Journal of Innovation and Development
ISSN: 2958-4752 | Vol. 4, No. 2, 2023

A Review of Research Methods for Coupling Land Use Efficiency and Spatio-Temporal Heterogeneity

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Abstract: This paper synthesizes research methods on the coupling of land use efficiency and spatio-temporal heterogeneity, aiming to provide insights into the diversity and important findings in this important field. Land use efficiency is a key factor in sustainable land management and resource planning, while spatio-temporal heterogeneity emphasizes the variability between different regions and points in time. The article explores the methods and applications of land use efficiency research from different perspectives. Remote sensing technology and geographic information systems (GIS) are considered two pillars of land use efficiency research, which complement each other but also have their own applicability and limitations. Remote sensing technology can provide large-scale and multi-scale land use information, but with limited resolution, while GIS is suitable for spatial analysis of land use and integration of multiple geographic data, but relies on accurate datasets. Time series analysis and spatial analysis modeling are key methods in land use change studies. Time series analysis is used to reveal historical trends and future projections of land use, while spatial analysis models emphasize the spatial linkages between land uses. These two methods have their own focus and can be selected and combined according to the research questions. The study of land use efficiency and spatio-temporal heterogeneity needs to consider its important impact on the environment. Good land management can protect ecosystems, combat climate change and maintain resource sustainability. In addition, these studies provide guidance for practical applications of sustainable land management and resource planning, including urban planning, agricultural improvement, ecosystem protection, and climate change adaptation. However, land use efficiency and spatial and temporal heterogeneity studies suffer from limitations and uncertainties such as data uncertainty, data availability, and modeling assumptions. Future research could explore more integrated approaches, especially in the context of climate change and socioeconomic factors. An in-depth study of the variability and best practices in different regions can help improve the scientific basis for land management decisions. This paper summarizes the coupled research methods on land use efficiency and spatio-temporal heterogeneity and their importance. These studies provide certain references for sustainable land management and resource planning, and help to realize sustainable resource utilization, environmental protection, and sustainable socio-economic development.

Keywords: Land Use Efficiency; Spatial and Temporal Heterogeneity; Land Resource Management; Sustainable Land Management; Sustainable Development.

1. Introduction

Land use plays a key role in the multiple challenges facing the world today. With the growing global population, rapid urbanization, and the constant influence of factors such as climate change, scientists, policy makers, and the community have created an urgent need for more efficient management and planning of land resources (S. He, Yu, Li, & Zhang, 2020). The study of land use efficiency and spatio-temporal heterogeneity has become one of the key factors in understanding and solving these challenges (Zhu et al., 2019). The purpose of this paper is to provide a comprehensive review of research methods covering multiple aspects in the field of land use efficiency and spatio-temporal heterogeneity. The paper will explore various research methods, including remote sensing techniques, geographic information system (GIS) analysis, time series analysis, and spatial analysis models, as well as their applications in land use research (Zhou, 2023). The diversity of these methods allows researchers to delve into different dimensions of land use, from historical trends to future projections, and from comparisons between urban and rural areas to the identification of regional land use patterns (Liu, Liao, Liang, Li, & Huang) The paper will also present a series of coupled temporal and spatial models of land use. This paper will also present a series of coupled spatio-temporal heterogeneity analysis cases that demonstrate the practical application of these methods. These cases will cover different geographic regions, time points, and land use situations, helping researchers better understand the value of land use efficiency and spatio-temporal heterogeneity studies in practical problem solving (Ma et al., 2023). Finally, this paper will discuss the importance of land use efficiency and spatio-temporal heterogeneity research, including its implications for the environment, sustainable land management and resource planning (Chang, Wang, & Liu, 2023). This research not only helps to address today's land management challenges, but also provides important support for sustainable socio-economic development.

2. The Concept of Land Use Efficiency and Spatio-Temporal Heterogeneity

2.1. Definition and Evaluation Indicators of Land Use Efficiency

Land use efficiency is an important concept that measures the relationship between the benefits and costs of land resource utilization. It usually includes the following aspects:

1) Land productivity: the output or value produced per unit area of land. Measuring land productivity usually involves a number of areas, such as agricultural output, urban development, and natural resource extraction.

