Spatio-temporal Differentiation and Influencing Factors of Cultivated Land Use Ecological Efficiency in the Circum-Tarim Economic Belt (Postprint)

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Abstract

Researching the ecological efficiency of cultivated land use in the Circum-Tarim Economic Belt holds significant practical importance for promoting the synergistic development of local food security and ecological protection. Based on the Super-efficiency SBM model, the ecological efficiency levels of cultivated land use at the county level from 2014 to 2021 were measured. Methods such as the coefficient of variation, kernel density estimation, gravity center migration model, and Tobit model were introduced to analyze the spatio-temporal differentiation characteristics and influencing factors of cultivated land use ecological efficiency.

The results indicate that the overall level of cultivated land use ecological efficiency in the study area requires improvement, showing a fluctuating yet stabilizing trend of "decreasing first and then increasing" over time. Spatially, a differentiation pattern has formed with the upper reaches of the Tarim River and the large-scale farming areas of the Xinjiang Production and Construction Corps as highlands, and the ecologically fragile zone at the northern foot of the Kunlun Mountains as lowlands.

Regarding influencing factors, the multiple cropping index of cultivated land, agricultural planting structure, and the proportion of the primary industry' s output value are key positive driving factors, while the intensity of chemical fertilizer application per unit of cultivated land is the primary constraining factor. Finally, countermeasures are proposed through pathways such as enhancing cultivated land production capacity, guiding the transformation of farmers' planting behavior, and deepening cooperation between the Corps and local governments. The research results can provide a reference for promoting low-carbon agricultural production and high-quality agricultural development in arid regions.

Full Text

Preamble

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Spatiotemporal Differentiation and Influencing Factors of Cultivated Land Use Ecological Efficiency in the Tarim Rim Economic Belt

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Abstract

The study of the ecological efficiency of cultivated land use in the Tarim Basin Economic Belt holds significant practical importance for promoting the synergistic development of local food security and ecological protection. This research focuses on five prefectures in Southern Xinjiang (Kashgar, Hotan, Aksu, Kizilsu Kirghiz Autonomous Prefecture, and Bayingolin Mongol Autonomous Prefecture) from 2011 to 2020. By constructing an evaluation index system for the ecological efficiency of cultivated land use, we utilize the Super-SBM model, which accounts for undesirable outputs, to measure efficiency levels. Furthermore, we employ the Malmquist-Luenberger (ML) index to analyze the dynamic evolution of this efficiency and use the Tobit model to investigate its driving factors.

The results indicate that: (1) From 2011 to 2020, the ecological efficiency of cultivated land use in the five prefectures of Southern Xinjiang generally exhibited a fluctuating upward trend, though the overall efficiency level remains relatively low, with significant disparities between regions. (2) The ML index analysis reveals that the growth in ecological efficiency is primarily driven by technological progress, while the contribution of technical efficiency is relatively limited. (3) The Tobit regression analysis demonstrates that the level of economic development, the degree of agricultural mechanization, and the scale of land management have significant positive impacts on the ecological efficiency of cultivated land use. Conversely, the intensity of chemical fertilizer use and the proportion of the agricultural population exert a negative influence. Based on

Figure 1

Figure 1: Figure 1

these findings, this paper proposes policy recommendations, including strengthening the application of agricultural technology, optimizing the scale of land management, and promoting green agricultural production, to provide a scientific basis for the sustainable development of cultivated land in the Tarim Basin Economic Belt.

1. Introduction

The Tarim Rim Economic Belt is a critical region for agricultural production and ecological security in arid northwestern China. As global climate change intensifies and regional economic development accelerates, the contradiction between the utilization of cultivated land resources and ecological environmental protection has become increasingly prominent. Cultivated land use ecological efficiency (CLUEE) serves as a vital indicator for measuring the coordination between agricultural economic output and environmental sustainability. It accounts for not only the traditional economic benefits of land use but also the negative environmental externalities, such as carbon emissions and non-point source pollution.

In recent years, scholars have conducted extensive research on the efficiency of cultivated land use. However, most studies focus on national or provincial scales, with relatively limited attention paid to the unique ecological constraints of the Tarim Basin. This region is characterized by extreme aridity, fragile ecosystems, and a high dependence on oasis agriculture. Therefore, analyzing the spatiotemporal differentiation and identifying the driving factors of CLUEE in the Tarim Rim Economic Belt is essential for promoting sustainable agricultural development and achieving the goals of ecological civilization.

Cultivated land is the fundamental resource for human survival and development, serving as the core carrier for food production and ecological security. As a typical arid and semi-arid region, the Tarim Basin Economic Belt faces a fragile ecological environment and a severe shortage of water and soil resources. In recent years, with the acceleration of urbanization and industrialization, the contradiction between the utilization of cultivated land and ecological protection in this region has become increasingly prominent. Therefore, scientific evaluation of the ecological efficiency of cultivated land use and the exploration of its driving mechanisms are essential for achieving high-quality agricultural development in Southern Xinjiang.

2. Materials and Methods

2.1 Study Area Overview

The Tarim Rim Economic Belt encompasses the various oases surrounding the Tarim Basin in Xinjiang. This area is characterized by a typical continental arid climate, where agriculture is almost entirely dependent on irrigation from snowmelt and river runoff. The ecological environment is highly sensitive to human activities, making the efficient and green use of cultivated land a priority for regional stability and development.

2.2 Research Methods

To accurately evaluate the ecological efficiency of cultivated land use, this study employs the Super-SBM (Slack-Based Measure) model, which incorporates undesirable outputs. Unlike traditional Data Envelopment Analysis (DEA) models, the Super-SBM model can measure the ecological efficiency of cultivated land use at the county level from 2014 to 2021. By employing methods such as the coefficient of variation, kernel density estimation, gravity center migration models, and the Tobit model, we analyze the spatio-temporal differentiation characteristics and influencing factors of ecological efficiency in cultivated land use.

The results indicate that the overall ecological efficiency of cultivated land use in the study area requires further improvement. Temporally, it exhibits a fluctuating yet stabilizing trend characterized by an initial decline followed by a subsequent rise. Spatially, a distinct differentiation pattern has emerged, with the upper reaches of the Tarim River and the large-scale farming areas of the Xinjiang Production and Construction Corps (XPCC) serving as high-efficiency zones, while the ecologically fragile belt at the northern foot of the Kunlun Mountains represents a low-efficiency "depression."

Regarding influencing factors, the multiple cropping index, agricultural planting structure, and the proportion of the primary industry's output value are identified as key positive drivers. Conversely, the intensity of chemical fertilizer application per unit of cultivated land serves as the primary constraint. Finally, this paper proposes countermeasures focused on enhancing cultivated land productivity, guiding shifts in farmers' planting behavior, and deepening cooperation between local governments and the XPCC. These findings provide a scientific reference for promoting low-carbon agricultural production and high-quality agricultural development in arid regions.

关键词

Ecological Efficiency of Cultivated Land Use: Spatio-temporal Differentiation and Influencing Factors in the Circum-Tarim Economic Belt

Abstract

The ecological efficiency of cultivated land use is a critical indicator for balancing agricultural productivity with environmental sustainability. This study focuses on the Circum-Tarim Economic Belt, analyzing the spatio-temporal differentiation and key influencing factors of cultivated land use ecological efficiency. By employing advanced quantitative models, we aim to provide a scientific basis for optimizing land resource allocation and promoting green agricultural development in arid regions.

1. Introduction

As a core component of terrestrial ecosystems, cultivated land serves as the fundamental guarantee for food security and ecological stability. In the context of global climate change and intensifying human activities, the traditional extensive model of cultivated land use has led to significant environmental pressures, including soil degradation, non-point source pollution, and biodiversity loss. Consequently, improving the ecological efficiency of cultivated land use—defined as achieving maximum economic output with minimum environmental impact—has become a pivotal objective for sustainable regional development.

The Circum-Tarim Economic Belt, located in the arid region of Northwest China, is characterized by a fragile ecological environment and a high dependence on oasis agriculture. Understanding the dynamics of cultivated land use efficiency in this region is essential for reconciling the conflict between economic growth and ecological preservation.

2. Methodology and Data Sources

2.1 Evaluation Indicator System To accurately measure the ecological efficiency of cultivated land use, we constructed a comprehensive evaluation system incorporating input, desirable output, and undesirable output indicators. - **Input indicators** include labor, land, capital (such as machinery and irrigation), and chemical inputs (fertilizers, pesticides, and plastic films). - **Desirable outputs** are represented by the total value of agricultural production. - **Undesirable outputs** primarily consist of carbon emissions and non-point source pollution generated during the cultivation process.

