A model to calculate the temporal and spatial distribution characteristics of urban land green use efficiency (ULGUE) in the Beijing-Tianjin-Hebei urban agglomeration

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Abstract

Green development has become a key global response to environmental challenges, including in China, where it is prioritized in the national development strategy. However, rapid urbanization and industrialization in China have led to inefficient land use and environmental issues. Achieving a balance between economic growth and ecological protection poses a major challenge. Urban agglomerations are crucial in China's development, but they face obstacles related to land inefficiency and reliance on traditional approaches. Environmental concerns necessitate a shift towards green economic development, including diversifying industries and reducing dependence on coal.This study used the Super-Efficiency SBM model to evaluate the urban land green use efficiency (ULGUE) within Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019. The findings indicated, temporally, the overall efficiency of the urban agglomeration showed a fluctuating upward trend over time, although there was a growing disparity in ULGUE among different cities. And the impact of technical efficiency on the improvement of ULGUE surpassed that of technological progress. Additionally, there was a noticeable differentiation trend in ULGUE among the cities within the urban agglomeration. Spatially, there was a consistent pattern of high efficiency levels in the southeast and low efficiency levels in the northwest. However, spatial correlation in ULGUE was observed only in 2016, with High-High type areas concentrated in Tianjin and Cangzhou. This pattern was highly related to the policies implemented in 2016. To address the challenges, this research suggested implementing differentiated regional land use control policies, optimizing production factors, and leveraging spatial agglomeration effects to improve the ULGUE and achieve the coordinated development in the Beijing-Tianjin-Hebei urban agglomeration.

Keywords: urban land green use efficiency, Super-Efficiency SBM model, Beijing-Tianjin-Hebei urban agglomeration, temporal and spatial distribution characteristics

Contents

List of figures

List of tables

1.Introduction

1.1 Research background

In today's world, environmental issues are increasingly prominent, such as climate change, resource depletion, and biodiversity loss, posing significant threats to our planet and the future of humanity. At this crucial moment in history, green development has become a highly discussed topic and a crucial response to environmental issues. The concept of green development emphasizes the balance between economic growth and environmental protection, aiming to achieve sustainable development goals. The emergence and development of green development are closely intertwined with the global context. Over the years, excessive exploitation of natural resources and environmental pollution have led to a series of serious problems, including climate change, water scarcity, and land degradation. These issues not only directly impact human society but also have destructive effects on ecosystem stability and biodiversity. With the deepening of scientific research and increased environmental awareness, people have gradually recognized the need to change past development models, adopt sustainable approaches to meet human needs, and protect and restore the natural environment. Simultaneously, countries around the world have also realized the severity of environmental issues and have strengthened international cooperation to collectively address global environmental challenges. In China, as one of the world's largest developing countries, green development has become an important component of the national development strategy. The Chinese government attaches great importance to environmental protection and sustainable development, proposing a series of policies and measures for green development. In particular, important documents such as the "The thirteenth Five-Year Plan" and the "Rural Revitalization Strategy" have identified green development as the direction and goal for China's future development.

Land, as the carrier of all human production and livelihood, is an essential natural resource necessary for human survival and development. Urban land not only reflects the progress of social development but also guides the allocation and flow of economic and social elements such as capital and technology. Therefore, to some extent, the rapid development of the urban economy relies on the supply of urban land resources. However, with the acceleration of urbanization and industrialization processes, China's demand for land has been growing linearly, leading to continuous changes in the utilization structure and methods of urban land. Due to the irrational allocation of land resources, there is a severe problem of urban land waste and low use efficiency. Additionally, industrial pollutant emissions far exceed the absorption and purification capacity of land resources. Under the current extensive expansion model and unreasonable utilization methods, the progress of urban green development has been severely constrained. Balancing development with ecological environmental protection and achieving green and efficient land use is a major challenge that affects the overall goal of green development.

The rise of urban agglomerations is an important sign of economic development entering a new stage. In the context of globalization and informatization, urban agglomerations are becoming a regional development model and spatial combination pattern of global significance. In recent years, China has attached increasing importance to the development of urban agglomerations and elevated it to the national strategic level. In 2014, the central government proposed the "establishment of a coordination mechanism for the development of urban agglomerations". In 2016,“The thirteenth Five-Year Plan”[1] deployed 19 urban agglomerations, and “The Fourteenth Five-Year Plan”[2] in 2020 put forward the goal of developing and strengthening urban agglomerations and metropolitan areas. With the advancement of China's urbanization process, urban agglomerations have become the most dynamic and promising core regions in the country's economic development pattern.

The Beijing-Tianjin-Hebei urban agglomeration, as one of the largest urban agglomerations in northern China, has experienced rapid economic growth. However, there is still widespread inefficient use of land and over-exploitation of land resources. These mismatches have lead to waste of land resource and exacerbated the contradictions between resource utilization and environmental ecology. Currently, resource and environmental issues have become significant "weak points" in the development of the Beijing-Tianjin-Hebei urban agglomeration. According to “The 2021 China Ecological and Environmental Status Report”[3], the average proportion of days with air pollution exceeding standards in the Beijing-Tianjin-Hebei and surrounding areas ("2+26 cities") was 32.8% for the whole year. Among them, mild pollution accounted for 24.0%, moderate pollution for 5.7%, severe pollution for 2.0%, and very severe pollution for 1.2%. Environmental issues are driving the Beijing-Tianjin-Hebei urban agglomeration to fundamentally achieve a green transformation in its economic development approach, changing the current situation of a single industrial structure and over-reliance on coal in the energy structure.

1.2 Research aim

The practice of social development has proven that there is a mutually influential relationship between land use and economic development, necessitating corresponding adjustments to land use patterns based on different stages of development. China is currently at a critical period of economic adjustment and social transformation and implementing a green development strategy is crucial for achieving coordinated economic and social development. Therefore, this study aims to address the issue of achieving land green use by guiding land use patterns with the principles of green development, promoting economic transformation and spatial optimization.

[1] https://baike.so.com/doc/10958512-11495833.html
[2] https://baike.so.com/doc/26230783-27457302.html
[3] https://www.gov.cn/xinwen/2022-05/28/5692799/files/349e930e68794f3287888d8dbe9b3ced.pdf

Promoting land green use enables complementary functions and coordinated development among different cities within urban agglomerations, which holds significant scientific and societal significance for fostering harmonious industrial and economic development within these agglomerations. Thus, this research focuses on the Beijing-Tianjin-Hebei urban agglomeration, aiming to achieve efficient and environmentally friendly land use within the agglomeration, thereby achieving a harmonious integration of economic development and environmental protection. Additionally, the findings of this study can also provide valuable insights for promoting healthy and green development in other urban agglomerations.

1.3 Research significance

1.3.1 Scientific relevance

(1) Enrich the theoretical understanding of urban land green use efficiency (ULGUE). This study combines the theory of urban agglomerations and regional coordination and development, incorporating interdisciplinary theories such as regional economics, land management, and econometrics. It broadens the scope of the discipline and enriches the research on urban land utilization.

(2) Improve the evaluation index system for ULGUE in urban agglomerations. Existing research mostly focuses on constructing land use efficiency indicators based on input factors, economic expected output, and environmental unexpected outputs. This study reinterprets the concept of ULGUE in the new era, incorporating social and environmental factors into the expected output assessment. It also introduces unexpected outputs related to industrial sulfur dioxide emissions, industrial wastewater discharge, and industrial dust emissions to more accurately reflect the actual utilization of urban land.

(3) Considering urban agglomerations as spatial carriers, analyze the temporal and spatial distribution characteristics of land green use within urban agglomerations. This analysis contributes to a deeper understanding of the spatial evolution process of urban agglomerations and provides a theoretical basis for future planning of urban agglomerations.

1.3.2 Societal relevance

(1) By studying the temporal and spatial distribution characteristics of land green use in the Beijing-Tianjin-Hebei urban agglomeration, we can understand the dynamic trends and causes of spatial disparities, grasp the spatial differentiation features of ULGUE, and

provide strategies and measures for achieving a balance between economic development and environmental protection of urban land use.

(2) Evaluating the efficiency of land green use in urban agglomerations is beneficial for government departments to standardize and optimize land resource management, maximize economic and ecological benefits, promote the sustainable utilization and green development of land resources in China, and achieve the goal of ecological civilization construction.

(3) Research on ULGUE can drive the optimization of economic development structure and transformation of approaches, and it has important practical value in promoting economic coordinated development. The construction of a logical system for "land allocation and utilization - spatial layout" helps the government strengthen land use control, promote the implementation of the national strategy of coordinated development in the Beijing-Tianjin-Hebei region, scientifically guide population movement and industrial layout, orderly relocate non-capital functions from Beijing, and optimize the spatial structure of urban agglomerations.

1.4 Research questions

Based on the current era of green development, this thesis takes the logical starting point of exploring the land use patterns that can better address the issues of economic development and environmental protection. By reviewing and summarizing existing research and considering the current status of China's economic development, this study focuses on a new land use pattern, namely, land green use, that adapts to the current economic and social development and the characteristics of the region. The research focuses on the Beijing-Tianjin-Hebei urban agglomeration, using the Super-Efficiency SBM model to construct a quantifiable evaluation model, taking into account the economic, social, and environmental aspects from an input-output perspective. The study examines the temporal and spatial distribution characteristics of urban land green use efficiency (ULGUE) from 2009 to 2019 within the urban agglomeration. Additionally, this study explores strategies to optimize regional ULGUE and provides feasible recommendations to enhance the environmentally friendly utilization of land for cities in the urban agglomeration.

Therefore, this thesis project will try to answer the question:

What is the urban land green use efficiency (ULGUE) of the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019 ?

Firstly, in order to understand the annual ULGUE value in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019, as well as the changing trend and characteristics in these 11 years, this study constructs the first research question:

RQ1: What are the temporal distribution characteristics of urban land green use efficiency (ULGUE) in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019?

Answering this question will provide insights into the overall and each city-level variations in ULGUE within the Beijing-Tianjin-Hebei urban agglomeration during the period of 2009-2019. On this basis, this study will explore the factors influencing these trends and give rational explanations.

Secondly, the establishment of the Beijing-Tianjin-Hebei urban agglomeration aims to promote coordinated development among cities within the agglomeration, leveraging the spatial driving role of core cities. To investigate its spatial influences, the second research question is formulated as follows:

RQ2: What are the spatial distribution characteristics of urban land green use efficiency (ULGUE) in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019?

Answering this question will provide insights into the areas within the urban agglomeration exhibiting high and low ULGUE among the 11 years. And it will also explore whether there are spatial distribution patterns of high and low-efficiency areas during this 11-year period. Additionally, by employing the spatial autocorrelation analysis will be conducted to verify whether there are spatial associations and clustering tendencies in ULGUE.

1.5 Research outline

The present report is structured as shown in Figure 1. Chapter 1 serves as an introductory section, providing an overview of the research background, research aim, research significance, research questions as well as the research outline.

Chapter 2 is the theoretical framework which aims to present the progress made in ULGUE. The former part of the chapter is to summarize the existing research on green development and urban land use efficiency at both the international and national levels. The latter part of the chapter will focus on introducing relevant theories which include the regional coordinated and development theory, green development theory, and the law of diminishing returns of land to provide theoretical backing.