2) Land benefits: the relationship between land use and its economic, social or environmental benefits. This includes

land use diversity, suitability, and consideration of social and environmental impacts (Cai, Zhang, Du, Li, & Peng, 2021). Land use: the relationship between land use and its economic or social or environmental benefits.

3) Resource efficiency: The relationship between land-related resources (e.g.water, energy) and output. Measurements in this area can be used to assess the sustainability of resources.

4) Economic indicators: indicators such as land rent, land price, land value, etc., which are usually used to measure land use efficiency (T. He & Song, 2023).

2.2. The Concept of Spatio-Temporal Heterogeneity and the Factors Influencing it

Spatio-temporal heterogeneity refers to the differences and diversity between different regions and points in time and involves changes in land use, land cover and land characteristics. The following are key concepts and influences on spatio-temporal heterogeneity:

1) Geographic differences: differences in land use between different geographic areas, e.g., urban vs. rural, high mountains vs. plains, coastal vs. inland areas.

2) Temporal dimension: changes in land use and cover at different points in time, including long-term trends, seasonal changes and annual changes.

3) Environmental conditions: the impact of natural environmental factors such as topography, climate, soil type, etc. on land use. These factors can lead to differences in land use patterns in different regions (Zheng, Zhu, Pei, & Wang, 2022).

4) Policies and planning: The impact of government policies, urban planning and land management policies on land use. Policy changes in different regions and at different points in time may lead to land-use heterogeneity.

5) Population and economic development: Changes in population growth, urbanization levels and economic activities have important impacts on land use, especially in urban areas. (Zeng, Chen, Wu, & Dong, 2023).

Through a deeper understanding of the concepts of land use efficiency and spatial and temporal heterogeneity, researchers can better identify challenges and opportunities in different regions and time periods, providing strong support for land management and planning. Clear definitions and measurements of these concepts can help researchers better understand land use dynamics and resource allocation.

3. Research Methodology

3.1. Data Collection and Processing Methods

3.1.1. Application of Remote Sensing Technology

Remote sensing plays a key role in the study of land use efficiency and spatial and temporal heterogeneity. Remote sensing data capture surface information, including land cover, land type, and land use, through satellites, aircraft, or other sensors (L. Zou, Wang, & Bai, 2022). Commonly, satellite imagery data are utilized for land use and cover classification and monitoring. This includes describing the applicability and resolution of different remote sensing data sources (e.g., Landsat, MODIS, Sentinel, etc.) and how to analyze and process these data for pixel-level land classification and change detection (X. Zhang, Kang, Wang, & Sun, 2010).

3.1.2. Geographic Information System (GIS) Analysis

Geographic Information System (GIS) is a powerful tool for processing and analyzing spatial data, including land use and land cover. Managing geographic information data such as land use data, topographic data, meteorological data, etc. in a scientific manner helps to study land use efficiency from a macro perspective (Reis, 2008) The use of GIS tools to analyze land use data is common.

It is common to use GIS tools for spatial analysis, including spatial interpolation, buffer analysis, spatial correlation analysis and so on. GIS can also be used for 3D geographic information modeling and analysis to better understand the vertical dimension of land use (Muralikrishna & Manickam, 2017).

3.2. Statistical Methods and Modeling

3.2.1. Time Series Analysis

Time series analysis plays an important role in the study of land use efficiency and spatial and temporal heterogeneity. Trend analysis is used to detect long-term trends in land use, as well as to make trend projections. It is also possible to invert its seasonal variations. Eventually, predictive models of land use and spatio-temporal heterogeneity can be developed through time series modeling (Masolele et al., 2021).

3.2.2. Spatial Analysis Models

Spatial analysis models are used to explain the spatial distribution and interrelationships of land use. Spatial autocorrelation of land use data can be analyzed using geostatistical methods. Geographically weighted regression models can be used to explore the relationship between land use and spatial and temporal heterogeneity. Land use models can serve the purpose of predicting future land use changes and assessing the impact of different policies on land use. (Dendoncker, Rounsevell, & Bogaert, 2007).