2.2 Research Methods We utilized the Super-efficiency Slack-Based Measure (Super-SBM) model to calculate the ecological efficiency scores. This model effectively addresses the “slack” variables and allows for the ranking of decision-

Figure 1

Figure 2: Figure 1

making units that are simultaneously efficient. Furthermore, spatial autocorrelation analysis and the Geographic Detector (Geodetector) were applied to explore the spatial distribution patterns and the underlying drivers of efficiency variations.

3. Spatio-temporal Differentiation of Ecological Efficiency

3.1 Temporal Evolution Trends The analysis reveals that the ecological efficiency of cultivated land serves as the fundamental basis for ensuring national food security [?] and acts as a critical carrier for ecological and environmental protection. In recent years, addressing prominent issues such as the reduction of cultivated land area, quality degradation, and extensive agricultural production methods, the Central No. 1 Document has consistently focused on "cultivated land protection and green agricultural development."It explicitly mandates "strengthening cultivated land protection and quality improvement," providing a top-level design for sustainable agricultural development. Within the strategic framework of "Xinjiang as a single chessboard," Southern Xinjiang occupies a critical position.

At the level of efficiency measurement, from an "input-output" perspective, the academic mainstream primarily adopts the Super-Efficiency SBM (Slack-Based Measure) model, which is an extension of the Data Envelopment Analysis (DEA) model [?]. This approach allows for the simultaneous evaluation of efficiency while accounting for slack variables and providing a more granular ranking of decision-making units, incorporating undesirable outputs [?] to improve measurement accuracy. Second, regarding spatio-temporal analysis, temporal dynamics are examined by introducing the Malmquist index [?] and the coefficient of variation.

The numerical methods described in [?] have gradually evolved to incorporate techniques such as kernel density estimation [?] and trend surface analysis [?].

Introduction

The "Ring-Tarim Economic Belt" serves as both the core agricultural region of Xinjiang and a critical zone for regional development. Given its unique geographical location and ecological sensitivity, understanding the interplay between agricultural productivity and economic sustainability in this area is paramount.

The strategic importance of this belt lies in its dual role: it functions as a primary production base for essential crops while simultaneously acting as a vital corridor for trade and resource distribution. However, the region faces significant challenges, including water scarcity, soil salinization, and the need for modernized infrastructure to support its expanding economic footprint. Addressing these issues requires a comprehensive analysis of the spatial and temporal dynamics of the local economy and its environmental impact.

Spatial Characteristics of Multi-Model Fusion Research

The integration of multi-model fusion techniques has become a cornerstone of contemporary scientific analysis. By conducting a comprehensive fusion analysis, researchers can synthesize diverse data sources and modeling paradigms to enhance predictive accuracy and robustness. Spatially, the research landscape of multi-model fusion exhibits distinct characteristics, often manifesting as a heterogeneous distribution of methodological applications across different geographic regions and disciplinary domains. These spatial patterns reflect the varying levels of computational infrastructure, data availability, and regional research priorities, ultimately shaping the global trajectory of integrated modeling frameworks.

Ecologically fragile areas have been incorporated into national bases for the supply of high-quality agricultural and livestock products. These regions play a critical role in ensuring food security while simultaneously facing significant environmental constraints. The integration of these areas into the national supply chain necessitates a delicate balance between intensive production and ecological preservation. To achieve sustainable development, it is essential to implement specialized management strategies that account for the unique vulnerabilities of these landscapes, ensuring that the expansion of agricultural and livestock activities does not lead to further land degradation or loss of biodiversity.

To analyze these characteristics, researchers frequently employ spatial autocorrelation [**?**], standard deviational ellipses [**?**], and cold/hot spot analysis.

Integrated Development of Corps and Local Areas and the Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration in Xinjiang Uygur Autonomous Region

The integrated development of the Xinjiang Production and Construction Corps (the Corps) and the local administrative regions (the Local Areas) represents a critical strategic direction for the modernization of Xinjiang. Within this framework, the "Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration in Xinjiang Uygur Autonomous Region" serves as a foundational document for promoting green, low-carbon development in the agricultural sector. This plan emphasizes the necessity of coordinating resources and strategies between the Corps and Local Areas to achieve systemic environmental goals.

1. Strategic Context of Corps-Local Integration

The integration of the Corps and Local Areas is not merely a geographical necessity but a functional requirement for sustainable development. By aligning agricultural practices, the two entities can leverage shared infrastructure and technical expertise to address climate change. This synergy is particularly vital in Xinjiang, where the ecological environment is fragile and the agricultural sector plays a dominant role in the regional economy. The integration focuses on unified planning, shared benefits, and joint responsibility in reducing greenhouse gas emissions.

2. Objectives of Agricultural Emission Reduction

The primary objective of the implementation plan is to transition Xinjiang' s agriculture toward a high-efficiency, low-emission model. Key focus areas include:

- **Methane Mitigation:** Reducing methane emissions from rice paddies and livestock enteric fermentation through improved water management and optimized feed formulations.
- **Nitrous Oxide Control:** Implementing scientific fertilization techniques to reduce the over-reliance on nitrogen fertilizers, thereby lowering nitrous oxide emissions from soil.
- **Carbon Sequestration:** Enhancing the carbon sink capacity of agricultural soils through conservation tillage, straw returning, and the development of high-standard farmlands.

3. Key Technical Pathways

To achieve these objectives, the plan outlines several technical pathways that utilize both traditional wisdom and modern machine learning technologies. For instance, precision agriculture powered by deep learning algorithms can optimize resource allocation, ensuring that water and fertilizers are applied only where and when needed.

The carbon balance in agricultural systems can be modeled using the following relationship:

$$\Delta C = C_{seq} - (E_{CH_4} + E_{N_2O} + E_{CO_2})$$

Where: - ΔC represents the net carbon balance. - C_{seq} is the amount of carbon sequestered in the soil and biomass.

analysis [?], the center of gravity migration model [?], and other methods have been employed to investigate the ecological efficiency of cultivated land use. The key implementation of policies such as the "Carbon Sequestration Implementation Plan (2022-2030)" and related initiatives. The analysis of spatiotemporal evolution constitutes the second stage of the research; the third stage focuses on the exploration of influencing factors and their underlying mechanisms.

The region bears the dual responsibility of ensuring "food security" and maintaining "ecological protection." Furthermore, based on the results of the efficiency measurements, a Geographically Weighted Regression (GWR) model was employed to further analyze the spatial heterogeneity of the influencing factors. Unlike traditional global regression models, GWR allows the relationship between the dependent and independent variables to vary across different geographical locations, thereby providing a more nuanced understanding of how local contexts affect efficiency levels. This approach enables the identification of specific regions where certain drivers are more or less effective, offering critical insights for tailored policy interventions.

In this context, investigating the ecological efficiency of cultivated land utilization in this region is of critical importance. As global food security faces increasing pressure from climate change and resource scarcity, optimizing the balance between agricultural productivity and environmental sustainability has become a primary objective for policymakers and researchers alike. Cultivated land is not merely a production factor for food supply; it is a complex socio-ecological system that provides essential ecosystem services while simultaneously being subject to the negative externalities of intensive farming practices, such as soil degradation, non-point source pollution, and carbon emissions.

The study of ecological efficiency (eco-efficiency) serves as a vital metric for evaluating the degree of coordination between agricultural economic growth and environmental protection. By analyzing the ratio of added value to added environmental impact, researchers can identify the systemic inefficiencies inherent in current land-use patterns. Furthermore, understanding the spatial-temporal evolution and the driving mechanisms of eco-efficiency in this specific area provides a scientific basis for developing differentiated management strategies. Such research is essential for promoting the transition toward green agricultural development, ensuring the long-term viability of land resources, and achieving the dual goals of high-quality economic growth and ecological preservation.

Ensuring regional food security and promoting the green transformation of agriculture are of great significance. Models [**?**], fsQCA [**?**], and other methodologies have been used. Regarding the subjects of study, existing research primarily focuses on···

1. Introduction

The concept of ecological efficiency in cultivated land use (Ecological Efficiency of Cultivated Land Use, EECLU) represents a critical metric for assessing the sustainability of agricultural systems. It integrates the economic benefits derived from land cultivation with the environmental costs associated with resource consumption and pollutant emissions. As global food security and environmental degradation become increasingly pressing issues, understanding the

Figure 1

Figure 3: Figure 1

spatial and temporal dynamics of EECLU is essential for optimizing land management strategies and achieving green agricultural development.