Chapter 3 provides an overview of the methodology utilized in this research. It introduces the Super-Efficiency Slack-Based Measure (SSBM) model and the Malmquist index as the key analytical tools employed to study the temporal distribution characteristics. The chapter also examines the spatial distribution characteristics using Moran's index. Furthermore, it constructs an evaluation model for ULGUE, taking into account the economic, social, and environmental aspects from an input-output perspective.

Chapter 4 involves empirical analysis. Using the Super-Efficiency SBM model to evaluate the ULGUE and the Malmquist index to analyze the dynamic difference characteristics to study the temporal distribution characteristics of the urban agglomeration. Furthermore, this thesis uses the ArcGIS software and the Moran's index to study the spatial distribution characteristics of the urban agglomeration among 2009 to 2019.

Chapter 5 provides an analysis of the temporal and spatial distribution characteristics of urban land green use efficiency (ULGUE) in the Beijing-Tianjin-Hebei urban agglomeration. This section also highlights the innovative aspects of the research and discusses its limitations.

Chapter 6 presents the conclusions and suggestions. It summarizes and synthesizes the distribution and evolutionary characteristics of urban land green use within the urban agglomeration. Based on these findings, the latter of this chapter explores strategies to optimize regional ULGUE and provides feasible recommendations to enhance the environmentally friendly utilization of land in these cities.

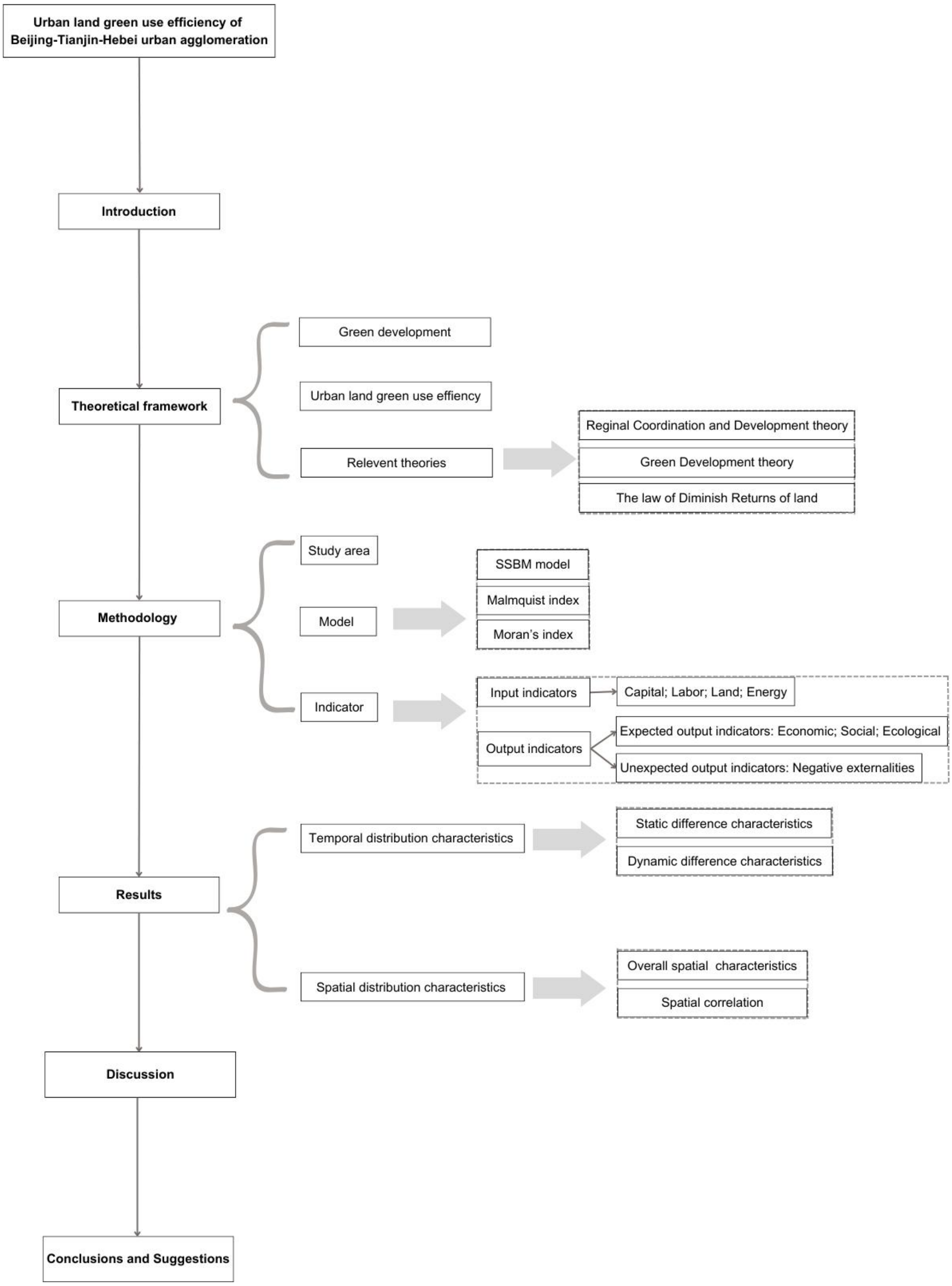

Figure 1. Research outline

2. Theoretical framework

This chapter aims to present the progress made in ULGUE. The former part of the chapter is to summarize the existing research on green development and urban land use efficiency at both the international and national levels. The latter part of the chapter will focus on introducing relevant theories which include the regional coordinated and development theory, green development theory, and the law of diminishing returns of land to provide theoretical backing.

2.1 Green development

The academic research on green development can be traced back to the publications such as "The Silent Spring" (1962), "The Limits to Growth" (1972), and "The Closing Circle"(1971), which sounded the alarm on the ecological crisis. In subsequent years, American scholars such as Boulding, Daly, and Pearce further developed the concept by exploring steady-state economics, green economics, and ecological economics. In 1989, British environmental economist David Pearce first proposed the concept of "green economy" in his book "Blueprint for a Green Economy", arguing that economic development should be constrained within the limit that the natural environment can withstand. In 2002, the United Nations Development Programme put forward the term "green development" for the first time in its "China Human Development Report 2002: Making Green Development a Choice"(Monks F, 2003). Since then, domestic and foreign scholars have extensively discussed the related connotations of green development.

2.1.1 International level

The main focus of foreign scholars' research on green development has been on energy efficiency and environmental pollution. They have explored the impact of factors such as resource utilization, environmental policies, and technological innovation on green development and conducted green growth assessments. Jaffe et al. (2015) believed that the monopolistic supply of non-renewable resources and the imperfect upstream industrial chain would lead to serious market failures, making it difficult to maximize social welfare. In the field of green economic growth, because non-renewable resources such as oil were necessary in the production process and were difficult to replace, as the reserves gradually ran out, manufacturers were forced to reduce investment, resulting in a decrease in effective output and capital return, thus dragging down the economic growth rate. At this point, only technological innovation could offset the negative effects of declining capital returns and reduced resource availability (Jackson and Victor, 2011).

To achieve sustainable green economic growth, countries often implemented environmental policies to reduce the dependence of economic development on non-renewable resources. Rick van der Ploeg et al. (2013) believed that research and development subsidies could be combined with pollution control and economic development, by continuously increasing reliable carbon taxes, suppressing cumulative carbon emissions, and accelerating the transition to a carbon-free era, thus achieving green growth. In the specific implementation process, Hendlandl and Loschel (2015) believed that environmental taxes could be levied first in sectors with low resource consumption and minimal economic impact, and then gradually expanded to resource production sectors such as coal and thermal power. Shironitta (2016) based on data from 40 countries from 1995 to 2009 found that changes in domestic industrial structure and import structure played different roles according to group types. Therefore, when formulating policies, it was necessary to consider the structural changes of different countries.

While, Resnick (2012) and others believed that the introduction of environmental policies did not necessarily promote economic growth, and currently effective environmental policies were only limited to the household or certain project levels. It was unknown whether it could promote total economic growth as a national strategy. In addition, when environmental policies required a reduction in the extraction of certain fossil fuels, it not only reduced the marginal output of capital, but also reduced innovation activities in that area. The reduction in capital returns further reduced the intensity of corporate technological investment. Aghion and Howitt (1998) referred to the negative impact of this environmental policy on technological innovation as the "crowding-out effect of technology".

2.1.2 National level

In China, the concept of "green development " originated from “The Tenth Five-Year Plan”[4], which laid the foundation for the formation of a set of "green development" ideas. Subsequently, “The Twelfth Five-Year Plan (2011-2015)”[5] elevated "green" to the concept of "green development," that is, "establishing a green, low-carbon development concept," and added content related to "green living and consumption patterns," among others. “The Thirteenth Five-Year Plan (2016-2020)” proposed firmly establishing and implementing the development concept of innovation, coordination, green, openness, and sharing, and emphasized integrating green development into the entire process of economic construction. In 2017, the 19th National Congress of the Communist Party of China proposed that China should promote green development and build a modernization characterized by harmonious coexistence between humans and nature. It aims to form a green development mode and lifestyle and firmly take the path of civilized development that promotes production development, affluent living, and good ecology. “The Fourteenth Five-Year Plan (2021-2025)” proposed accelerating the promotion of green, low-carbon development, promoting the comprehensive green transformation of economic and social development, and firmly taking the road of green development.

Currently, China's achievements in green development are increasingly abundant, and the concept of green development has been integrated into various fields of the economy and society. Scholars have conducted many beneficial studies in their respective fields based on different research perspectives, such as green finance, green industry, green cities,

[4] https://www.gov.cn/gongbao/content/2001/content_60699.htm
[5] https://baike.so.com/doc/6705485-6919469.html

and green technological innovation. On the basis of theoretical exploration and development path discussion, research on the measurement of green development level has also become increasingly in-depth, using research methods ranging from hierarchical analysis and cluster analysis to efficiency measurement based on econometric models. With the increasingly prominent contradiction between environmental protection and economic development, green economic efficiency has received significant attention as an effective indicator for balancing economic growth with resource and environmental development (Wang et al.,2019 ; Liu, 2022). Nowadays, domestic scholars are mainly researching green economic efficiency in the following three aspects.

The first aspect is related to the measurement of green economic efficiency. The primary method now for measuring green economy efficiency is the SBM (Slack-Based Measure) efficiency evaluation model, which addresses the limitations of the traditional DEA model by considering the non-zero slackness of inputs or outputs (Tone, 2001). However, the SBM model does not consider the comparison between effective decision units with an efficiency of 1 (Ban and Yuan, 2016; Liu, 2022). To address this issue, Wang et al. (2019) and Liu (2022) have developed the Super-Efficiency SBM model to measure green economic efficiency, which incorporates energy consumption as an input factor in the production function along with capital and labor, while environmental pollution factors are included as unexpected output.

The second aspect is the regional distribution characteristics. Qian and Liu (2013) used the SBM model to measure the green economic efficiency of Chinese provinces during the period from 1996 to 2010 and discovered that the level of green economic efficiency showed a regional difference, declining from the eastern to the central and then to the western regions. Nie and Wen (2015) measured the green economic efficiency of 286 cities in China at or above the prefecture level from 2005 to 2011 and found that coastal cities had a comprehensive advantage in green economic efficiency, while the central cities had the lowest efficiency. Ban and Yuan (2016) employed the Super-Efficiency SBM model to assess the green economic efficiency of eight major regions in China between1991 and 2013. They found that there was a considerable spatial positive correlation in green efficiency and showing a local clustering feature. Liu and Shang (2020) measured the green economic efficiency of four major urban agglomerations along the eastern coast of China from 2007 to 2016 and discovered that the Pearl River Delta urban agglomeration had the highest green economic efficiency, followed by the Yangtze River Delta, Beijing-Tianjin-Hebei and Shandong Peninsula urban agglomerations.