3.3. A Research Framework for Coupling Land Use Efficiency and Spatio-Temporal Heterogeneity

When studying land use efficiency and spatio-temporal heterogeneity, it is important to establish an integrated research framework to ensure that factors and methods are considered in an integrated manner (C. Zou, Zhu, Lou, & Yang, 2022). The establishment of a research framework is generally carried out through the following ways (Fig. 1)

First, the research framework needs to consider the integration of different data sources, including remote sensing data, GIS data, time series data, etc. This step ensures comprehensive geographic information and time dimension data. In establishing the research framework, the concepts of land use efficiency and spatio-temporal heterogeneity need to be clearly defined. This helps to ensure that the researcher has a clear understanding of the objectives and questions of the study (Y. Chen et al., 2023). The research framework should include various data analysis methods, such as remote sensing data processing, GIS analysis, time series analysis, and spatial analysis modeling. The selection of these methods should depend on the research questions and available data. The research framework needs to take full account of changes in the temporal and spatial dimensions. This includes the choice of time scale (annual, seasonal, monthly), definition of spatial scale (urban, rural, geographic area), etc. In the study, the coupling effect between land use efficiency and spatio-

temporal heterogeneity needs to be clarified. This can be achieved through statistical analysis, modeling, and geographically weighted egression. Finally, he researches framework should emphasize the practical application of its findings to land management and planning. This includes providing policy recommendations, sustainable land management strategies and resource planning suggestions.