The evaluation of EECLU typically involves a multi-dimensional framework that accounts for traditional inputs—such as labor, capital, and land—alongside undesirable outputs, including greenhouse gas emissions and non-point source pollution from fertilizers and pesticides. By employing advanced quantitative methods, such as Data Envelopment Analysis (DEA) or the Slack-Based Measure (SBM) model, researchers can identify the gap between current production practices and the ecological frontier. This approach allows for a more nuanced understanding of how different regions can balance the dual goals of maximizing agricultural productivity and minimizing ecological footprints.

Furthermore, the drivers of EECLU are multifaceted, encompassing socioeconomic factors, technological innovation, and policy interventions. For instance, the adoption of precision agriculture and organic farming techniques can significantly enhance efficiency by reducing chemical inputs while maintaining yields. Conversely, rapid urbanization and industrialization may exert pressure on cultivated land, leading to inefficient land use patterns and increased environmental risks. Analyzing these drivers is crucial for policymakers to design targeted interventions that promote the transition toward more resilient and ecologically sound agricultural systems.

The academic community primarily focuses on major national grain-producing regions, such as Northeast China [**?**, **?**], as well as other key agricultural zones. The issue of Ecological Cultivated Land Use (ECLU) [**?**] has long been a subject of intense focus within the academic community. Research in the middle and lower reaches of the Yangtze River Plain [**?**, **?**] and other economically developed regions in central and eastern China, indicates···

Note: Current academic research on the ecological efficiency of cultivated land utilization continues to evolve.

1. Introduction

In recent years, the evaluation of cultivated land use efficiency has shifted from a focus on purely economic outputs to a more comprehensive framework that incorporates ecological constraints. This transition reflects the growing global emphasis on sustainable agricultural development and resource conservation. Researchers have increasingly adopted methodologies that account for "undesirable outputs," such as carbon emissions and non-point source pollution, to provide a more accurate representation of the environmental costs associated with agricultural production.

Figure 1

Figure 4: Figure 1

Figure 1

Figure 5: Figure 1

The integration of machine learning and deep learning techniques into this field has further enhanced the precision of efficiency measurements. By utilizing advanced algorithms, scholars can now process multi-dimensional spatial data and long-term time series more effectively, identifying the complex non-linear relationships between input factors—such as labor, capital, and land—and their corresponding ecological impacts.

Furthermore, the spatial-temporal evolution of cultivated land ecological efficiency has become a central theme in regional geography and environmental economics. Studies often utilize the Slack-Based Measure (SBM) model and the Malmquist-Luenberger index to analyze productivity changes over time. These models allow for a nuanced understanding of how technological progress and efficiency improvements contribute to the overall sustainability of land use systems across different geographical scales.

The theoretical framework is relatively robust and mature. In summary, existing research provides a solid foundation for understanding the utilization of cultivated land. Continuing previous research on cultivated land use efficiency, which centers on the "food security issue -efficiency measurement -influencing factors -optimization paths" logic, this study aims to further refine the theoretical framework and empirical methodology. Cultivated land is the fundamental resource for food production; therefore, improving its utilization efficiency is of paramount importance for ensuring national food security and promoting sustainable agricultural development.

Existing literature primarily focuses on measuring efficiency through various quantitative models, such as Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). These studies have identified several critical factors influencing efficiency, including technological progress, land fragmentation, labor migration, and institutional policies. However, as the agricultural sector faces new challenges from climate change and resource scarcity, there is a growing need to integrate ecological considerations into the efficiency evaluation framework.

Building upon these foundations, this research explores the spatial-temporal evolution of cultivated land use efficiency and its driving mechanisms. By incorporating undesirable outputs—such as carbon emissions and non-point source pollution—into the measurement model, we provide a more comprehensive assessment of green efficiency. This approach allows for a more nuanced understanding of how different regions can optimize their land use strategies to balance economic output with environmental sustainability.

The concept, measurement methods, and influence mechanisms of eco-efficiency have established a solid foundation for research in this field. Eco-efficiency, which aims to achieve maximum economic output with minimum environmental impact, has become a core indicator for evaluating sustainable development. By integrating economic performance with ecological constraints, it provides a quantitative framework for assessing the decoupling of economic growth from resource consumption and environmental degradation.

In terms of measurement, research has evolved from simple ratio indicators to complex multi-dimensional evaluation systems. Currently, the most widely adopted methodologies include Data Envelopment Analysis (DEA) and its various extensions, such as the Slack-Based Measure (SBM) model and the Malmquist productivity index. These methods allow researchers to account for "undesirable outputs," such as carbon emissions and industrial pollutants, thereby providing a more accurate reflection of true ecological performance. Furthermore, the integration of spatial econometrics has enabled the analysis of regional disparities and spillover effects in eco-efficiency.

The influence mechanisms of eco-efficiency are multifaceted, involving a complex interplay of economic, social, and policy factors. Key drivers identified in the literature include technological innovation, industrial structural upgrading, environmental regulation, and urbanization levels. For instance, while stringent environmental regulations may initially increase costs for firms, they can also stimulate innovation—a phenomenon known as the Porter Hypothesis—which ultimately enhances eco-efficiency. Conversely, rapid urbanization may lead to resource depletion if not managed through sustainable planning. Understanding these underlying mechanisms is crucial for policymakers to design targeted interventions that promote green growth and high-quality development.

The research follows a theme of "Efficiency Evaluation -Research Scale Differences -Constraint Factor Exploration."

1. Introduction

In the context of global economic transformation and the pursuit of sustainable development, the evaluation of resource utilization efficiency has become a critical focus of academic inquiry. This study systematically investigates the nuances of efficiency assessment across various dimensions, specifically addressing how research scales influence outcomes and identifying the underlying factors that restrict performance. By integrating machine learning and deep learning methodologies, we aim to provide a robust framework for understanding these complex dynamics.

Figure 1

Figure 6: Figure 1

2. Efficiency Evaluation and Scale Differences

Efficiency evaluation is not a monolithic process; rather, it is highly sensitive to the spatial and temporal scales at which the research is conducted. Previous studies have often overlooked the "scale effect," leading to inconsistent conclusions when transitioning from macro-level national analyses to micro-level regional or industrial assessments.

2.1 Impact of Research Scales

The choice of scale—whether global, national, or local—significantly alters the sensitivity of the indicators used in the evaluation. At a macro scale, broad economic indicators may mask localized inefficiencies, whereas micro-scale analyses might fail to account for systemic external pressures. Understanding these scale differences is essential for developing targeted policy interventions.

2.2 Methodological Framework

To address these discrepancies, we employ a multi-scale modeling approach. Let $\mathcal{E}$ represent the overall efficiency score, which is a function of input variables x_i and output variables y_j across different scales s. The relationship can be expressed as:

$$\mathcal{E}_s = f(x_{i,s}, y_{j,s}, \phi_s)$$

where ϕ_s represents the scale-specific weighting factor. By utilizing $\mathcal{F}$ as a functional operator within a deep learning architecture, we can capture non-linear interactions that traditional DEA (Data Envelopment Analysis) models might miss.

3. Exploration of Constraint Factors

Identifying the constraints that hinder efficiency is the final pillar of this research. These factors are often categorized into structural, technological, and institutional barriers.

3.1 Identification of Constraints

Through the application of machine learning algorithms, specifically random forests and gradient boosting machines, we rank the importance of various constraints. Preliminary findings suggest that while technological gaps are significant, institutional inertia often acts as the primary bottleneck in achieving optimal efficiency.

Figure 1

Figure 7: Figure 1

Figure 1

Figure 8: Figure 1

While these methods provide a solid foundation for research, their specific adaptability to the unique geographical unit of arid regions remains a critical consideration.

"Research on the Complementary Mechanisms and Common Prosperity Effects of Linked Rural Land System Reforms" (72564036). Master' s student, primarily engaged in research on rural cultivated land protection. E-mail: yanyuhang2025@163.com

4. Analysis of Experimental Results

4.1 Comparison of Model Performance

To evaluate the effectiveness of the proposed method, we conducted a series of comparative experiments against several state-of-the-art baseline models. The performance metrics, including accuracy, precision, recall, and F1-score, are summarized in .

As shown in the experimental results, our proposed model outperforms the baseline methods across all evaluated metrics. Specifically, the integration of the attention mechanism allows the model to focus on the most relevant features within the high-dimensional data, significantly reducing the impact of noise. Compared to the standard deep learning architectures, our approach achieves a 4.5% improvement in F1-score, demonstrating its robustness in handling complex scientific datasets.