The last aspect is the influencing factors. Wu and Huang (2018) used the Tobit model to investigate the factors that influenced industrial green economic efficiency in the Yangtze River Economic Belt from 2011 to 2015. They revealed that industrial structure, energy structure, human capital and the level of openness to the outside world had a significant positive promotion effect on the efficiency of industrial green development in the Yangtze River Economic Belt. Yue and Xue (2020) analyzed panel data from 2005 to 2017 to identify the factors affecting the green economic efficiency in the Yellow River Basin based on panel data from 2005 to 2017. They found that economic development and industrial structure significantly promoted the green development efficiency in the Yellow River Basin, while technology and foreign investment had a significant negative effect on it. Moreover, the relationship between urbanization and green development efficiency in the Yellow River Basin followed a "U" -shaped curve, and environmental regulation did not have a significant effect. Liu (2022) found that the level of economic development, industrial structure and technology development significantly influenced the green development efficiency in the Beijing-Tianjin-Hebei region. However, environmental regulations had an insignificant positive effect on improving green development efficiency, while urbanization and energy consumption significantly had a significant negative impact on improving it.

In summary, despite the fact that green development has been extensively studied by governments and scholars both nationally and internationally, there is still no unified concept and definition due to different research perspectives and focuses. However, existing studies revolve mainly around two key aspects. One is green development as a development strategy for addressing ecological problems and environmental protection, emphasizing the importance of resource conservation and ecological protection in economic development. The other is that green growth as a new driving force for economic growth and a new opportunity for economic transformation. There is a consensus that green development is the main approach to resolving the contradictions between resource and environmental constraints and economic development. It is believed that resource and environmental factors are not only constraints on economic development, but also inherent elements of economic development, and attempts have been made to incorporate them into green efficiency evaluation models.

2.2 Urban land green use efficiency (ULGUE)

Land, as the spatial carrier of production, living and ecology, is an essential production factor for socio-economic development. The introduction of urban land green use as a new land use mode was proposed to improve the land use efficiency. It is based on the concept of green development and expands the sustainable land use model both in time and space. Nowadays, many scholars have adopted urban land use efficiency as a measure of urban land use. ULGUE can be viewed as an extension of urban land use efficiency. At present, the research on the ULGUE at international and national level could be summarized as follows:

2.2.1 International level

The research on urban land use efficiency started earlier abroad, initially originating from the study of the spatial use of urban land by the ecological school that emerged in 1920. It mainly focused on developed countries with land private ownership as the basis in the late stage of industrialization development, such as the United Kingdom, the United States, and Japan. Since the 1950s, Western countries have conducted a large number of studies on land use evaluation. In the 1970s, land use evaluation research developed towards precision and integration with the emergence of remote sensing and other technologies. After 1985, dynamic land evaluation developed in the direction of multidimensional and composite information. After 1990, with the development of landscape ecology research, many new directions in urban land use research have emerged. Since the new century, the research methods on urban land use have become more diverse, and scholars with different disciplinary backgrounds, such as urban economics and geography, have conducted relevant research on urban land use issues. Currently, foreign research on land use efficiency mainly focuses on intensive use of land resources, optimal allocation of urban land resources, and exploring the factors that affect urban land use efficiency (Vergurg et al.,2010; Halleux et al., 2012).

2.2.2 National level

Scholars at home are mainly researching ULGUE in the following three aspects. The first aspect is related to the measurement of the ULGUE. In China, scholars initially used a single index evaluation method to represent land use efficiency, which is the ratio of a single input to a single output. For example, Li et al. (2014) used the ratio of the output of the second and third industries to the urban built-up area. However, this method cannot fully reflect the efficiency relationship between multiple inputs and multiple outputs in the process of urban land use. Therefore, the evaluation of urban land use efficiency has shifted from single-index evaluation to multi-index evaluation, which objectively weights the indicators related to land use efficiency and calculates comprehensive weights to represent it. For example, Guan and Chen (2013) constructed an indicator system for evaluating urban land use efficiency from three aspects: total land consumption, utilization intensity, and land use structure. However, the multi-index comprehensive evaluation method has problems such as unclear connotation definition, subjective weighting of evaluation indicators, and difficult determination of ideal values, which affect the objectivity of evaluation results. Therefore, the data envelopment analysis (DEA) method emerged, which is not influenced by subjective factors and can more objectively evaluate the decision units with multiple inputs and outputs while also calculating redundant inputs and outputs. Subsequently, Li and Hu (2020); Xiong et al. (2017) constructed an indicator evaluation system for land use efficiency based on the "input-output" perspective using the traditional DEA method which just included input and expected output indicators.

While, expected outputs are not the only outputs in land use, and the unexpected outputs also need to be considered in efficiency measurement to more accurately measure the true situation of land use efficiency (Zhang , 2022). Hu (2018) considered unexpected outputs such as wastewater, waste gas, and carbon emissions from construction land to calculate the value of ULGUE and constructed an SBM-Undesirable model based on the output perspective, which can calculate slack variables and make up for the traditional

DEA model's inability to calculate unexpected outputs. Furthermore, scholars also selected different dimensions in the indicator system. Wang and Pang (2019) selected land, capital, labor, and energy as input factors, GDP as the expected output indicator, and industrial "three waste emissions" as unexpected output indicators, to construct an evaluation indicator system for ULGUE, but it did not consider social and ecological environmental benefits in the expected output indicators. Xu (2021) included more input and output factors in the index system. Among them, the expected output factors include economic benefits, social benefits, and ecological benefits, while the unexpected outputs include industrial wastewater, industrial SO2, and industrial smoke and dust.

The second aspect is on the temporal and spatial differences and evolutionary characteristics of ULGUE. Lu et al. (2022) calculated the land green use efficiency of 285 Chinese cities at or above the prefecture level from 2009 to 2018 using the unexpected SSBM model and found that the overall trend of urban land green use efficiency was fluctuating and rising, with significant agglomeration characteristics. In terms of regional distribution, the pattern showed that the land green use efficiency in western China was higher than that in eastern China, and that in eastern China was higher than that in central China. He (2022) measured the land green use efficiency of 53 cities in the Yellow River Basin from 2003 to 2018 using the unexpected output SSBM model, and found that the land green use efficiency in the Yellow River Basin showed a continuous upward trend, but the gap in land green use efficiency between upstream cities continued to widen, while the gap in land green use efficiency between middle reaches cities gradually narrowed, and the gap in land green use efficiency between downstream cities first narrowed and then widened. Zhang (2022) studied the land green use efficiency of the Chengdu-Chongqing Economic Circle in 2003-2019, and found that the overall trend of regional land green use efficiency had a weak upward trend, but there was a problem of "the two cities dominate", which means that apart from the core cities (Chongqing and Chengdu), the central cities (Mianyang, Deyang, Yibin, Luzhou, Nanchong, Dazhou, and Leshan) and regional cluster cities (Suining, Neijiang, Ziyang, Meishan, Ya'an, Zigong, and Guangan) were in a low or inefficient state in most years.

The third aspect is about the factors influencing the ULGUE. Currently, research on the factors influencing urban land use efficiency mainly focuses on economic, social, environmental and policy aspects. Hu et al. (2018) have pointed out that the factors influencing urban land use efficiency under the concept of green development are different from traditional ones based on their econometric analysis results. At the same time, due to the differences in regional and urban resource attributes, the results produced by each influencing factor may vary (Irwin, 2010). Ding et al. (2021) took the Yellow River Basin in China from 2009 to 2018 as an example and found that growth-oriented cities are more significantly affected by industrial structure and economic factors, mature cities are mainly affected by scientific and technological factors, while the negative impact of industrial structure and policy on declining cities is more significant. Zhang (2022) found that technology support and government control have a significant positive impact on the land green use efficiency in the Chengdu-Chongqing economic circle. Environmental regulations have different impacts through industrial structure and economic development, and urbanization level and external openness have a negative impact on land green use efficiency, but the situation varies in different regions. Lu et al. (2022) found that the land green use efficiency is the result of the interaction of many factors, and each driving factor has obvious spatial heterogeneity characteristics. Meanwhile, it is pointed out that the level of economic development, advanced industrial structure, ecological resource endowment, and environmental regulation mainly have a positive impact on the land green use efficiency ; land finance and land marketization mainly have a negative impact.

In summary, based on the existing research, this thesis defines ULGUE as "under certain production technology conditions, inputting land, capital, labor, and energy factors into the system, while comprehensively considering the expected output of the three systems of economic, social, and ecological environment benefits, it strives to minimize environmental pollution and ecological damage."

2.3 Relevant theories

Based on the key words of the thesis, this study will utilize three theories to provide guidance for the research. Firstly, the regional coordinated and development theory will be employed to provide support for the Beijing-Tianjin-Hebei urban agglomeration. Secondly, the green development theory will be applied to redefine the efficiency of green land use in cities, aiming for coordinated development and the promotion of environmentally-friendly urban development. Lastly, by integrating the law of diminishing returns of land with efficiency analysis, this thesis aims to explore the input-output aspects and find an optimal solution.

2.3.1 Regional Coordination and Development Theory

Coordination development refers to the collaboration of two or more individuals or elements within the same system to achieve a common goal and ultimately achieve common development by exerting their respective advantages. The theory of coordination was first proposed by German scientist Herman Haken in 1971. He believed that the essence of coordinated development is a coordinated effect, which allows the interaction between different systems to form a new system. Nowadays, coordinated development theory is one of the important theories in the field of social sciences, especially in the research of regional sustainable development. In the context of the great changes in the world political and economic situation, China has proposed to accelerate the construction of a new development pattern with the domestic cycle as the main body and the dual-cycle of domestic and international circulation promoting each other. Regional coordinated development is a major strategy to achieve the domestic cycle. As the highest spatial organizational form of urban development in the mature stage, urban agglomerations are one of the significant measures for China to achieve regional coordinated development. Therefore, it is of great significance to plan and coordinate the improvement of the ULGUE from the perspective of regional overall planning. Hence, the theory of regional coordination and development can provide theoretical support for the research on the coordinated development of ULGUE in this article.

2.3.2 Green Development Theory

In 1987, the United Nations officially proposed the concept of sustainable development, defining it as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The green development theory is a further development of the sustainable development theory. It emphasizes innovation, ecology, humanism, and sharing. Specifically, innovation means pursuing coordinated development of economic, social, and ecological values, rather than focusing on one aspect; ecology means adopting intensive and efficient use methods to minimize pollution to the environment in the process of development; humanism means that green development should focus on people, achieving harmonious coexistence between humans and nature, and satisfying people's basic needs in the process of development; sharing means that the achievements of green development should be shared by all of humanity. The green development theory takes sustainable development as a guiding principle for economic development, providing theoretical guidance for the coordinated and unified goal of social and economic development and ecological system stability in urban land development and use.