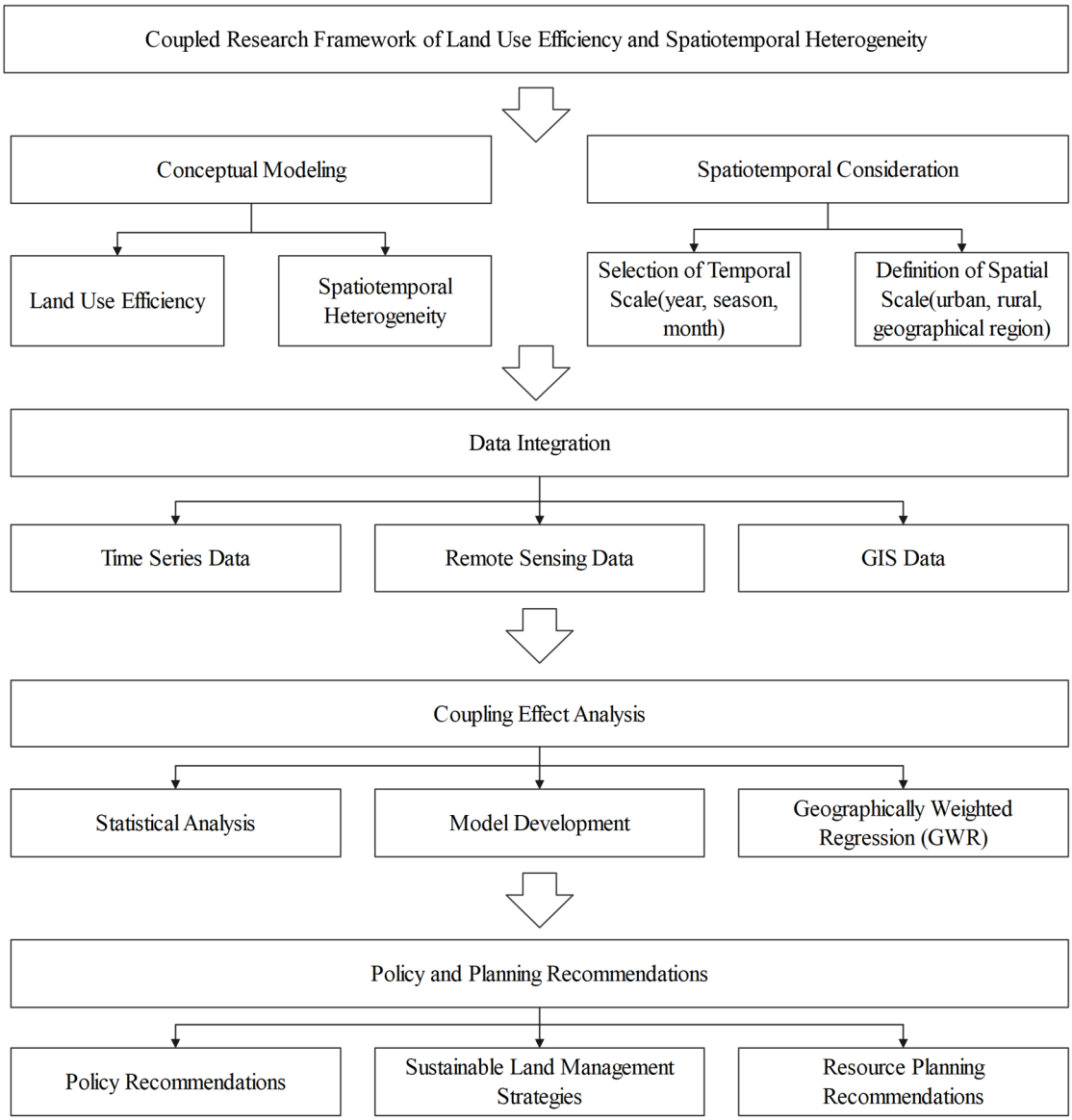

Fig 1. Research framework for coupling land use efficiency and spatio-temporal heterogeneity

This integrated research framework helps researchers to systematically study land-use efficiency and spatial and temporal heterogeneity for a better understanding of land resource management and sustainable development issues.

By integrating different data, concepts and methods within a framework, researchers can analyze and address this complex issue in a more comprehensive manner and provide stronger support to policymakers.

4. Progress in Research

The study by Wang et al. established a coupled coordination analysis and a spatio-temporal heterogeneity model to study the coupled effects of energy- environmental efficiency and urbanization along the Silk Road Economic Belt in China, and found that the coupled effects of energy-environmental efficiency and urbanization are significant, and that the degree of coupled coordination has a significant impact on ecological and environmental quality (Ariken, Zhang, Chan, & Kung, 2021). The coupled coordination analysis is an important tool for studying land use and urbanization. Coupled coordination analysis is a common method to study the relationship between land use efficiency and spatial and temporal heterogeneity (Yuan, Bian, Yan, & Kung, 2021). (Yuan, Bian, Yan, & Pan, 2019), and this approach helps to understand the coupling effects between different variables, such as energy-environmental efficiency and urbanization (Ariken et al., 2021). Spatio-temporal heterogeneity analysis is another important method to study land use efficiency and spatio-temporal heterogeneity (M. Zhang et al., 2023). This approach helps to identify temporal and spatial differences between land use and other variables such as urbanization and ecology (Ariken et al., 2021). The Time series analysis is commonly used in coupled studies to analyze temporal patterns and trends in land use change (M. Zhang et al., 2023). This approach provides valuable insights into the dynamics of land use and its impacts on the environment and social development. A study by Zhang et al. investigated the spatial and temporal changes in land use carbon emissions in Zhejiang Province, China, and found that

there are significant spatial and temporal variations in land use carbon emissions, with key influencing factors including population density, economic development, and land use intensity (M. Zhang et al., 2023). The key influencing factors include population density, economic development and land use intensity. Li et al. used spatio-temporal coupled analysis to analyze the coordination between urbanization and aquatic ecosystems in the Yangtze River Economic Zone in China, and found that the coordination between urbanization and aquatic ecosystems varied according to the spatial gradient and temporal scale, and the key influencing factors included population growth, economic development, and environmental policies (Han, Li, & Zhang, 2010). (Han, Li, & Zhang) The key influences include population growth, economic development and environmental policies (Han, Li, & Zhang). The coupled research methodology of land-use efficiency and spatio-temporal heterogeneity often involves the integration of various data sources, such as remotely sensed data, socio-economic data and environmental data. Such integration contributes to a comprehensive understanding of the complex relationship between land use, the environment, and social and economic development. The coupled research method of land use efficiency and spatio-temporal heterogeneity can be applied to various contexts such as urbanization, ecological environment, water ecosystems, mining cities, etc. (Cai et al., 2021)

The This versatility allows researchers to analyze the coupled coordination and spatio-temporal heterogeneity between land use and other variables in different environments, providing valuable insights for land management and resource planning.

