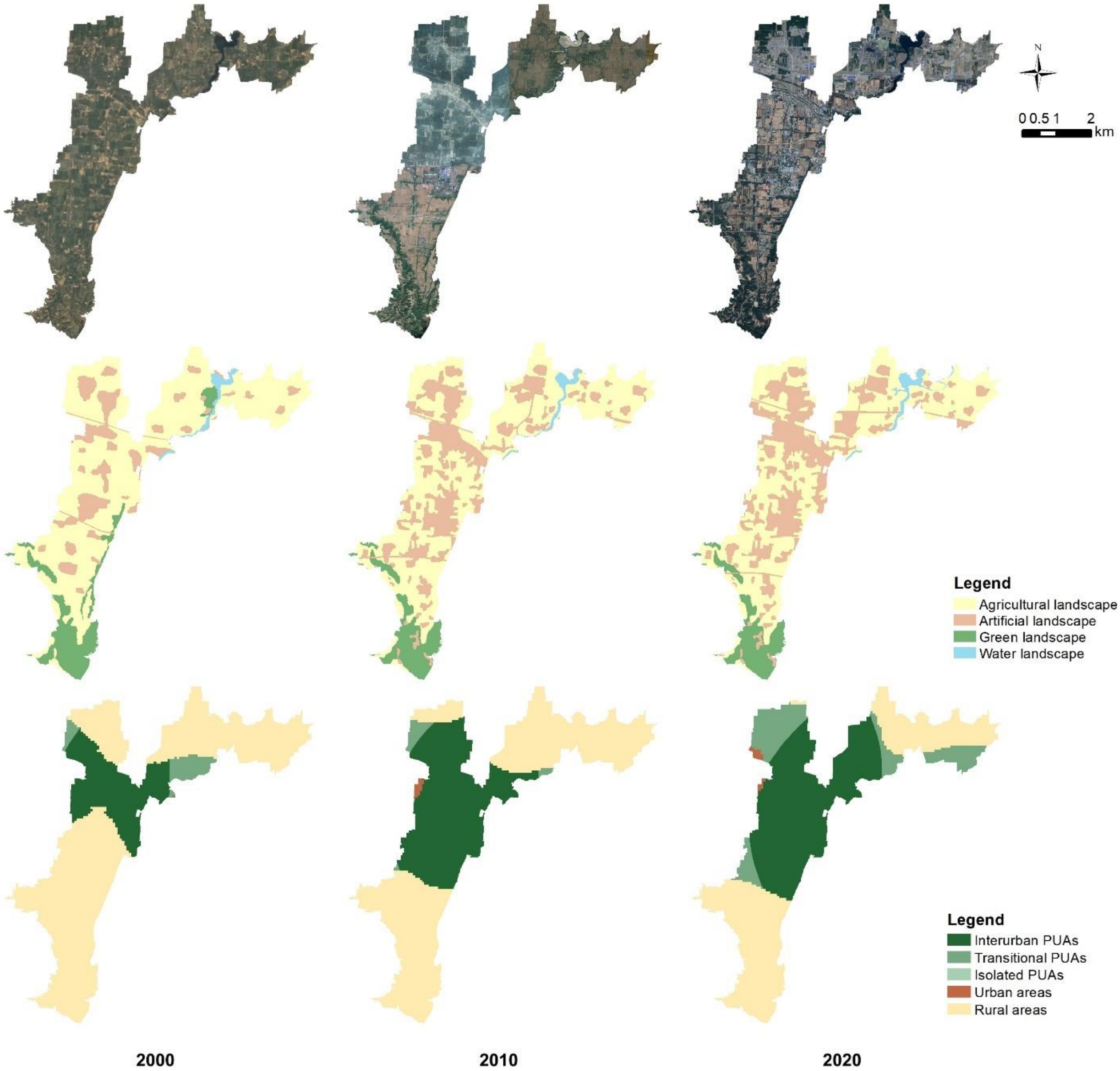
Appendix 11: The zoning map in the Zhengzhou Territorial Spatial Master Plan (2021-2035). Taking Transitional PUAs as an example to illustrate the overlapping areas with the zoning map.



Appendix 12: Remote sensing images, landscapes, and PUAs evolution in Mazhai Town.



Appendix 13: Remote sensing images, landscapes, and PUAs evolution in Baisha Town.



Appendix 14: Remote sensing images, landscapes, and PUAs evolution in Chengguan Town.