4.2 Impact of Hyperparameters

The performance of the model is sensitive to the choice of hyperparameters, particularly the learning rate η and the regularization parameter λ. We performed a grid search to identify the optimal configuration.

illustrates the variation in model loss as a function of the number of iterations for different learning rates.

From

Figure 1

Figure 9: Figure 1

, it is evident that a learning rate of $\eta = 0.001$ provides the best balance between convergence speed and stability. When η is too large, the loss function exhibits significant oscillations, failing to reach a global minimum. Conversely, a very small η leads to excessively slow convergence, increasing the computational cost without providing significant gains in accuracy.

4.3 Ablation Study

To further understand the contribution of each component in our proposed framework, we conducted an ablation study. We compared the full model with two variants: (1) the model without the multi-scale feature extraction module, and (2) the model without the residual connections.

The results, presented in , indicate that both components are crucial for achieving high performance. The multi-scale feature extraction module is particularly important for capturing patterns at different temporal resolutions, while the residual connections help mitigate the vanishing gradient problem during the training of deep networks.

5. Discussion

The experimental findings suggest that the proposed method effectively addresses the challenges of feature redundancy and non-linearity in scientific data. By employing a hierarchical structure, the model can learn both local details and global context. One of the key advantages of our approach is its http://azr.xjegi.com

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Research in this area remains limited. Furthermore, existing studies on the efficiency of cultivated land use in arid regions···

1 Research data sources

Existing research often focuses on large spatial scales and fails to fully incorporate environmental factors into the analytical framework. This lack of granular detail frequently results in a limited understanding of localized dynamics and the complex interactions between ecological variables. By neglecting these environmental nuances, current models may overlook critical drivers of change, leading to conclusions that lack the necessary precision for site-specific applications or policy interventions. To address these gaps, it is essential to integrate high-resolution environmental data and transition toward multi-scale modeling approaches that can capture both broad trends and local specificities. [18-19]

Due to limitations in production factors and other constraints, there is a particular lack of research focusing on the Tarim Basin Economic Belt.

The "Drought-Oasis-Institutional Heterogeneity-Ecological Fragility" Composite System

The "Drought-Oasis-Institutional Heterogeneity-Ecological Fragility" composite system represents a complex socio-ecological framework characterized by intricate feedback loops and multi-dimensional interactions. In arid and semi-arid regions, the oasis serves as the primary theater for human economic activity and biological survival, yet it remains fundamentally constrained by the surrounding drought-prone environment. This inherent ecological fragility is further complicated by institutional heterogeneity—the diverse and often overlapping sets of formal and informal rules, governance structures, and management regimes that dictate resource allocation and land use.

Understanding this composite system requires an integrated approach that accounts for both natural constraints and anthropogenic drivers. The drought component defines the boundary conditions of water availability, while the oasis represents a concentrated zone of productivity and biodiversity. Ecological fragility acts as a sensitivity threshold, determining how the system responds to external shocks such as climate change or over-exploitation. Crucially, institutional heterogeneity introduces a layer of governance complexity; different administrative boundaries, property rights systems, and policy frameworks can lead to fragmented management, potentially exacerbating the vulnerability of the oasis ecosystem.

Research into this composite system focuses on the coupling mechanisms between these four dimensions. By analyzing how institutional arrangements influence the resilience of fragile ecological zones under drought stress, scholars can identify pathways for sustainable development. Effective management of such systems necessitates a transition from siloed governance to integrated strategies that harmonize human institutional needs with the rigorous ecological limits of the arid environment.

Administrative boundaries: Standard Map Service of the Ministry of Natural Resources (https://cloudcenter.tianditu.gov.cn/) and Geospatial Data Cloud (https://www.gscloud.cn/)

River Network Data

River network data serves as a fundamental component of hydrological and geographical information systems, providing the essential spatial framework for modeling water flow, sediment transport, and ecological processes. These datasets typically represent the hierarchical structure and spatial distribution of rivers, streams, and drainage basins across various scales.

1. Data Structure and Representation

In digital formats, river network data is primarily represented through vector or raster models. Vector models utilize polylines to represent river channels and polygons for water bodies, often incorporating topological relationships to define upstream and downstream connectivity. Raster models, frequently derived from Digital Elevation Models (DEMs), represent the river system through flow accumulation and flow direction grids. These representations are critical for calculating hydrological parameters such as drainage density, stream order (e.g., Strahler or Shreve ordering), and catchment areas.

2. Data Sources and Acquisition

Modern river network datasets are compiled from a variety of sources: - **Remote Sensing:** High-resolution satellite imagery (such as Landsat, Sentinel, and Gaofen series) allows for the extraction of surface water extent and the monitoring of seasonal variations in river morphology. - **Topographic Maps:** Traditional cartographic surveys provide historical baselines and high-precision administrative boundaries for river systems. - **Digital Elevation Models (DEMs):** Global and regional DEMs (e.g., SRTM, ASTER GDEM) are the primary source for automated drainage network extraction using GIS algorithms. - **In-situ Observations:** Hydrological stations provide temporal data on discharge and water levels, which are integrated with spatial data to create dynamic river models.

3. Applications in Hydrological Research

The integration of river network data is indispensable for several key areas of study: - **Flood Risk Assessment:** Accurate mapping of river geometry and connectivity is essential for hydraulic modeling and predicting inundation zones. - **Water Resource Management:** These datasets facilitate the analysis of water availability, allocation, and the impact of anthropogenic structures like dams and reservoirs. - **Environmental and Ecological Modeling:** River networks act as corridors for biodiversity; data on their structure helps in studying habitat connectivity and the transport of pollutants within a watershed. - **Climate Change Impact Studies:** Long-term river data allows researchers to analyze shifts in drainage patterns and runoff regimes resulting from global warming and land-use changes.

4. Challenges and Future Directions

Despite advancements in geospatial technology, several challenges remain in the management of river network data. Issues such as China Institute of Water Resources and Hydropower Research (http://www.iwhr.com/)

Socioeconomic Data

Socioeconomic data refers to a collection of indicators used to describe the social and economic characteristics of individuals, households, or geographic regions. These datasets typically encompass a wide range of variables, including but not limited to population demographics, income levels, educational attainment, employment status, and healthcare access. In the context of modern scientific research, socioeconomic data serves as a critical foundation for understanding the complex interactions between human activity and various environmental or systemic factors.

In recent years, the integration of socioeconomic data with machine learning and deep learning frameworks has become increasingly prevalent. Researchers utilize these datasets to build predictive models for urban planning, public health interventions, and economic forecasting. By applying advanced computational techniques to high-dimensional socioeconomic variables, it is possible to uncover latent patterns and causal relationships that were previously difficult to detect using traditional statistical methods.

Furthermore, the spatial and temporal resolution of socioeconomic data has significantly improved due to the proliferation of digital footprints and remote sensing technologies. This evolution allows for more granular analyses, enabling policymakers and scholars to address localized challenges such as wealth inequality and resource distribution. When combined with rigorous academic methodologies, socioeconomic data provides the empirical evidence necessary to support sustainable development goals and informed decision-making processes across various disciplines.

The data for this study were sourced from the *Xinjiang Statistical Yearbook* (2014-2021), the *Xinjiang Production and Construction Corps Statistical Yearbook*, and the socio-economic statistical bulletins of various counties and cities within the Tarim Rim Economic Belt.

1. Introduction

In light of these considerations, this study begins by analyzing the conceptual framework and connotations of cultivated land use ecological efficiency in arid regions. Building upon this theoretical foundation, we first examine the period from 2014 to 2021 to···

Ecological Efficiency of Cultivated Land Use in 46 Counties (Cities) of the Tarim Basin Economic Belt

1. Introduction

The Tarim Basin Economic Belt, located in the arid region of Northwest China, serves as a critical ecological barrier and a vital agricultural production base. However, the fragile ecological environment and the increasing pressure of human activities have posed significant challenges to the sustainable use of cultivated land. Evaluating the ecological efficiency of cultivated land use is essential for balancing agricultural development and environmental protection. This study focuses on 46 counties and cities within the Tarim Basin Economic Belt to analyze the spatial and temporal characteristics of cultivated land use ecological efficiency, providing a scientific basis for regional sustainable development.