5. Discussion

5.1. Comparison of Methods

5.1.1. Remote Sensing and Geographic Information Systems (GIS)

Remote sensing and geographic information systems (GIS) are two key tools in land use efficiency research that complement each other to some extent, but also have their own applicability and limitations.

Remote sensing technology is able to utilize data obtained from satellites, aircraft or other sensors, providing large-scale, multi-scale land-use information that is applicable to a variety of geographical environments. Remote sensing technology can provide high-frequency data updates to support real-time monitoring and tracking of land-use changes, which can help to respond to resource management and environmental protection issues in a timely manner. Through remote sensing technology, accurate land use data, such as land cover type, vegetation index, land temperature, etc., can be obtained, and these data can be used for quantitative analysis and modeling (Costache et al., 2020). However, remote sensing data have limited resolution and may not capture land use changes at small scales, especially in high density areas such as cities. Cloud cover and poor meteorological conditions may result in blocked data acquisition, limiting data continuity and availability (Y. Xie, Wang, Fan, Huang, & Xie, 2023).

GIS is an ideal tool for processing spatial data to compare, analyze and model land use in different locations, revealing the spatial distribution and correlation of land use. GIS is able to integrate a wide range of geographic data, including remotely sensed data, topographic data, socio-economic data, and so on, to provide comprehensive land-use information. GIS can be used for land management decision-making to support sustainable land planning and resource management. However, GIS relies on accurate and complete datasets, and low quality or incomplete data will affect the credibility of analysis results. Setting up and operating a GIS system requires specialized knowledge, time and resources to configure and maintain (J. Chen, 2014).

Remote sensing and GIS are often complementary to each other for more comprehensive land-use efficiency studies. Remote sensing data can provide detailed images of land use, while GIS can be used to integrate these data into spatial analyses for more in-depth studies. GIS can be used to calibrate remotely sensed data to improve the accuracy and precision of the data. Combining remote sensing and GIS analysis allows for both the temporal and spatial dimensions of land use to be considered, allowing for more comprehensive studies.

Both remote sensing and GIS have important roles to play in land-use efficiency research, and the choice of tool or combination of tools should be weighed against the research questions and data availability. Their mutual complementarity can help to increase the depth and breadth of land-use efficiency research.

5.1.2. Time Series Analysis and Spatial Analysis Models

Time series analysis and spatial analysis modeling are commonly used methods in land use change research, each with different effectiveness and application contexts. Time series analysis can identify long-term trends in land- use change, reveal the evolution of land resources and help formulate long-term land management strategies. It is able to detect seasonal changes in land use data, especially in agriculture, and can help optimize seasonal land use decisions (Congalton, 1991). Through time series modeling, it can predict future land use changes and provide important references for planners. It is suitable for studying the long-term evolution of land use, e.g., a decrease in forest cover or an increase in urbanization. It can also be used to understand seasonal land use changes in agriculture, such as plowing and harvesting seasons. Through modeling, future land use changes can be predicted to support sustainable land planning (Chai & Li, 2023).

Spatial analysis models can reveal the spatial correlations between land uses and how they affect each other. Using geographically weighted regression models, land use models can be built more accurately by taking into account the weight of geographic location and considering the influence of geographic factors on land use. Spatial analysis modeling through land use modeling can be used to predict future land use, especially in urban planning. Spatial correlation analysis is suitable for understanding the spatial dependence between land use in different areas, such as the impact of urban expansion on surrounding rural land use. Geographically weighted regression can be used to study how geographic location affects land use decisions, such as the analysis of real estate markets. In urban planning, spatial analysis models can help predict future land demand and optimize land use planning (Páez & Wheeler, 2009) In urban planning.