2.3.3 The Law of Diminishing Returns of Land

In the mid-17th century, British economist William Petty discovered the phenomenon of diminishing returns of land. Later, economists from various countries continuously supplemented, developed, and improved upon the concept. In the early 19th century, West formally proposed the concept of the "Law of Diminishing Returns of Land" (West, 1992), which has been integrated into the relationship between land input and output. It refers to the phenomenon that, with a continuous increase in the input of a certain factor per unit of land, and with constant technology and other factors, the marginal returns will eventually decrease. In other words, the total returns brought by input factors will increase as the input increases, but when a certain limit is reached, the returns will begin to decrease. The Law of Diminishing Returns of Land is an objective economic law and the theory for seeking the optimal input amount and factor combination in the process of land use. It is a rule that should be followed for intensive land management and provides a theoretical basis and approach for the research of intensive land use. Therefore, to improve the efficiency of urban land use, it is necessary to scientifically and reasonably study the optimal input of urban land (Bi, 2016).

2.4 Summary

The above contents has provided a comprehensive review of national and international research on green development and ULGUE, which has enriched the research perspectives and laid a solid foundation for this thesis. However, it has been found that there are still some gaps in the research on ULGUE, despite the extensive theoretical and empirical studies conducted by scholars in China and abroad. Firstly, regarding the research content, there have been studies on the connotation and measurement of ULGUE, but the connotation is not yet clear enough, and the evaluation indicator system is not standardized due to different research perspectives. Secondly, in terms of research methods, the existing studies on measuring ULGUE has not constituted a unified method due to varying research perspectives, subjects, and objectives. Lastly, as for the scale of the research, most studies have focused on national-level cities, provincial-level regions with developed economies, and river basins, and pays less attention to urban agglomerations. Therefore, these gaps should be the focus of future research on ULGUE.

This thesis, based on the deficiencies of the existing research, selects the Beijing-Tianjin-Hebei urban agglomeration as the research area. And using the Super-Efficiency SBM model to reveal the temporal and spatial distribution patterns of land green use efficiency (ULGUE) within the urban agglomeration from 2009 to 2019. Furthermore, it will explore the optimization path for regional urban land green use efficiency and provides feasible suggestions to improve the cities' land green use efficiency in the urban agglomeration.

3. Methodology

Chapter 3 provides an overview of the methodology utilized in this research, focusing on the Beijing-Tianjin-Hebei urban agglomeration. It introduces the Super-Efficiency Slack-Based Measure (SSBM) model and the Malmquist index as the key analytical tools employed to study the temporal distribution characteristics. The chapter also examines the spatial distribution characteristics using Moran's index in two forms: the Global Moran's index and the Local Moran's index. Furthermore, it incorporates the theoretical analysis and presents the input and output indicators for measuring ULGUE, considering the economic, social, and environmental dimensions (Figure 2).

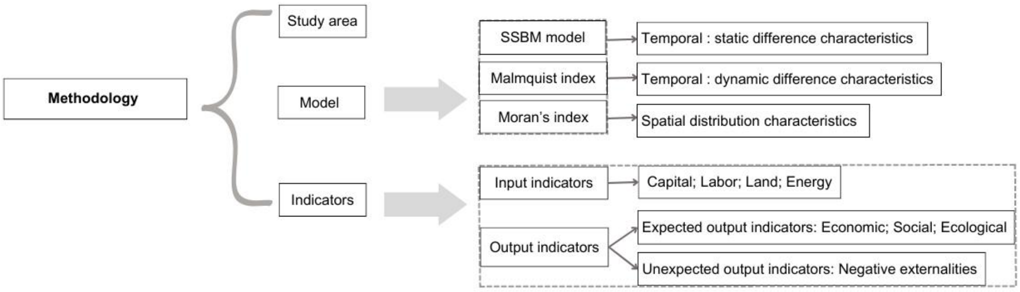

Figure 2. The framework of the Methodology

3.1 Study area

The Beijing-Tianjin-Hebei urban agglomeration is located in the core area of Northeast Asia and the Asia-Pacific Economic Circle on the west coast of the Pacific Ocean. It encompasses the two municipalities of Beijing and Tianjin, as well as 11 prefecture-level cities in Hebei Province, which includes Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, and Hengshui (Figure 3). This region covers an area of 216,000 square kilometers and has a population of over 100 million (State Statistics Bureau,2019)[6]. It holds significant political and locational advantages and is a focal point for economic restructuring in northern China.

Beijing, as the capital of China, serves as a political, cultural, and economic center. It is a modern international metropolis that acts as a significant hub for scientific research, education, and innovation on a national scale. Tianjin, situated in the eastern coastal area of Beijing, is a direct-controlled municipality and an important economic center in northern China, with well-developed industries and services. Hebei Province, part of the Beijing-Tianjin-Hebei urban agglomeration, is one of the most populous provinces in China. It is rich in resources, including vast farmland and abundant mineral resources. Cities within Hebei Province, such as Shijiazhuang, Tangshan, and Handan, play crucial roles in the region's economy and industry.

[6] https://www.gov.cn/xinwen/2023-02/26/content_5743341.htm

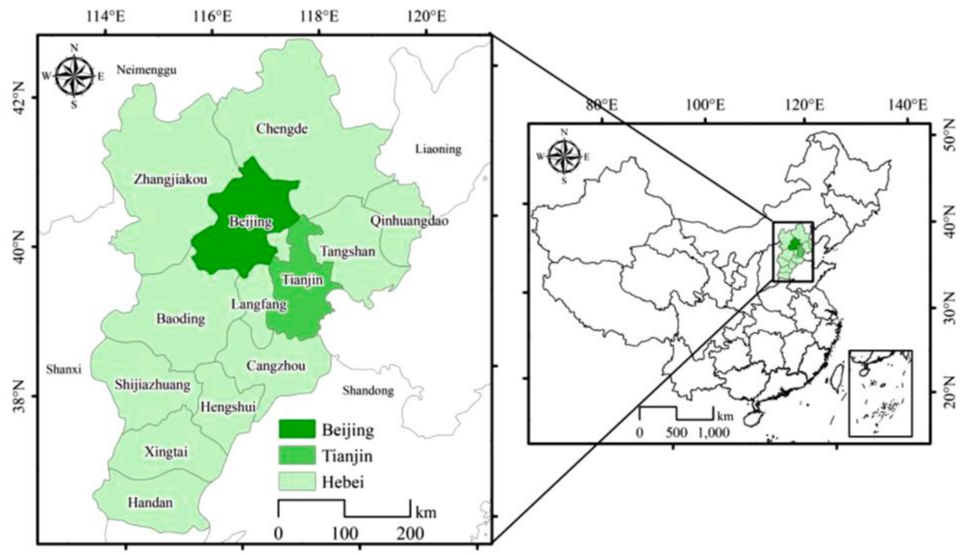

Figure 3. Location and administrative divisions of the Beijing-Tianjin-Hebei urban agglomeration (source: doi:10.1016/j.scs.2022.103985)

The coordinated development of the Beijing-Tianjin-Hebei region was established in 2008 by the State Council. In 2014, General Secretary Xi Jinping proposed the coordinated development of this region, which was subsequently elevated to the national strategic level. The successful implementation of this strategy relies on effective land use management. "The Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan (2016-2020) "[7] was reviewed and approved by the Communist Party of China's Central Political Bureau in 2015, clarifying the functional positioning of the region. The "General Plan for Land Use in the Beijing-Tianjin-Hebei Urban Agglomeration (2015-2020)"[8] and the "Coordinated Ecological and Environmental Improvement in the Beijing-Tianjin-Hebei Region"[9] emphasize the importance of managing and protecting land resources while promoting intensive land use.

The formation and development of the Beijing-Tianjin-Hebei urban agglomeration have been facilitated by its strategic geographical location and strong interconnectivity. Efficient transportation networks have fostered a closely connected economic sphere. With rapid economic growth in China, the Beijing-Tianjin-Hebei urban agglomeration plays a significant role in national and international economic and social development. However, along with rapid urbanization and industrialization, the Beijing-Tianjin-Hebei urban agglomeration also faces widespread inefficient use of land and over-exploitation of land resources. These mismatches have led to waste of land resources and exacerbated the contradictions between resource utilization and environmental ecology. Currently, resource and environmental issues have become significant "weak points" in the development of the Beijing-Tianjin-Hebei urban agglomeration. Therefore, it is of great

[7] https://baike.so.com/doc/8395069-8714131.html
[8] http://app.www.gov.cn/govdata/gov/201605/03/379783/article.html
[9] http://www.caep.org.cn/zclm/jjjqyhjlhyjzx/

significance to study and improve the ULGUE in the Beijing-Tianjin-Hebei urban agglomeration to achieve sustainable development and optimizing resource allocation.

3.2 Super-Efficiency SBM model (SSMB)

Currently, the Data Envelopment Analysis (DEA) method is widely used in land use efficiency evaluation. However, the traditional DEA model ignores the slack problem of input and output variables, which can easily lead to biased results. The subsequently proposed SBM model for unexpected output uses a non-radial metric method to address the shortcomings of the traditional DEA model, but the SBM model cannot solve the problem when multiple decision units are all efficient in the standard efficiency model. Tone (2002) proposed a non-radial and non-parametric SBM model based on slack variables, which combines the Super-Efficiency model with the SBM model. This model can effectively overcome the shortcomings of the traditional SBM model by decomposing the effective decision units with an efficiency value of 1 while handling unexpected output.

$$\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x}}{x_{ik}}}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\frac{\overline{y^d}}{y_{sk}^d}+\sum_{q=1}^{r_2}\frac{\overline{y^u}}{y_{qk}^u}\right)}$$

$$s.t.\begin{cases} \overline{x} \geq \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j \\ \overline{y^d} \leq \sum_{j=1, j\neq k}^{n} y_{sj}^d\lambda_j \\ \overline{y^u} \geq \sum_{j=1, j\neq k}^{n} y_{qj}^u\lambda_j \\ \overline{x} \geq x_{ik};\ \overline{y^d} \leq y_{sk}^d;\ \overline{y^u} \geq y_{qk}^u;\ \lambda_j \geq 0, \\ i = 1,2,\cdots,m;\ j = 1,2,\cdots,n\ (j \neq k) \\ s = 1,2,\cdots,r_1;\ q = 1,2,\cdots,r_2 \end{cases} \quad (1)$$

In Eq.（1）, assume there are n decision-making units, and each unit consists of inputs (m), expected outputs (r_1), and unexpected outputs (r_2). x, y^d, and y^u represent the elements of the corresponding input matrix, expected output matrix, and unexpected output matrix, respectively, while ρ represents the value of ULGUE. When $\rho \geq 1$, it indicates that the decision-making unit is effective; when $0 \leq \rho < 1$, it indicates that the decision-making unit is in an inefficient or ineffective state, and there is room for efficiency improvement.