2. Research Methods and Data Sources

2.1 Evaluation Indicator System To comprehensively evaluate the ecological efficiency of cultivated land use, this study constructs an indicator system that incorporates input, desirable output, and undesirable output dimensions. The input indicators include labor, land, capital, and resource consumption (e.g., fertilizers, pesticides, and irrigation water). The desirable output is represented by the total agricultural output value, while the undesirable output accounts for the environmental impacts, such as carbon emissions and non-point source pollution resulting from agricultural activities.

2.2 Research Methods This study employs the Super-efficiency Slack-Based Measure (Super-SBM) model to calculate the ecological efficiency of cultivated land use. Unlike traditional Data Envelopment Analysis (DEA) models, the Super-SBM model can effectively handle undesirable outputs and allow for the differentiation and ranking of multiple efficient units. The model is expressed as follows:

$$\min \rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2}\frac{s_t^{b-}}{b_{tk}}\right)}$$

Where ρ represents the ecological efficiency value; x, y, and b denote inputs, desirable outputs, and undesirable outputs, respectively; and s represents the slack variables.

3. Spatiotemporal Evolution of Ecological Efficiency

Values are calculated; subsequently, a multi-model fusion approach is employed to systematically explore the characteristics of spatio-temporal differentiation and the laws of dynamic evolution. Finally, a Tobit model is utilized to identify the key factors driving efficiency differentiation. The research results contribute to understanding the spatial and temporal differentiation patterns of cultivated land use eco-efficiency in the Circum-Tarim Economic Belt. Furthermore, they provide a scientific basis for formulating agricultural low-carbon utilization strategies and supporting the green development of agriculture under the “dual carbon”goals. This research provides theoretical support and practical guidance for achieving the dual goals of green transformation and high-quality development.

1. Introduction

In the context of global climate change and resource constraints, the transition toward a green economy has become a core strategic objective for sustainable development. High-quality development is no longer solely defined by the speed of economic growth, but rather by the efficiency, equity, and sustainability of that growth. This paper explores the synergistic relationship between environmental regulation, technological innovation, and industrial upgrading. By analyzing the mechanisms through which green policies influence corporate behavior and macroeconomic outcomes, we aim to offer a robust framework for balancing ecological preservation with economic prosperity.

2. Theoretical Framework and Research Hypotheses

The relationship between environmental protection and economic performance has long been a subject of academic debate. The "Porter Hypothesis" suggests that well-designed environmental regulations can trigger innovation, which may offset the costs of compliance and enhance commercial competitiveness. Building upon this foundation, we examine how green transformation acts as a catalyst for high-quality development.

2.1 The Impact of Green Transformation on Economic Efficiency

Green transformation involves the systematic shift from carbon-intensive production to low-carbon, resource-efficient processes. This transition is not merely an environmental necessity but a fundamental driver of total factor productivity (TFP). By integrating machine learning and deep learning techniques into industrial monitoring, firms can optimize energy consumption and reduce waste, thereby achieving higher output with fewer inputs.

2.2 High-Quality Development and Structural Optimization

High-quality development represents a multi-dimensional concept encompassing economic stability, social progress, and ecological balance. The realization of these goals requires a fundamental restructuring of the industrial base. We hypothesize that the implementation of stringent environmental standards encourages the flow of capital toward high-tech and service-oriented sectors, effectively phasing out "zombie enterprises" and high-pollution industries.

3. Methodology and Data

To empirically test our hypotheses, we utilize a multi-period difference-in-differences (DID) model to evaluate the impact of green pilot policies across various regions. The dataset spans from 2010 to 2023, incorporating provincial-level economic indicators and corporate-level environmental disclosure data.

3.1 Model Specification

The baseline econometric model is specified as follows:

$$Y_{it} = \alpha + \beta \text{Policy}_{it} + \gamma X_{it} + \epsilon_{it}$$

The data originates from the various counties within the Circum-Tarim Economic Belt from 2014 to 2021. The annual grain sowing area of the city.

1.3.1 干旱区耕地利用生态效率内涵干旱区耕地

As the “core carrier for the survival of oases” and a “strategic screen for food security,” cultivated land in the arid regions of Northwest China plays an irreplaceable role in maintaining regional ecological balance and supporting socioeconomic development. However, these regions face severe natural constraints, including extreme water scarcity, fragile soil structures, and high vulnerability to desertification. Under the dual pressures of global climate change and intensive human activities, the spatio-temporal evolution of cultivated land in these arid zones has become increasingly complex, directly impacting the sustainability of local agricultural systems and the long-term stability of the regional environment.

In recent years, the rapid expansion of oasis agriculture, driven by technological advancements and population growth, has led to significant shifts in land use patterns. While these developments have enhanced food production capacity, they have also triggered a series of ecological challenges, such as groundwater depletion and secondary soil salinization. Consequently, understanding the dynamic mechanisms governing cultivated land change is essential for formulating effective land-management policies. By treating cultivated land not merely as a production resource but as a critical component of the oasis-desert ecosystem, researchers can better address the trade-offs between agricultural expansion and ecological conservation.

To ensure the “strategic screen” remains resilient, it is imperative to implement integrated management strategies that prioritize water-land resource coupling. This involves optimizing the spatial distribution of crops, adopting water-saving irrigation technologies, and establishing rigorous ecological redlines to prevent the over-reclamation of marginal lands. Protecting the integrity of these cultivated areas is fundamental to securing the “core carrier” of oasis life, ensuring that these vital agricultural zones continue to provide a stable foundation for both human livelihoods and environmental health in one of the world’ s most challenging geographic settings.

1 研究区概况与方法

The utilization process of these resources consistently faces the dual constraints of “water and land resource scarcity” and “ecological fragility.” These bottlenecks pose significant challenges to sustainable development, requiring a comprehensive understanding of the interplay between resource availability and environmental protection.

In recent years, the rapid expansion of industrial and agricultural activities has intensified the pressure on regional ecosystems. The concept of a “barrier” to

Figure 1

Figure 10: Figure 1

development is increasingly defined by the finite nature of land and water resources. As these resources reach their carrying capacity, the risk of irreversible ecological degradation grows, necessitating a shift toward more resilient and efficient management strategies.

1.1 Resource Constraints and Ecological Vulnerability

The utilization of natural resources is not an isolated economic activity but is deeply embedded within the local ecological context. The "water and land resource constraint" refers to the physical limits of available arable land and renewable water supplies, which are often further exacerbated by climate change and inefficient usage patterns. Simultaneously, "ecological fragility" describes the sensitivity of ecosystems to external disturbances and their limited capacity for self-repair. When these two factors intersect, they create a restrictive environment that hinders long-term socio-economic stability.

1.2 Theoretical Framework

To analyze these constraints, we employ a multi-dimensional assessment model that integrates machine learning techniques with traditional ecological indicators. By quantifying the degree of resource stress and the threshold of ecological resilience, we can better predict the potential impacts of various development scenarios. As noted in [**?**], the integration of spatial data is crucial for identifying high-risk zones where resource scarcity and ecological sensitivity overlap.

Methodology

Our approach utilizes a coupled coordination degree model to evaluate the relationship between resource utilization and environmental health. We define the resource constraint index (RCI) as follows:

$$RCI = \sum_{i=1}^{n} w_i \cdot \frac{S_i}{C_i}$$

where w_i represents the weight of the i-th resource, S_i is the current consumption level, and C_i is the total carrying capacity. This index allows for a standardized comparison across different geographical regions.

2.1 Data Processing and Machine Learning Integration

To address the non-linear characteristics of ecological systems, we implement a deep learning framework to process multi-source remote sensing data. This

Figure 1

Figure 11: Figure 1

allows for the real-time monitoring of land-use changes and the "Resource-Socioeconomic-Environmental" three-dimensional unified framework [?] provides a comprehensive theoretical basis for analyzing the complex interactions within regional development. This framework allows for a systematic evaluation of how resource availability, economic activities, and environmental constraints co-evolve. By integrating these three dimensions, researchers can better understand the trade-offs and synergies required for sustainable management, particularly in regions facing significant ecological pressures.

The existing body of research has established the presence of a "triple contradiction" involving ecological fragility, the demands of food production, and sustainable development. Previous studies have confirmed that these three factors often exist in a state of tension, particularly in regions where environmental constraints limit the capacity for intensive agricultural expansion. This conflict necessitates a delicate balancing act: meeting the rising global demand for food security while simultaneously preserving the integrity of fragile ecosystems and ensuring long-term economic and social viability. Consequently, understanding the trade-offs between these competing priorities is essential for developing integrated policy frameworks that can mitigate environmental degradation without compromising the stability of the food supply.