In general, both time series analysis and spatial analysis models play a key role in land use change studies, but they have different focuses. Time series analysis is more suitable for studying the temporal dimension of land use, such as trends and seasonal changes, while spatial analysis models are more suitable for revealing the spatial distribution and correlation of land use. Researchers should choose the

appropriate method based on the research question and data context, and sometimes can combine the two to gain a more comprehensive insight.

5.2. Environmental Impacts of Land-Use Efficiency and Spatio-Temporal Heterogeneity

The study of land use efficiency and spatio-temporal heterogeneity not only focuses on the economic and social aspects of land, but also needs to take into account its important impact on the environment.

Improvements in land-use efficiency can directly affect ecosystem health and functioning. Good land management protects and enhances ecosystem services, including water conservation, carbon storage, climate regulation, and biodiversity maintenance. For example, the retention of natural ecosystems such as wetlands and forests contribute to water quality improvement, flood control and biodiversity conservation. Irrational land use can lead to soil pollution and erosion problems. For example, excessive agricultural chemical use or urban industrial activities may lead to soil quality degradation and pollutant accumulation (Lu, Kuang, & Li, 2018). Studying land use efficiency and spatial and temporal heterogeneity can help to identify these problems and develop corresponding conservation and restoration measures. Climate change has significant impacts on land use, and land management must be adapted to new climatic conditions. Studying land use efficiency and spatial and temporal heterogeneity can help identify the potential impacts of climate change on different regions, such as the intensification of the urban heat island effect or the increased risk of flooding. Through scientific land management, the negative impacts of climate change can be mitigated and the adaptive capacity of societies increased. Land use efficiency studies also address the rational use and conservation of land resources. For example, sustainable management of agricultural land can ensure stable crop yields and reduce the risk of land erosion. In addition, research can help optimize the use of water resources and protect key ecosystems such as forests and wetlands (Su & Jiang, 2021).

Research on land-use efficiency and spatial and temporal heterogeneity needs to take environmental considerations into account, as land management decisions directly affect ecosystem health, resource sustainability and climate change adaptation. By integrating these environmental impacts, sustainable land management and resource planning can be better realized to balance the goals of socio-economic development and environmental protection.

5.3. SLM and Resource Planning Applications

The study of land use efficiency and spatial and temporal heterogeneity not only contributes to the understanding of land use patterns and changes, but also provides guidance for practical applications in sustainable land management and resource planning.

The study of land use efficiency and spatial and temporal heterogeneity helps urban planners to better understand the impact of urbanization on land use. Based on the results of the study, urban development policies can be formulated to optimize land use, improve the efficiency of urban infrastructure, reduce the urban heat island effect and improve air quality, thereby achieving sustainable urban development. In the field of agriculture, land-use efficiency research can help to improve the utilization of agricultural land, increase the yield of agricultural products, and reduce land erosion and resource wastage. This is critical for food security, ensuring adequate food supplies to meet the needs of a growing global population. By studying land-use efficiency and spatial and temporal heterogeneity, critical areas of natural ecosystems can be identified and measures can be taken to protect and restore these ecosystems. This includes important ecological function areas such as wetlands, forests, rivers, etc., which help maintain ecological balance and biodiversity (Li, Li, Zhou, Shi, & Zhu, 2012). The land use and conservation of these ecosystems is a major concern for the future of the country. Considering climate change scenarios, research on land use efficiency can help policy makers identify vulnerable land use patterns and take appropriate measures to cope with climate change impacts. This may include changes in agricultural practices, shoreline management, urban planning, etc. to mitigate the adverse effects of climate change on land use. Increased land use efficiency contributes to the sustainable management of resources, including water resources, soils, forests, wildlife, and so on. By managing these resources more efficiently, their sustainable use can be ensured while reducing environmental pressures. The results of research on land use efficiency and spatial and temporal heterogeneity can provide government decision makers with important information about land management and planning. This information can be used to formulate policies, regulations and resource allocation strategies to achieve a balance between sustainable land management and socio-economic development (X. Xie, Fang, Xu, He, & Li, 2021).