3.3 Malmquist index

The calculation result of the Super-Efficiency SBM model is a relative efficiency value, which represents the static efficiency of each city during the same period. Therefore, there are limitations in conducting dynamic comparisons. This thesis introduces the Malmquist index, which has the advantage of flexibility in using dimensional input-output data and can effectively analyze and decompose the characteristics of dynamic efficiency changes (Jin & Wang, 2016). The ratio of the current year efficiency to the previous year efficiency, that is, the change of the whole factor energy efficiency, is measured from the point of view of dynamic change (Zhang et al.,2021). Based on the Super-Efficiency SBM model, the Malmquist index formula constructed in this thesis is expressed as Eq. (2) :

$$M(x^t, y^t, x^{t+1}, y^{t+1}) = \left[\frac{d^t(x^{t+1}, y^{t+1})}{d^t(x^t, y^t)} * \frac{d^{t+1}(x^{t+1}, y^{t+1})}{d^{t+1}(x^t, y^t)} \right]^{\frac{1}{2}} \qquad (2)$$

Based on Färe's (1994) FGLR approach, the Malmquist index is decomposed. In this model, the Total Factor Productivity Change Index (TFPCH) is further decomposed into two components: the Technical Efficiency Index (EFFCH) and the Technological Progress Index (TECH). The Technical Efficiency Index (EFFCH) can be further decomposed into Pure Technical Efficiency (PECH) and Scale Efficiency (SECH).

$$TFPCH = EFFCH \times TECH = (PECH \times SECH) \times TECH$$

$$TFPCH = M(x^t, y^t, x^{t+1}, y^{t+1}) =$$

$$\frac{d^{t+1}(x^{t+1}, y^{t+1})}{d^t(x^t, y^t)} \left[\frac{d^t(x^t, y^t)}{d^{t+1}(x^t, y^t)} \times \frac{d^t(x^{t+1}, y^{t+1})}{d^{t+1}(x^{t+1}, y^{t+1})} \right]^{\frac{1}{2}}$$

$$EFFCH = \frac{d^{t+1}(x^{t+1}, y^{t+1})}{d^t(x^t, y^t)}$$

$$TECH = \left[\frac{d^t(x^t, y^t)}{d^{t+1}(x^t, y^t)} \times \frac{d^t(x^{t+1}, y^{t+1})}{d^{t+1}(x^{t+1}, y^{t+1})} \right]^{\frac{1}{2}} \qquad (3)$$

In Eq. (3) , (x^{t+1}, y^{t+1}) 、 (x^t, y^t) represent the input and output vectors of period t and $t+1$; $d^t(x^t, y^t)$ 、 $d^t(x^{t+1}, y^{t+1})$ 、 $d^{t+1}(x^t, y^t)$ 、 $d^{t+1}(x^{t+1}, y^{t+1})$ respectively represents the output distance function of the input-output vectors of period t and $t+1$, with the technological level of period t and $t+1$ as references.

If $TFPCH$ > 1, it indicates an improvement in total factor productivity compared to the previous period. If $EFFCH$ > 1, it suggests an improvement in technical efficiency, reducing the gap between the decision-making unit and the efficiency frontier. If $TECH$ > 1, it signifies progress in technology and innovation, expanding the production frontier. If $PECH$ > 1, it indicates an improvement in technology and management optimization leading to efficiency gains. If $SECH$ > 1, it represents an improvement in scale efficiency. The opposite holds true if these values are less than 1.

3.4 Moran’s index

3.4.1 Global Moran’s index

In order to further verify the spatial correlation of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration, this study used the global Moran's index to measure the overall spatial features. Its mathematical expression is as follows:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}$$

（4）

In Eq.(4), n is the number of samples, x_i and x_j are the geographic attribute observations for region i and region j. $\bar{x}$ represents the mean observation value, s^2 is the sample variance, w_{ij} is the spatial weight matrix, and I is the global spatial autocorrelation coefficient. If $I > 0$, it indicates a positive spatial distribution; if $I < 0$, it indicates a negative spatial distribution; and if $I = 0$, it indicates a random spatial distribution of attribute data.

3.4.2 Local Moran's index

Local Moran's index is used to identify and analyze local patterns of spatial autocorrelation within the dataset. It calculates the spatial association between each feature and its neighboring features to identify areas of clustering and outliers. Its mathematical expression is as follows:

$$I = \frac{(x_i - \bar{x})\sum_{j=1}^{n}(x_j - \bar{x})}{s^2}$$

（5）

The variables have the same meaning as in Eq. (5). If $I > 0$, it indicates that local units with similar attributes are clustered in space; if $I < 0$, it indicates that local units with dissimilar attributes are clustered in space; if $I = 0$, it indicates that local units are randomly distributed in space. Specifically, there are four types of spatial agglomeration: High-High (H-H), Low-High (L-H), Low-Low (L-L), and High-Low (H-L).

3.5 Input and output Indicators

3.5.1 Input Indicators

ULGUE in cities is conducted within a comprehensive factor framework, where traditional input factors (capital, labor, and land) still play a fundamental role. Furthermore, considering the increasing impact of energy consumption on the economy, society, and the environment (Wang & Pang, 2019), this thesis also included energy-related indicators. Due to data availability, this thesis ultimately selected the city's fixed asset investment, the number of employed individuals in the secondary and tertiary industries, the construction land area, and total energy consumption as input indicators (Table 1).

① Capital: Liang et al.(2022) emphasized that the size, speed, and structure of capital input during land use significantly affect a city's socio-economic benefits.Therefore, the city's fixed asset investment is chosen as the capital input factor in this study.
② Labor: Wang et al.(2019) indicated the labor input in urban land use predominantly stems from employees in the secondary and tertiary industries, who effectively convert input into economic output.Hence, the number of employed individuals in the secondary and tertiary industries as the labor input factor in this study.
③ Land: As a spatial carrier for a city's socio-economic development, land is one of the essential indicators for measuring land use efficiency (Wang & Pang , 2019). Consequently, this thesis chose the construction land area as the land input factor.
④ Energy: Considering the focus on green development in urban land use efficiency research, it is necessary to consider energy consumption. Drawing on existing research, this thesis converted regional total energy consumption into coal consumption to represent energy input (Liu, 2022).

3.5.2 Output Indicators

During the utilization of urban land, not only does it generate economic, social, and ecological benefits, but it also produces negative impacts such as environmental pollution. Therefore, this thesis constructed an output indicator framework from expected and unexpected output perspectives (Table 1).

(1) Expected Output Indicators

Based on the economic, social, and ecological aspects, this thesis selected the GDP, general budgetary revenue, and green coverage ratio as expected output indicators.

① Economic benefits: This refers to the economic value-added generated during urban land green use (Wang & Pang, 2019). Hence, this thesis chose the most direct and quantifiable indicator, GDP, to represent economic benefits.

② Social benefits: Green development aims to fulfill people's aspirations of a better life. General budgetary revenue is used to realize social public interests and promote social harmony and stability. Drawing on the research by Xu et al.(2021), this thesis chose general budgetary revenue as the social expected output indicator.

③ Ecological benefits: This refers to the positive effects on the urban ecological and living environment generated during urban land green use. Referring to the research by Lu et al. (2020), this thesis adopted urban green coverage rate as the ecological expected output indicator for ULGUE.

(2) Unexpected Output Indicators

Considering that industry activities are a main source of urban pollution, and based on existing studies (Liang et al.,2019; Wang & Pang, 2019; Lu et al.,2020 ;Xu et al.,2021), this thesis selected industrial sulfur dioxide emissions, industrial wastewater discharge, and industrial dust emissions as substitutes for the three forms of pollutants (gas, liquid, and solid), to represent the emission situation of major pollutants such as urban exhaust, wastewater, and solid waste.

Table 1. Indicator system of urban land green use efficiency

Type	Dimension	Indicator	Unit
Input	K	Fixed asset investment	10,000 yuan
	L	Number of employees in the secondary and tertiary industries	10,000 people
	M	Construction land area	km^2
	E	Total energy consumed (coal)	10,000 tons
Output	Expected	Economic : GDP	100 million yuan
		Social: General budget revenue	100 million yuan
		Ecological:Green coverage ratio	%
	Unexpected	Industrial sulfur dioxide emissions	ton
		Industrial wastewater discharge	10,000 tons
		Industrial smoke and dust emissions	ton

（K：capital; L: labor; E: energy; M: land）

In summary, this thesis developed an indicator framework for measuring ULGUE, drawing from existing research and the concept's definition. The framework included input and output indicators, as outlined in Table 1. The input indicators encompassed capital, labor, land, and energy aspects, specifically fixed asset investment, the number of employees in the secondary and tertiary industries, the construction land area, and total energy consumption. On the other hand, the output indicators were derived from economic, social, and ecological perspectives. Expected output indicators included GDP, general budgetary revenue, and green coverage ratio, while unexpected output indicators encompassed industrial sulfur dioxide emissions, industrial wastewater discharge, and industrial dust emissions.

3.6 Data sources

Taking into account data availability and comparability, this thesis selected the whole city as the research scope. The data was mainly derived from the "China Urban Statistical Yearbook" (2010-2020)[10] and the "Hebei Statistical Yearbook" (2010-2020)[11]. In addition, in order to better compare regional economic changes, this thesis adjusted fixed asset investment and GDP to 2003 as the base year using the Fixed Asset Investment Price Index and the Deflator of Gross Domestic Product (Lu et al.,2020).

4.Results

4.1 Temporal Distribution Characteristics

4.1.1 Analysis on static difference characteristics of the urban agglomeration

In this study, the Super-Efficiency SBM model was used to calculate the static difference characteristics of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019.

① Global temporal characteristics

The overall urban land green use efficiency of the Beijing-Tianjin-Hebei urban agglomeration showed a fluctuating upward trend over time. As shown in Figure 4, the average efficiency value increased from 0.798 in 2009 to 1.087 in 2019, with an average annual growth rate of approximately 0.377%. The first time node of change occurred in 2011. Prior to 2011, the efficiency value showed an increasing trend year by year. However, after 2011, it began to decrease until reaching 0.819 in 2013. Subsequently, the average efficiency value began to rise year by year but with significant fluctuations.

[10] http://www.stats.gov.cn/sj/
[11] https://www.yearbookchina.com/navisearch-2-0-3-1-hebei-0.html

Specifically, in 2014, there was a sharp increase to 0.907, but in 2015, it dropped to 0.837. Then, in 2016, efficiency value had another sharp rise to 0.928, but in 2017, it declined again. In 2018 and 2019, the average efficiency value showed a straight upward trend.