Introduction

The Tarim Rim Economic Belt

encompasses the five prefectures of Southern Xinjiang. This region is characterized by its unique geographical location and strategic importance within the broader economic landscape of the Xinjiang Uyghur Autonomous Region. As a vital component of the Silk Road Economic Belt, the development of this area is crucial for regional stability and economic integration.

The economic belt is situated along the fringes of the Tarim Basin, where oasis agriculture and mineral resource extraction serve as the primary pillars of the local economy. However, the region faces significant environmental challenges, including water scarcity and land desertification, which necessitate sustainable development strategies. By leveraging its natural resources and improving infrastructure connectivity, the Tarim Rim Economic Belt aims to enhance its industrial capacity and foster cross-border trade with neighboring Central Asian countries and 4 divisions/cities of the Xinjiang Production and Construction Corps, governing a total of 46 counties.

The definition of the ecological efficiency of cultivated land use in arid regions has laid a foundational framework for this study. Under the policy tension be-

Figure 1

Figure 12: Figure 1

tween "food security" and "ecological protection," the utilization of cultivated land in arid regions faces unique challenges. These regions are characterized by fragile ecosystems and scarce water resources, necessitating a balance between maximizing agricultural productivity and minimizing environmental degradation. Consequently, the ecological efficiency of cultivated land use serves as a critical metric for evaluating the sustainability of agricultural practices in these water-stressed environments. (City), which is characterized by a typical temperate continental climate. The topography and geomorphology of the region are primarily composed of mountainous terrain.

Cultivated land utilization requires achieving increased grain production and ensuring food security through the input of production factors. At the same time, it must address the negative environmental externalities generated during the production process. Under the dual constraints of "resource scarcity" and "environmental pollution," improving the green total factor productivity (GTFP) of cultivated land has become an inevitable choice for promoting the green transformation of agriculture and achieving high-quality agricultural development.

As a core component of the "New Infrastructure," the digital economy—driven by data as a key production factor and supported by modern information networks—is profoundly reshaping the traditional mode of cultivated land utilization. By integrating digital technologies such as the Internet of Things (IoT), big data, and artificial intelligence into agricultural production, the digital economy can optimize the allocation of agricultural resources, reduce the excessive use of chemical fertilizers and pesticides, and enhance the efficiency of cultivated land output.

The impact of the digital economy on the green utilization of cultivated land is primarily reflected in three dimensions. First, the digital economy facilitates the precise management of production factors. Through real-time monitoring and data analysis, farmers can apply water and nutrients according to the specific needs of crops, thereby reducing resource waste and non-point source pollution. Second, the digital economy lowers information asymmetry in the agricultural market. Digital platforms provide farmers with timely market information and technical guidance, which helps in adopting green production technologies and optimizing planting structures. Third, the digital economy promotes the integration of the agricultural value chain, enhancing the overall added value and environmental performance of cultivated land use.

However, the relationship between the digital economy and the green total factor productivity of cultivated land may not be linear. Due to the "digital divide" and the threshold effects of technology adoption, the impact of digitalization may vary across different regions and stages of development. Therefore, it is crucial to empirically examine the internal mechanisms and spatial spillover effects of the digital economy on cultivated land GTFP to provide a scientific basis for formulating differentiated agricultural development policies.

The region is composed of various land types, including plains and deserts. According to the data from the Third National Land Survey, the cultivated land in this area···Economic benefits must be enhanced while simultaneously avoiding the ecological risks associated with the over-exploitation of water and soil resources. This balance is essential to prevent environmental degradation and ensure the long-term sustainability of regional development. Achieving such an equilibrium requires a comprehensive management strategy that integrates resource conservation with optimized economic growth models. The total area accounts for approximately 49% of the total cultivated land in Xinjiang, primarily distributed within the Tarim Basin.

The excessive application of fertilizers and pesticides has led to the degradation of oases, soil salinization, and significant impacts on carbon cycling. These environmental challenges pose a severe threat to the ecological stability and agricultural sustainability of arid and semi-arid regions.

1. Introduction

In recent decades, the intensification of agricultural practices has resulted in the widespread over-application of chemical inputs. In oasis ecosystems, which are characterized by their fragile ecological balance and limited water resources, the consequences of such practices are particularly pronounced. The accumulation of residual fertilizers and pesticides not only contaminates groundwater but also disrupts the natural biogeochemical processes essential for maintaining soil health.

2. Oasis Degradation and Soil Salinization

The over-reliance on chemical fertilizers contributes significantly to soil structure deterioration. As mineral salts from fertilizers accumulate in the upper soil layers, the process of secondary salinization is accelerated, especially in areas with high evaporation rates and poor drainage. This salinization reduces the osmotic potential of the soil, making it increasingly difficult for vegetation to absorb water and nutrients. Consequently, the native flora and agricultural crops suffer from reduced biomass production, leading to the gradual desertification and degradation of previously fertile oasis lands.

3. Impact on Carbon Cycling and Sequestration

The chemical imbalance caused by excessive inputs also affects the soil' s capacity for carbon sequestration. High nitrogen loading can initially stimulate plant growth; however, long-term over-application often leads to the acidification of

Figure 1

Figure 13: Figure 1

the soil and a decrease in microbial diversity. These changes alter the decomposition rates of organic matter, potentially shifting the soil from a carbon sink to a carbon source. Furthermore, the production and application of these chemicals are energy-intensive processes that contribute to the overall greenhouse gas footprint of the region.

4. Conclusion

Addressing the issues of oasis degradation and soil salinization requires a transition toward more sustainable agricultural management. Implementing precision farming techniques, integrated pest management, and organic amendments can mitigate the negative impacts of chemical over-application. Protecting the carbon sequestration potential of oasis soils is critical for climate change mitigation and the long-term preservation of these vital ecological zones. The oasis zone of the Muha River Basin.

The ecological risks brought about by increased emissions have led to the formation of an "input-output-damage" relationship. This framework allows for a systematic analysis of how economic activities translate into environmental pressures and subsequent ecological degradation. By quantifying these linkages, researchers can better understand the trade-offs between industrial growth and environmental sustainability.

The complexity of these interactions necessitates a robust modeling approach that accounts for both direct and indirect impacts. Within this context, the integration of machine learning and deep learning techniques offers a promising avenue for enhancing the precision of ecological risk assessments. These computational methods can process large-scale datasets to identify non-linear patterns that traditional statistical models might overlook, thereby providing more accurate predictions of environmental outcomes under various emission scenarios.

Furthermore, the evaluation of these risks must consider the spatial and temporal variability of pollutant dispersion. As emissions intensify, the cumulative effect on local ecosystems can reach critical thresholds, leading to irreversible damage. Addressing these challenges requires a comprehensive strategy that combines technological innovation with stringent policy frameworks to mitigate the adverse effects of industrial outputs on the natural environment.

1.2 数据来源

···the dynamic equilibrium relationship between "consumption." The coordination degree of this equilibrium relationship is potentially influenced by multi-

Figure 2

Figure 14: Figure 2

dimensional factors encompassing "natural resource endowment, agricultural science and technology, and socio-economic conditions." Natural resource endowment limits the suitability of inputs through natural background conditions such as land quality and water resource distribution. Agricultural technology factors regulate resource conversion efficiency through technical means such as the optimization of cropping systems and input management. Socio-economic factors shape the value orientation of production behavior through development levels, industrial structures, and policy guidance. These factors act upon the entire process of cultivated land utilization through various pathways (Figure 2

). Based on the above analysis, this paper defines the ecological efficiency of cultivated land use in arid regions as follows:

Under the premise of maintaining and enhancing the carrying capacity of water and soil resources and the ecological stability of oases, and supported by existing agricultural science and technology, it represents the degree of "economic-social-ecological" synergistic optimization achieved by the input of elements such as cultivated land, water, labor, and agricultural materials. This is manifested as a comprehensive coordination level that maximizes socio-economic and positive ecological outputs while minimizing undesired environmental outputs.

Note: The base map was produced using the standard map from the National Platform for Common Geo-Information Services, No. GS(2024)0650, with no modifications to the base map boundaries. The same applies hereafter.

1 Schematic diagram of the study area

1.3.2 耕地利用生态效率评价体系基于前文干旱

Based on the analysis of the connotations of ecological efficiency in cultivated land use, and drawing upon existing research findings [?], this study refines the input and output dimensions (Table 2) to account for the regional characteristics of the Tarim Rim Economic Belt and the availability of relevant data.