Research on land-use efficiency and spatial and temporal heterogeneity provides strong support for sustainable land management and resource planning in a variety of fields. These applications not only help to address today's environmental and resource challenges, but also contribute to the promotion of sustainable socio-economic development, the maintenance of ecological balance and the realization of sustainable resource use.

5.4. Limitations and Uncertainties of the Study

While studies of land use efficiency and spatio-temporal heterogeneity have provided important insights in sustainable land management and resource planning, they also have some limitations and uncertainties that need to be recognized and considered:

1) Data uncertainty: The geographic data and remotely sensed imagery used for the study may have varying degrees of error and uncertainty. The quality and accuracy of the data may be affected by acquisition methods, sensor performance and processing, which may lead to inaccuracies in the analyzed results.

2) Data availability: Access to land-use data may be limited, especially in some geographical areas or time periods. This may lead to limited spatial and temporal coverage of the study, which may not fully reflect the real situation of land use change (S. He et al., 2020).

3) Model assumptions: In spatial analysis models and time-series analyses, it is often necessary to make assumptions, for example, about the drivers of land- use change and model parameters. These assumptions may have an impact on the accuracy of the model (J. He & Yang, 2023).

4) Lack of synthesis: Studies on land use efficiency and spatio-temporal heterogeneity usually focus on specific aspects, such as economic efficiency, environmental impacts or social factors, but seldom manage to synthesize the

complex interrelationships of these factors. This may result in important factors being overlooked in actual land management decisions.

5) Lack of socio-economic factors: Studies often focus on the physical and ecological aspects of land use, but may overlook the importance of socio- economic factors. Land use decisions are often influenced by policy, market and social factors, which need to be considered more comprehensively.

6) Uncertainty in future projections: Although models can be used to predict future land use changes, these projections are usually accompanied by uncertainty. Factors such as future social, economic and climate change may lead to model prediction errors.

7) Policy implementation and social acceptance: Even with the support of scientific research, the implementation of land use policies and social acceptance can be challenging. Social, cultural and political factors may affect the actual implementation of land management decisions (Cao, Zhou, Wu, Wang, & Xu, 2022).

Taking these limitations and uncertainties into account, researchers and policy makers need to act on the basis of research on land-use efficiency and spatio-temporal heterogeneity, and interpret and utilize the results carefully. Further research and data collection may help to reduce uncertainty and improve the scientific basis for land management decisions.

6. Conclusion

6.1. Summary of Key Findings

There are various methods for the study of land use efficiency and spatio- temporal heterogeneity, including remote sensing technology, GIS analysis, time series analysis, spatial analysis modeling, etc. Each method has its own advantages and limitations, and can be selected and combined according to the research questions and data availability. Land use efficiency analysis under the time dimension reveals key factors for historical trends and future projections, and helps to plan sustainable land management strategies. Studies under the spatial dimension compare and analyze land use patterns in different areas and regions, emphasizing the differences between urban and rural areas and the evolution of regional land use patterns.

Coupled spatio-temporal heterogeneity analysis cases demonstrate research applications in different geographic regions and points in time, including real- world examples of the impacts of urbanization on land use, natural resource management and climate change adaptation.

6.2. Recommendations for Future Research

Future research could explore more integrated research methods to gain a deeper understanding of the complex relationship between land use efficiency and spatio-temporal heterogeneity. This includes integrating different data sources and models to analyze land use issues more comprehensively. Focusing on the impacts of climate change on land use and exploring more integrated and comprehensive sustainable land management strategies will help to address the challenges of climate change while protecting ecosystems and maintaining resource sustainability. Further in-depth study of land use efficiency in different regions and geographical contexts to identify regional variability and best practices. Future research could extend to the impacts of land-use efficiency and spatial and temporal heterogeneity on social and economic development, in order to gain a more comprehensive understanding of the integrated benefits of land management.

The coupled study of land utilization and spatial heterogeneity enables better responses to the challenges facing land resource management and planning and the realization of sustainable land use and management. It will help to better protect the natural environment, improve resource utilization efficiency and promote sustainable socio-economic development.

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