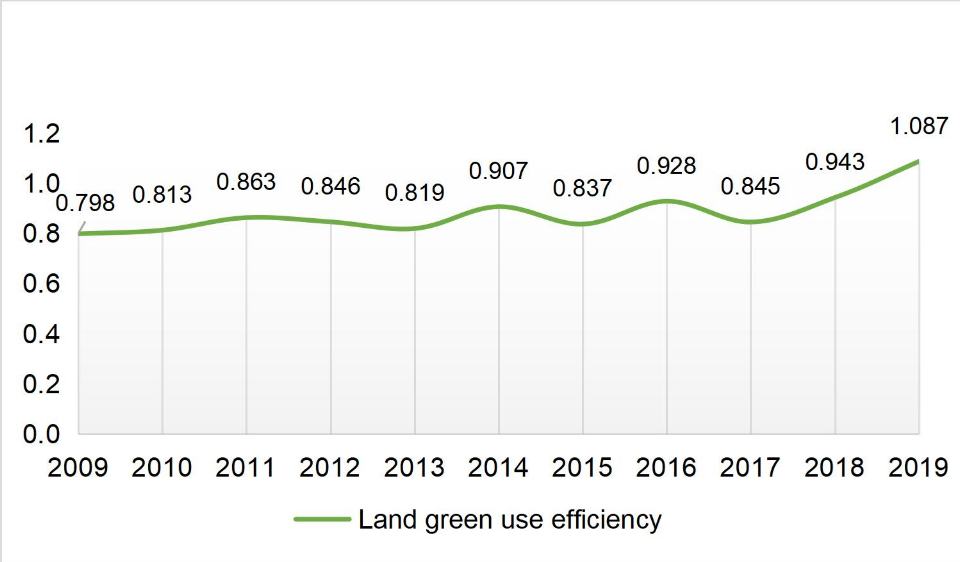

Figure 4. The overall urban land green use efficiency of Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019

The time changes in ULGUE in the Beijing-Tianjin-Hebei urban agglomeration were highly correlated with land and environmental protection policies. The "Green Olympics," as the top priority of the Beijing 2008 Olympics, resulted in many policy regulations being formulated and promulgated. In addition, Beijing and its surrounding provinces and cities adopted a linkage mechanism for environmental governance, making significant efforts and achieving significant results in achieving the "Green Olympics." Due to the influence of policy effects, ULGUE in the Beijing-Tianjin-Hebei urban agglomeration continued to rise after 2008, and by 2011, it had increased to 0.863.

However, in 2012 and 2013, the efficiency in the urban agglomeration both declined, followed by a rebound in 2014. This was mainly due to the diminishing marginal benefits as urban land use efficiency improved, leading to a slower or even reduced growth rate in ULGUE as inputs in capital, labor, land, and energy significantly increased, while technological progress was difficult to manifest in the short term. Furthermore, the promulgation of the "Green Building Evaluation Standards for the Beijing-Tianjin-Hebei Region"[12] in 2013 raised higher requirements for green buildings, creating pressure on construction costs and cycle times, which could also be one of the reasons for the decline in land green use efficiency in 2013. However, in March 2014, the Ministry of Land and Resources approved the Regulation on Saving and Intensive Use of Land for the first time at the first ministry meeting, which specifically standardized and guided the saving and intensive use of land, and had an important impact on the improvement of ULGUE in the urban agglomeration.

[12] http://www.rdywn.com.cn/html/news/jishuzhichi/15.html

In 2016, the state continuously strengthened its policy efforts in promoting ecological civilization construction and green development. It successively promulgated and implemented policies such as the "Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan (2016-2020)" ,"Assessment Target System for Ecological Civilization Construction"[13], and "Guiding Opinions on Building a Green Financial System"[14]. These policies have been promoting the green construction of the Beijing-Tianjin-Hebei urban agglomeration, which is beneficial to improving ULGUE.

Since 2017, the efficiency in the urban agglomeration has been continuously increasing. This is mainly due to the continuous formulation and implementation of policies by the government in land management and green development, which has contributed to the improvement of land green use efficiency. Furthermore, with the deepening of the concept of green development and the awareness of intensive and efficient land use, there has been an increasing emphasis on production reduction, emission reduction, and pollution control due to strengthening environmental awareness in the country. Combined with technological advancements, this has ultimately led to a reduction in unexpected outputs, resulting in an overall improvement in the efficiency of the urban agglomeration.

② Local temporal characteristics

In terms of individual cities within the urban agglomeration, there was a growing disparity in urban land green use efficiency among them. According to the study by Zhang et al.,(2020) , the coefficient of variation was calculated for the ULGUE values of these cities. The coefficient increased from 0.341 in 2009 to 0.443 in 2019, indicating a widening gap in efficiency among the cities. In 2009, there were four cities (Qinhuangdao, Cangzhou, Langfang, and Hengshui) with land green use efficiency values greater than 1. However, by 2019, the number of cities with values above 1 had increased to seven, including Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Langfang, and Hengshui. Throughout the period from 2009 to 2019, Hengshui remained the only city with ULGUE values consistently above 1 (Table 2).

Table 2. The urban land green use efficiency values for the 13 cities from 2009 to 2019

City	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Beijing	0.541	0.520	0.737	0.720	0.771	0.802	0.909	0.936	1.014	0.986	1.236	0.834
Tianjin	0.595	0.659	0.723	0.770	0.805	0.886	0.996	1.093	1.015	1.045	1.461	0.913
Shijiazhuang	0.578	0.614	0.695	0.718	0.734	0.657	0.640	0.674	0.701	1.148	1.109	0.752
Tangshan	0.636	0.681	1.011	1.017	1.007	0.947	0.909	1.002	0.963	1.018	1.003	0.927
Qinhuangdao	1.024	1.154	0.876	0.820	0.812	1.779	0.641	0.714	0.807	1.017	1.005	0.968
Handan	0.693	0.723	1.063	0.918	0.635	0.617	0.617	0.600	0.629	0.605	0.607	0.701
Xingtai	0.703	0.662	0.715	0.667	0.626	0.590	0.734	0.629	0.688	0.665	0.676	0.669
Baoding	0.584	0.635	0.677	0.670	0.715	0.665	0.635	0.710	0.766	0.739	0.750	0.686

[13] https://www.gov.cn/xinwen/2016-12/22/5151575/files/29be703efc974c1381fbe641a6d6524b.pdf
[14] https://www.mee.gov.cn/gkml/hbb/gwy/201611/t20161124_368163.htm

Zhangjiakou	0.599	0.591	0.628	0.629	0.653	0.664	0.699	0.759	0.674	0.715	0.727	0.667
Chengde	0.827	0.804	1.023	1.139	0.981	1.002	1.061	1.121	0.832	0.895	0.838	0.957
Cangzhou	1.408	1.227	1.049	0.951	1.007	0.965	0.989	1.460	1.021	0.937	0.884	1.082
Langfang	1.137	1.229	0.943	0.909	0.880	1.040	1.016	1.314	0.799	1.018	1.422	1.064
Hengshui	1.052	1.068	1.077	1.072	1.027	1.172	1.035	1.059	1.080	1.466	2.408	1.229
Mean	0.798	0.813	0.863	0.846	0.819	0.907	0.837	0.928	0.845	0.943	1.087	0.881

Examining the mean values of ULGUE for each city in Table 2, we can observe that Cangzhou, Langfang and Hengshui had average efficiency values greater than 1, namely 1.082, 1.064 and 1.229 respectively, indicating a state of complete efficiency. Tianjin, Tangshan, Qinhuangdao and Chengde still had room for improvement in ULGUE. Although the mean efficiency values of these four cities exceeded the overall mean value (0.881), they were relatively lower compared to Cangzhou, Langfang and Hengshui, with values of 0.913, 0.927, 0.968 and 0.957, respectively. Beijing's efficiency value was slightly below the mean value, at 0.834. The remaining cities exhibited efficiency values lower than the average for the urban agglomeration. Notably, Zhangjiakou had the lowest efficiency value of 0.667, approximately half of Hengshui's highest efficiency value.

Figure 5 presents the trend of urban land green use efficiency (ULGUE) for 13 cities within the Beijing-Tianjin-Hebei urban agglomeration. To analyze these trends, this study categorized them into three distinct types.

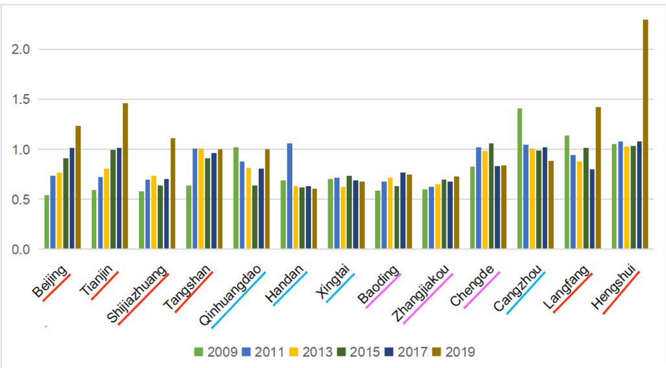

Figure 5. The temporal evolution of ULGUE for each city (Data points plotted at intervals of every two years)

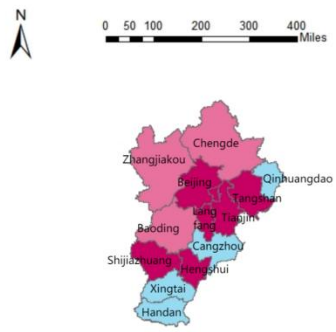

Figure 6. Three distinct types based on the evolution of ULGUE by city

Firstly, Beijing, Tianjin, Shijiazhuang, Tangshan, Langfang, and Hengshui (highlighted in red in Figure 6). These six cities have been experiencing an upward trend in efficiency values, surpassing 1. This trend is closely linked to the economic development of the Beijing-Tianjin-Hebei urban agglomeration. Beijing, Tianjin, and the provincial capital Shijiazhuang have higher levels of economic development and have driven the development of surrounding areas through their radiation effect. For instance, the Beijing-Langfang-Binhai New Area, focusing on the electronic information industry, serves as a high-tech industrial belt in the Beijing-Tianjin-Tangshan area. In addition, Tangshan, due to its superior geographical location, acts as a raw material base for Beijing and Tianjin and maintains close industrial cooperation with them. It acts as an intermediary between the economic centers of Beijing and Tianjin and the surrounding hinterland, contributing to the improvement of efficiency values. As for Hengshui, it has been actively promoting the adjustment and optimization of its industrial structure, emphasizing the development and support of high-tech industries and modern service sectors. Simultaneously, it has adopted energy-saving, environmentally friendly technologies, and clean production practices. For example, the amount of industrial wastewater discharged in the unexpected output index in 2019 was 1/7 of that in 2009. Consequently, Hengshui's land green use efficiency has remained high and continues to rise.

Furthermore, Baoding, Zhangjiakou, and Chengde (highlighted in pink in Figure 6) have been experiencing an upward trend in ULGUE, although they have not yet surpassed an efficiency value of 1. The main reason for this is that these three cities, due to their proximity to economically developed areas, benefit from the transfer of advanced technologies and concepts from the developed regions. This promotes intensive and efficient land use practices, leading to improvements in ULGUE. However, at the same time, these three cities are influenced by the suction effect of Beijing and Tianjin, with capital, labor, and resources flowing to Beijing and Tianjin to varying degrees. Additionally, they have absorbed high-energy-consuming and highly-polluting industries that have been relocated from Beijing and Tianjin. These factors make it difficult for Baoding, Zhangjiakou, and Chengde to surpass an efficiency value of 1.

On the other hand, Qinhuangdao, Handan, Xingtai, and Cangzhou (highlighted in blue in Figure 6) have been experiencing a downward trend ULGUE. This is mainly because these four cities are resource-based cities. Handan and Xingtai have been listed as resource-based cities in the "National Sustainable Development Plan for Resource-Based Cities (2013-2020)"[15]. Key projects for land subsidence control have been implemented in the Fengfeng Coal Mining Area in Handan and the Dongxing Coal Mining Area in Xingtai. In the case of Qinhuangdao and Cangzhou, in 2019, the proportion of employees in the secondary industry accounted for 31.67% and 27.54% of the total employed population, respectively (China Urban Statistical Yearbook, 2020). These cities have relatively single, industrial structures and, coupled with high levels of unexpected outputs, hinder the improvement of ULGUE in these cities.