Arid zones

2 Framework for analyzing the ecological efficiency of cultivated land use in arid areas

Focusing on the actual input of production factors, land input is measured by the total sown area of grain crops. Labor input is represented by the number of personnel employed in the primary industry. Capital input is measured by the total power of agricultural machinery. Regarding intermediate inputs, we select the quantity of chemical fertilizers applied (calculated by effective component) and the amount of agricultural plastic film used as representative indicators.

Figure 1

Figure 15: Figure 1

The descriptive statistics for the variables used in this study are presented in . The data indicates significant regional variations in both grain output and factor inputs across the provinces. To ensure the accuracy of the empirical analysis and to mitigate the impact of heteroscedasticity, all continuous variables are transformed into their natural logarithms before being incorporated into the econometric models. The total output of food crops will be utilized to anchor food security functions, while ecological considerations will be integrated into the broader framework.

1. Introduction

The stability of food crop production serves as the fundamental cornerstone for national food security. By anchoring food security functions to the total output of food crops, policymakers can establish a more resilient and measurable framework for agricultural stability. This approach ensures that the primary objective of land use remains the consistent provision of caloric requirements for the population. Simultaneously, the ecological dimensions of agricultural landscapes must be addressed to ensure long-term sustainability. The integration of ecological health with production targets allows for a synergistic relationship where environmental preservation supports, rather than hinders, agricultural productivity.

2. Methodology and Framework

To quantify the relationship between crop yield and ecological stability, we employ a multi-dimensional assessment model. This model integrates machine learning algorithms to predict yield fluctuations based on historical data and environmental variables.

2.1 Food Security Anchoring

The core of our strategy involves the calculation of the "Food Security Anchor Point" (FSAP), which is defined by the minimum total output required to maintain national self-sufficiency. This is expressed mathematically as:

$$FSAP = \sum_{i=1}^{n} (P_i \times A_i \times \eta_i)$$

where P_i represents the average yield per unit area for crop i, A_i denotes the total cultivated area, and η_i is the efficiency coefficient accounting for post-harvest losses. As noted in [**?**], maintaining this threshold is critical for economic stability.

2.2 Ecological Integration

Ecological functions are evaluated through the lens of ecosystem service values (ESV). We utilize the modified formula proposed by [?] to assess the impact of intensive farming on local biodiversity and soil health:

$$ESV = \sum_{j=1}^{m} (VC_j \times Area_j)$$

In this equation, VC_j represents the value coefficient for ecosystem service j, and $Area_j$ is the extent of the specific ecological land use type. By balancing $FSAP$ and ESV, we can identify optimal land-use configurations that satisfy both production and conservation goals.

3. Results and Discussion

Our analysis indicates that anchoring food security to total output provides a clear total area of cultivated land represents the fundamental physical carrier of agricultural production. Labor input is measured by the number of rural employees. The output introduces the total carbon sequestration from cultivated land utilization, reflecting the positive ecological effects of the system. Reflects labor allocation. Input of production materials covers fertilizer application rates, land⋯

In terms of undesirable outputs, the focus is placed on ecological risk management and control, specifically regarding carbon emissions from cultivated land utilization. The plastic film coverage area and the total power of agricultural machinery reflect the intensity of material inputs. Total emissions reflect environmental degradation. According to relevant studies [?], the total carbon emissions from cultivated land utilization are calculated using the following formula:

$$E = \sum E_i = \sum T_i \cdot \delta_i$$

In this equation, E represents the total carbon emissions from cultivated land; E_i represents the emissions from the i-th carbon source; T_i denotes the amount of the i-th carbon source used; and δ_i is the corresponding emission coefficient. Based on existing research, this study identifies six primary carbon sources associated with cultivated land utilization: chemical fertilizers, pesticides, agricultural films, diesel fuel, irrigation, and plowing. The specific emission coefficients for these sources are as follows: fertilizers (0.8956 kg/kg), pesticides (4.9341 kg/kg), agricultural films (5.1800 kg/kg), diesel fuel (0.5927 kg/kg), irrigation (20.476 kg/hm^2), and plowing (312.6 kg/km^2).

In this study, we simultaneously select agricultural diesel consumption and rural electricity consumption as key indicators to establish their correlation with agricultural production. These variables serve as critical proxies for measuring the intensity of energy inputs and the level of mechanization within the agricultural sector. By analyzing the interplay between these energy consumption metrics and agricultural output, we can better understand the efficiency of resource allocation and the environmental footprint of modern farming practices. This integrated approach allows for a more comprehensive assessment of how energy-driven technological advancements contribute to agricultural development and sustainability.

Methodology for Calculating Carbon Sequestration

The calculation of carbon sequestration (C) is performed using the following formula:

$$C = \sum_{i=1}^{n} (A_i \times C_{rate,i} \times t_i)$$

where A_i represents the area of the i-th vegetation type, $C_{rate,i}$ denotes the specific carbon sequestration rate for that vegetation category, and t_i signifies the duration of the sequestration period. This methodology allows for a comprehensive assessment of the total carbon sink capacity by aggregating the contributions of diverse ecosystem components over time.

2 Evaluation system of ecological efficiency of cultivated land use

The energy consumption of production serves as a primary input. Desired outputs are centered around the synergy of "economy-society-ecology." Specifically, economic output is measured by the total agricultural output value to reflect economic contribution. Social output is evaluated based on the capacity to ensure food security and support rural livelihoods. Ecological output focuses on the maintenance of ecosystem services and the mitigation of environmental degradation. This comprehensive framework allows for a multi-dimensional assessment of how cultivated land resources are utilized to balance productive efficiency with sustainable development goals.

Grain Sown Area

Rural practitioners

C represents the total carbon sequestration of cultivated land use ($\mathrm{t \cdot a^{-1}}$); C_i is the carbon sequestration rate of the i-th crop; E_i is the economic yield of the i-th crop ($\mathrm{t \cdot a^{-1}}$); W_i is the water content of the i-th crop (%); and Q_i is the economic coefficient of the i-th crop. Economic coefficients; n represents the number of crop types; relevant parameters are detailed in .

Chemical fertilizer application rate

Plastic film mulching area

3 Crop economic coefficient, water content and carbon absorption rate in the process of cultivated land use

Total Power of Agricultural Machinery

Agricultural diesel consumption

Undesirable outputs

Crop varieties

Water content / %

Rural electricity consumption

Gross agricultural output value

Total grain yield

Total carbon sequestration from cultivated land use

Total carbon emissions from cultivated land use

Yan Yuhang et al.: Spatiotemporal Differentiation and Influencing Factors of Ecological Efficiency of Cultivated Land Use in the Circum-Tarim Economic Belt

Based on relevant studies [?], the formula for calculating carbon emissions from cultivated land use is:

1.4.1 超效率 SBM 模型超效率 SBM 模型是 Tone [25]

In the formula: E represents the total carbon emissions from cultivated land utilization ($t \cdot a^{-1}$); j denotes the category of carbon sources. This model accounts for the impact of slack variables on the calculation results.

$$E = \sum E_j = \sum (G_v \delta_v)$$

Model type; m is the total number of carbon source types covered in the study; E_j represents the carbon emissions from the j-th carbon source. The carbon emissions from cultivated land utilization ($t \cdot a^{-1}$); G_v and δ_v represent the original quantity and the carbon emission coefficient of the v-th carbon source, respectively. Relevant parameters are detailed in .

Sources in the process of cultivated land use. The issue arises that efficient Decision Making Units (DMUs) cannot be further compared or ranked. When the efficiency value is ≥ 1, the DMU is considered efficient. Conversely, if the efficiency value is < 1, the DMU is considered inefficient. Furthermore, the model is not influenced by the units of measurement used for input and output indicators, eliminating the need for the normalization of raw data.

4 Carbon emission coefficients of major carbon sources in the process of cultivated land use. A data envelopment analysis (DEA) method proposed based on the SBM model, is present, indicating room for improvement; furthermore, the efficiency measurement results of this model are not.

Carbon emission coefficient / kg C $\cdot$ kg^{-1}

Reference data source: Oak Ridge National Laboratory (ORNL), USA. The data were subjected to dimensionless processing [**?**, **?**]. The ecological efficiency of cultivated land use in the study area was measured using this model in Matlab 2021 software, and Origin 2021 software was utilized for visual mapping. Due to space limitations, the specific calculation formulas are detailed in the literature [**?**].

1.4.2 变异系数引入变异系数（Coefficient of Vari

The coefficient of variation (C_v) was employed to quantitatively analyze the temporal variations in the ecological efficiency of cultivated land use within the study area. Institute of Resources, Ecosystem and Environment of Agriculture (IREEA), Nanjing Agricultural University. Intergovernmental Panel on Climate Change (IPCC). To analyze the degree of differentiation, Origin 2021 software was utilized for data visualization and mapping. The coefficient of variation (C_v) served as the primary metric for this assessment.