4.1.2 Analysis on dynamic difference characteristics of the urban agglomeration

The results obtained from the Super-Efficiency SBM model (SSBM) represent the relative efficiency values, indicating the static efficiency of each city within the same period. However, it has limitations when it comes to conducting dynamic comparisons. To overcome this limitation, the Malmquist index is employed in this study, which offers the advantage of utilizing dimensional input-output data and effectively analyzing and

[15] https://www.gov.cn/zwgk/2013-12/03/content_2540070.htm

decomposing the characteristics of dynamic efficiency changes. By applying the Malmquist index, the changing patterns of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019 are investigated. The analysis focuses on measuring the ratio of current year efficiency to previous year efficiency, representing the change in overall factor energy efficiency from a dynamic perspective. Additionally, the study obtains the change index of total factor productivity and its decomposition results to further examine the dynamic efficiency changes over time.

① Global temporal characteristics

The urban land green use efficiency showed an unstable trend in the urban agglomeration from 2009 to 2019. Table 3 presents the mean value of total factor productivity (TFPCH), technical efficiency(EFFCH), and technological progress (TECH) for land green use in the urban agglomeration, which were 0.947, 1.000, and 0.947, respectively. Notably, the impact of technical efficiency on the improvement of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration surpassed that of technological progress. The decline in technological progress was at least one of the factors contributing to the decrease of ULGUE in the urban agglomeration.

Additionally, the growth level of total factor productivity experienced continuous fluctuations. The highest growth rate occurred in 2010-2011 (27.7%), followed by a declining trend with negative growth rates in 2011-2013. The growth rate turned positive during 2013-2015, but from 2015 to 2017, it became negative and exhibited a continuous decline. In 2017-2018, the growth rate showed a slight recovery but remained negative (-1.6%). Finally, in 2018-2019, the growth rate turned positive at 2.4%. Therefore, we can conclude that the land green use efficiency displayed an unstable pattern in the urban agglomeration from 2009 to 2019.

Table 3. The annual mean Malmquist index and its decomposition in the Beijing-Tianjin-Hebei urban agglomeration

Year	TFPCH	EFFCH	TECH	PECH	SECH
2009-2010	0.954	1.012	0.943	1.000	1.012
2010-2011	1.277	0.990	1.289	0.990	1.000
2011-2012	0.949	1.002	0.947	1.001	1.000
2012-2013	0.963	1.007	0.957	1.007	1.000
2013-2014	1.022	1.002	1.020	1.003	1.000
2014-2015	1.017	1.000	1.017	1.000	1.000
2015-2016	0.757	0.972	0.779	1.000	0.972
2016-2017	0.658	1.014	0.649	1.000	1.014
2017-2018	0.984	1.001	0.983	0.993	1.008
2018-2019	1.024	1.006	1.017	1.007	0.999
Mean	0.947	1.000	0.947	1.000	1.000

(TFPCH: Total Factor Productivity Change Index; EFFCH: Technical Efficiency ; TECH: Technological Progress ; PECH: Pure Technical Efficiency; SECH: Scale Efficiency)

② Local temporal characteristics

In terms of the cities, there was a trend of differentiation in urban land green use efficiency among them within the urban agglomeration. The mean total factor productivity was 0.947, indicating a declining trend from 2009 to 2019. Furthermore, only three cities, namely Beijing, Tianjin, and Shijiazhuang, exhibited a total factor productivity greater than 1, while the remaining ten cities had a total factor productivity below 1 (Table 4).

Table 4. Decomposition of urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019

City	TEPCH	EFFCH	TECH	PECH	SECH
Beijing	1.065	1.000	1.065	1.000	1.000
Tianjin	1.125	1.000	1.125	1.000	1.000
Shijiazhuang	1.018	1.003	1.014	1.000	1.003
Tangshan	0.949	1.000	0.949	1.000	1.000
Qinhuangdao	0.930	1.000	0.930	1.000	1.000
Handan	0.909	0.989	0.919	1.000	0.989
Xingtai	0.865	1.000	0.865	1.000	1.000
Baoding	0.904	1.014	0.892	1.000	1.014
Zhangjiakou	0.874	1.000	0.874	1.000	1.000
Chengde	0.895	1.000	0.895	1.000	1.000
Cangzhou	0.923	1.000	0.923	1.000	1.000
Langfang	0.998	1.000	0.998	1.000	1.000
Hengshui	0.893	1.000	0.893	1.000	1.000
Mean	0.947	1.000	0.947	1.000	1.000

(TFPCH: Total Factor Productivity Change Index; EFFCH: Technical Efficiency ; TECH: Technological Progress ; PECH: Pure Technical Efficiency; SECH: Scale Efficiency)

Regarding technical efficiency (EFFCH), only Handan had a technical efficiency value below 1, while the other twelve cities showed an upward trend in technical efficiency . When decomposing technical efficiency into pure technical efficiency (PECH) and scale efficiency (SECH), we found that the mean values of both pure technical efficiency and scale efficiency were 1, indicating relative stability. As for pure technical efficiency, all cities had a value of 1, indicating that each city in the Beijing-Tianjin-Hebei urban agglomeration effectively utilized input factors at the existing technological level, demonstrating a higher level of technical management. Concerning scale efficiency, only Shijiazhuang and Baoding exceeded 1, with values of 1.003 and 1.014, respectively, while Handan had a scale efficiency value below 1 at 0.989. The scale efficiency values for the other cities were all 1. This indicates that the overall urban agglomeration in the Beijing-Tianjin-Hebei region has a suitable input factor scale, but Handan could benefit from expanding its input factor scale to align production factors with production scale, thereby enhancing ULGUE.

Analyzing the technological progress index (TECH), the average annual growth rate of technological progress was -5.3%, indicating an overall decline in technological progress within the urban agglomeration. Among them, only Beijing, Tianjin, and Shijiazhuang had technological progress indices greater than 1, while the remaining eleven cities had technological progress indices below 1. This highlights the importance for each city to maintain a sense of innovation during the development process and increase investment in technology innovation in terms of funds and manpower. It is crucial to introduce advanced technology and management methods in the early stages as much as possible to promote the improvement of ULGUE.

4.2 Spatial Distribution Characteristics

4.2.1 Global spatial characteristics of ULGUE in the urban agglomeration

Referring to the research by Zhu & Gao (2022), this study used the natural breakpoints method in ArcGIS software to examine the spatial distribution of urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019. Six specific years, namely 2009, 2011, 2013, 2015, 2017, and 2019, were selected to generate a spatial distribution map (Figure 7). The map classified the efficiency levels into low, moderately low, moderate, moderately high, and high categories. The findings revealed a spatial distribution pattern in the Beijing-Tianjin-Hebei urban agglomeration characterized by high efficiency levels in the southeast and low efficiency levels in the northwest.

The areas with high efficiency primarily included Beijing, Tianjin, Tangshan, and the southeast region of Hebei Province encompassing Hengshui, Cangzhou, and Langfang. Beijing and Tianjin, as the core cities of the urban agglomeration, exhibited a high level of economic development and exerted a certain radiating influence on neighboring cities like Tangshan and Langfang, thus enhancing their ULGUE. Hengshui City actively pursued industrial structural adjustment and optimization, focusing on the development and support of high-tech industries and modern service sectors. These efforts resulted in a significant reduction in unexpected outputs and a higher efficiency level.

Conversely, the areas with low efficiency were mainly located in the northwest (e.g., Zhangjiakou) and central (e.g., Shijiazhuang and Baoding) regions of Hebei Province.
Research conducted by Song et al. (2021) indicated that these two regions serve as important ecological function areas, as well as grain and agricultural product production areas within the Beijing-Tianjin-Hebei urban agglomeration. Due to the constraints of economic attributes and the socio-economic development foundation, the development

scale and types of the secondary and tertiary industries in these regions are somewhat restricted, resulting in lower efficiency levels compared to other areas.

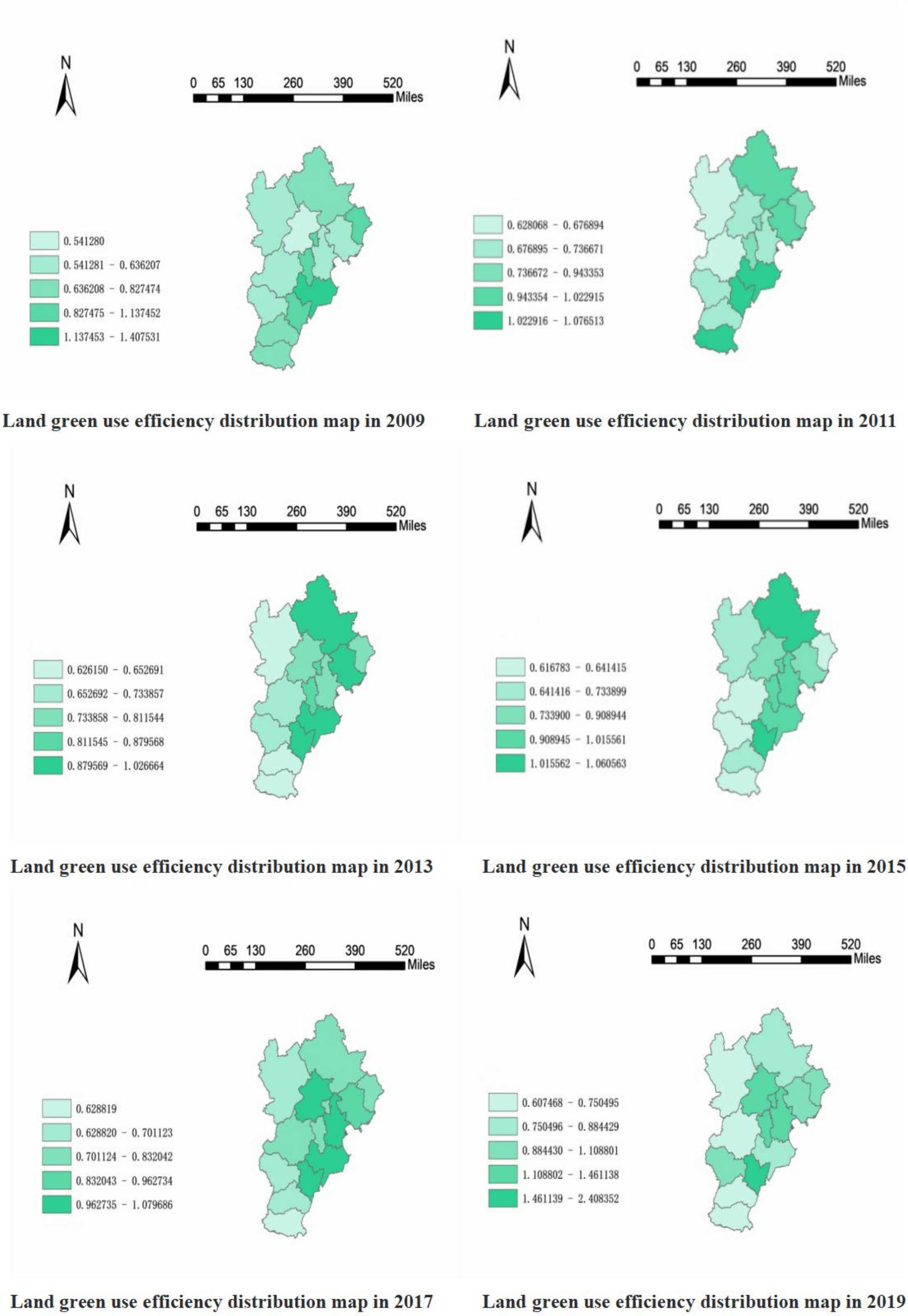

Figure 7. Spatial distribution of urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019

4.2.2 Spatial correlation of ULGUE in the urban agglomeration

①Global spatial autocorrelation analysis

In order to further verify the spatial correlation of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration, this study used the global Moran's index to measure the overall spatial features.The results, presented in Table 5, indicate the following findings.

Between 2009 and 2019, the values of the global Moran's index for urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration ranged from -0.164 to 0.293. Only in 2016, the P value was 0.045 less than 0.05, and the Z value was 2.003 over 1.96, indicating significant spatial correlation. However, for the other years, the P values were greater than 0.05, indicating a lack of statistical significance. Essentially, this implied that spatial correlation in ULGUE was observed only in 2016, while the remaining years showed no spatial autocorrelation.The findings indicated a spatial distribution pattern of ULGUE values characterized by randomness, lacking significant clustering or dispersion trends. This pattern can be attributed to the distinct variations in conditions among the cities within the urban agglomeration.

Table 5. Moran's index value of urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Moran's I	0.025	0.020	-0.163	-0.164	0.156	0.161	0.072	0.293	0.137	0.032	-0.118
P	0.550	0.590	0.686	0.671	0.216	0.111	0.429	0.045	0.256	0.511	0.819
Z	0.598	0.539	-0.405	-0.425	1.238	1.593	0.791	2.003	1.137	0.657	-0.228

Only the ULGUE in 2016 showed spatial autocorrelation, which was mainly related to the coordinated development policies of the Beijing-Tianjin-Hebei urban agglomeration. In June 2015, the Communist Party of China Central Committee and the State Council issued and implemented the "Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan (2016-2020)". This comprehensive plan depicted a grand blueprint for the collaborative development of the Beijing-Tianjin-Hebei region from various aspects such as strategic significance, overall requirements, positioning and layout, orderly relocation of non-capital functions from Beijing, promoting breakthroughs in key areas, promoting innovation-driven development, and coordinating and synergizing development tasks. It provided the basic basis and action guidelines for guiding the collaborative development of the Beijing-Tianjin-Hebei region in the present and future periods.

In February 2016, the "National Economic and Social Development Plan for the Beijing-Tianjin-Hebei Region during the 13th Five-Year Plan Period"[16] was implemented. This was the first regional "13th Five-Year Plan" spanning multiple provinces and cities in China, which took the Beijing-Tianjin-Hebei region as a whole and comprehensively planned the development of urban agglomerations, industrial transformation and upgrading, transportation infrastructure construction, and improvement of people's livelihood. The plan aimed to achieve a new development pattern characterized by common goals, integrated measures, complementary advantages, and win-win development in the Beijing-Tianjin-Hebei region.

Moreover, in June 2016, the Ministry of Industry and Information Technology, together with Beijing, Tianjin, and Hebei, jointly formulated the "Guidelines for Industrial Transfer in the Beijing-Tianjin-Hebei Region"[17]. This policy aimed to promote collaborative development of industries in the Beijing-Tianjin-Hebei region, leverage the comparative advantages of the three areas, guide the orderly transfer and integration of industries, and establish a development pattern with reasonable spatial layout, organic industrial chain connection, and optimized allocation of various production factors. The issuance of these collaborative development policies in 2016 provided a significant explanation for the observed spatial correlation in ULGUE within the urban agglomeration.

②Local spatial autocorrelation analysis

To further explore the clustering characteristics of local spatial units in space, this study employed the local Moran's index and utilized ArcGIS software to generate the LISA cluster map, which examined the local spatial characteristics of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration in 2016 (Figure 8).

In 2016, the High-High type areas were primarily located in Tianjin and Cangzhou. This spatial clustering can be attributed to the promulgation of the "Enhanced Measures for Air Pollution Prevention and Control in the Beijing-Tianjin-Hebei Region (2016-2017)"[18] by the Ministry of Environmental Protection in June 2016. These measures introduced stricter regulations on the emissions of air pollutants. As a result, Tianjin and Cangzhou exhibited relatively lower levels of unexpected outputs, such as industrial sulfur dioxide emissions, industrial wastewater discharge, and industrial smoke and dust emissions. The reduction in these factors contributed to higher ULGUE, thus forming the High-High type areas.

[16] http://www.cicpmc.org/information_view.aspx?nid=34&typeid=50019&id=696
[17] http://www.mofcom.gov.cn/article/b/g/201608/20160801384086.shtml
[18] https://www.chndaqi.com/news/242562.html

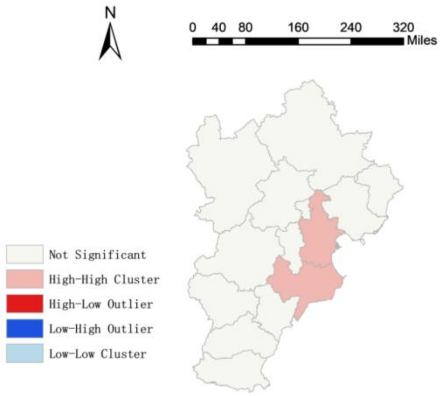

Figure 8. Spatial autocorrelation analysis of urban land green use efficiency in the Beijing-Tianjin-Hebei urban agglomeration in 2016

5.Discussion

Temporally, the overall efficiency of the Beijing-Tianjin-Hebei urban agglomeration showed a fluctuating upward trend over time, closely tied to land and environmental protection policies. However, there was a growing disparity in land green use efficiency (ULGUE) among individual cities within the urban agglomeration, which can be attributed to factors such as economic development level, location, and industrial structure.

In terms of dynamic characteristics, the study found that technical efficiency had a greater impact on improving ULGUE in the urban agglomeration compared to technological progress. The decline in technological progress was identified as one of the factors contributing to the decrease in ULGUE. Among the cities, only Beijing, Tianjin, and Shijiazhuang, with higher economic development levels, exhibited a total factor productivity greater than 1, while the remaining ten cities had a total factor productivity below 1. It means the development of economics plays an important role in the ULGUE.

Regarding spatial distribution, the urban agglomeration demonstrated a consistent pattern of high ULGUE levels in the southeast and low ULGUE levels in the northwest from 2009 to 2019. However, spatial correlation in ULGUE was observed only in 2016, with high-high type areas predominantly concentrated in Tianjin and Cangzhou. In the remaining years, no spatial autocorrelation was observed, indicating a spatial distribution pattern resembling randomness. The policies implemented in 2016 played a significant role in explaining the observed spatial correlation by leveraging the advantages of the three areas (Beijing, Tianjin, and Hebei) and establishing a well-planned spatial layout and interconnected industrial chains.

This MSc thesis project effectively achieved its objectives by analyzing the temporal and spatial distribution patterns of ULGUE in the Beijing-Tianjin-Hebei urban agglomeration. It contributes to advancing theoretical knowledge and offering practical guidance for sustainable development and the construction of an ecological civilization in the region.

However, there are some limitations to consider. Firstly, due to limited data availability, spatial correlation in ULGUE was observed only in 2016, while other years showed no spatial autocorrelation. This implies that the spatial characteristics may vary over time and need to be further examined. Secondly, the analysis predominantly relies on quantitative data, overlooking qualitative factors that may influence ULGUE, such as social and cultural aspects. Incorporating qualitative research methods and gathering additional data would provide a more comprehensive understanding of the factors affecting ULGUE. Lastly, the study period covers the years from 2009 to 2019, and more recent data would provide insights into the current state of ULGUE and enable a more up-to-date analysis. Addressing these limitations and conducting further research could provide a more nuanced understanding of ULGUE and its implications for sustainable development in the Beijing-Tianjin-Hebei urban agglomeration.

6.Conclusions and Suggestions

The study focuses on analyzing the temporal and spatial distribution characteristics of urban land green use efficiency (ULGUE) within the Beijing-Tianjin-Hebei urban agglomeration from 2009 to 2019. The research employs the Super-Efficiency SBM model to construct a quantifiable evaluation framework that incorporates economic, social, and environmental aspects from an input-output perspective. The main conclusions of the study are as follows:

1.Temporally, the overall efficiency of the urban agglomeration exhibited a fluctuating upward trend over time, although there was an increasing disparity in ULGUE among different cities.

2.The impact of technical efficiency on improving ULGUE was found to be more significant than that of technological progress. Additionally, there was a noticeable differentiation trend in ULGUE among the cities within the urban agglomeration.

3.Spatially, a consistent pattern emerged with high efficiency levels in the southeast and low efficiency levels in the northwest. However, spatial correlation in ULGUE was observed only in 2016, characterized by concentrated High-High areas in Tianjin and Cangzhou. This pattern was highly related to the policies implemented in 2016.

Based on these research findings, several recommendations are proposed to enhance urban land green use efficiency and promote sustainable development within the Beijing-Tianjin-Hebei urban agglomeration.

Firstly, to improve ULGUE, it is crucial to implement differentiated regional land use control policies that consider the unique characteristics of each region. This involves analyzing factors such as geographical location, economic development level, and resource endowment. Tailoring land use control measures to specific regions and cities can revitalize and transform old driving forces in high-efficiency cities. Promoting industrial structural transformation and upgrading, gradually phasing out high-polluting and high-energy-consuming industries, and optimizing the overall urban land use structure are important steps. Opportunities presented by old city renovation and urban renewal should also be maximized to maximize the ecological and social benefits of urban land use. Low-efficiency cities should prioritize the control and governance of polluting enterprises and industries, with scientific and reasonable planning of industrial bases and parks to promote intensive and efficient utilization of urban land.

Secondly, optimizing the input of production factors plays a crucial role in achieving green and high-quality development in urban land use. It is recommended to optimize various production factors while focusing on environmental protection. This can be achieved by improving technological management, organizational management, and industrial structure, as well as promoting technological progress and fostering innovation awareness. Financial incentives for technological innovation should be increased, talent development and recruitment should be prioritized, and an environment conducive to advancing land use efficiency should be created. Adhering to an ecological priority strategy, establishing a negative list for polluting enterprises, and implementing effective land use control measures for these enterprises and related industries are important. Additionally, expanding the scale of input factors based on the characteristics of each city, taking advantage of economies of scale, can lead to increased efficiency and productivity.

Lastly, leveraging the spatial agglomeration effects and functional attributes of urban agglomerations is crucial. Strengthening the spatial spillover effects of core cities on neighboring cities is important for enhancing the overall efficiency and effectiveness of urban land use. This can be achieved through consolidating regional development consensus, enhancing cooperation and communication among cities, and promoting coordinated development within the urban agglomeration. By maximizing the benefits of spatial agglomeration, such as resource sharing, knowledge exchange, and specialized labor markets, the region can move towards a more sustainable and environmentally friendly path.

In conclusion, the suggestions put forward based on the research findings aim to improve ULGUE and achieve the coordinated development of the Beijing-Tianjin-Hebei urban agglomeration. Implementing differentiated regional land use control policies, optimizing production factors, and leveraging spatial agglomeration effects are key strategies to achieve sustainable and efficient land use. These measures contribute to the long-term well-being and prosperity of the region and its inhabitants.

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