1.3.3 耕地利用生态效率影响因素评价体系基于

Based on statistical standards for dispersion, a coefficient of variation ($C_v \leq 0.05$) is defined as a small difference. Based on the preceding analysis of the connotations of ecological efficiency in cultivated land use within arid regions, and referring to existing research results [**?**, **?**], this study considers the actual conditions of the research area and data availability to construct an evaluation system. A larger value indicates stronger dispersion and more significant differences between regions. Specifically, ($0.05 < C_v \leq 0.1$) is categorized as a moderate difference, while ($C_v > 0.1$) is categorized as a significant difference. The calculation formula is as follows:

An evaluation system for the factors influencing the ecological efficiency of cultivated land use in the Around-Tarim Economic Belt was established . Within the dimension of natural resource endowment, the multiple cropping index, per capita cultivated land area, and agricultural planting structure were selected to represent the intensity of cultivated land use, the level of per capita land ownership, and the resource-ecological differences in crop combinations, respectively.

Regarding the dimension of agricultural science and technology, the total power of agricultural machinery per unit area of cultivated land and the intensity of chemical fertilizer application per unit area were used as indicators. These reflect the intervention of mechanization levels and fertilizer input intensity on resource conversion efficiency.

In the dimension of socio-economic factors, per capita GDP and the proportion of the primary industry' s output value were included. These indicators reflect the impact of regional development levels and the policy orientations underlying industrial structures on cultivated land use behavior.

5 Evaluation system of influencing factors of the ecological efficiency of cultivated land use

Cultivated Land Use Ecological Efficiency: Cultivated land use ecological efficiency value

Natural resource endowment: Cultivated land multiple cropping index; Per capita cultivated land area; agricultural planting structure; total power of agricultural machinery per unit area of cultivated land; chemical fertilizer application rate per unit area of cultivated land; socio-economic factors

Per capita GDP

In the formula: i represents the unit being measured; C_v is the coefficient of variation for the cultivated land use ecological efficiency of unit i; σ is the standard deviation for unit i; and μ is the mean value for unit i.

1.4.3 核密度估计核密度估计在分析耕地利用生

When analyzing ecological efficiency, it is possible to accurately characterize dynamic evolution and underlying correlations. Therefore, Stata 18 software was employed to conduct visual mapping and analysis of the density distribution and dynamic evolution of cultivated land utilization ecological efficiency within the study area over time. This temporal dimension allows for a comprehensive assessment of how these efficiencies shift across different periods, providing insights into the trajectory of agricultural sustainability.

1.4.4 重心迁移模型重心变化可以反映时空迁移

Agricultural Science and Technology Level process; therefore, this model was constructed and visualized using ArcGIS 10.8 software. Mapping to analyze the distribution of the center of gravity and the evolutionary trends of cultivated land use eco-efficiency within the study area across different years.

1.4.5 标准差椭圆标准差椭圆能够较好反映耕地

To analyze the distribution patterns of ecological efficiency in cultivated land use, we utilized ArcGIS 10.8 software. This software was employed to construct the model and generate visual maps, enabling a detailed analysis of the spatial distribution characteristics of cultivated land utilization ecological efficiency within the study area.

Figure 1

Figure 16: Figure 1

1.4.6 Tobit 模型 Tobit 模型具有偏差小、精确度高

Due to its inherent advantages, the Tobit regression model within the SPSSAU platform was employed to analyze the impact. This analysis aims to determine the direction and magnitude of the influence exerted by various explanatory variables on the ecological efficiency of cultivated land use. The proportion of the primary industry’ s output value. Arid region. Regarding the fluctuation range of the ecological efficiency of cultivated land use, the various prefectures and counties exhibit···

2 结果与分析

The fluctuation range of ecological efficiency in cultivated land utilization exhibits a spatial distribution pattern characterized by “high in Hotan and low in the eastern regions.” Specifically, the high-value areas are primarily concentrated in the Hotan region, while the low-value areas are distributed across the eastern part of the study area. This spatial heterogeneity suggests that the ecological pressure and resource utilization efficiency of cultivated land vary significantly across different geographical units.

The temporal evolution of ecological efficiency further reveals a complex dynamic. During the study period, the overall efficiency level underwent several phases of adjustment, influenced by both natural environmental constraints and human interventions such as agricultural management practices and land-use policies. In regions with higher ecological efficiency, the integration of traditional farming wisdom with modern sustainable practices has likely contributed to maintaining a more balanced ecosystem. Conversely, the eastern regions, which exhibit lower efficiency, may be facing challenges related to intensive land exploitation, soil degradation, or inefficient resource allocation.

To further analyze these trends, we employ a series of quantitative indicators. Let the ecological efficiency be denoted by η, which is defined as the ratio of the desired output to the total environmental impact. The relationship can be expressed as:

$$\eta = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{j=1}^{m} v_j x_j + \sum_{k=1}^{l} s_k z_k}$$

where y_i represents the i-th beneficial output, x_j represents the j-th resource input, and z_k represents the k-th undesirable environmental output (such as carbon emissions or chemical runoff). The weights w_i, v_j, and s_k are determined through the Data Envelopment Analysis (DEA) model as described in

Figure 2

Figure 17: Figure 2

Figure 3

Figure 18: Figure 3

[?]. By applying this model, we can objectively evaluate the relative efficiency of different administrative units and identify the primary drivers of efficiency fluctuations.

The spatial autocorrelation analysis, as shown in

, confirms that the ecological efficiency of cultivated land is not randomly distributed but exhibits significant spatial clustering. The Global Moran' s I index was calculated to be positive, indicating that regions with high efficiency tend to be adjacent to other high-efficiency regions. This "neighborhood effect" suggests that regional cooperation and the diffusion of sustainable agricultural technologies play a crucial role in enhancing the overall ecological

2.1 耕地利用生态效率时序特征

The spatial distribution exhibits a gradient pattern characterized by "Hotan Prefecture > Kashgar Prefecture > Aksu Prefecture." This is followed by "Kashgar Prefecture > Bayingolin Mongol Autonomous Prefecture > Kizilsu Kirghiz Autonomous Prefecture."

2.1.1 Efficiency Evaluation Results

As illustrated in

and , the county-level average efficiency of the Circum-Tarim Economic Belt from 2014 to 2021 remained relatively stable. The average efficiency value for the counties in the Circum-Tarim Economic Belt was maintained at 0.835. The values fluctuated around the 0.8 threshold, failing to reach the efficiency frontier of 1.

During the study period, the county-level ecological efficiency of cultivated land use showed a fluctuation range of 0.72 to 1.14, representing the region with the highest degree of volatility. The fluctuation range of cultivated land use ecological efficiency in the Bayingolin Mongol Autonomous Prefecture followed as the second highest.

For the convenience of analysis and considering the geographical distribution of the Xinjiang Production and Construction Corps (XPCC) cities, the administrative divisions in this figure are defined as follows: the Bayingolin Mongol Autonomous Prefecture includes the XPCC Second Division (Tiemenguan City); the Aksu Prefecture includes the XPCC First Division (Aral City); the Kashgar

Prefecture includes the XPCC Third Division (Tumxuk City); and the Hotan Prefecture includes the XPCC Fourteenth Division (Kunyu City).

3 Zonal differences in the ecological efficiency of cultivated land use

6 Average Ecological Efficiency of Cultivated Land Use in Counties and Cities around the Circum-Tarim Economic Belt

[FIGURE:6]

The average ecological efficiency of cultivated land use in the counties and cities surrounding the Circum-Tarim Economic Belt is illustrated in [FIGURE:6]. Among these regions, Tumxuk City stands out as a significant point of analysis within the broader economic and ecological landscape of the belt. Taxkorgan Tajik Autonomous County. The mean values for the divisions and cities of the Xinjiang Production and Construction Corps (XPCC). Yanqi Hui Autonomous County. Local County (City) Mean.

Spatio-temporal Differentiation and Influencing Factors of Cultivated Land Use Eco-efficiency in the Tarim Rim Economic Belt

Abstract

The Tarim Rim Economic Belt is a critical ecological barrier and an important base for agricultural production in Northwest China. Improving the eco-efficiency of cultivated land use is essential for achieving sustainable regional development and ensuring food security. This study evaluates the cultivated land use eco-efficiency (CLUEE) of 42 counties (cities) in the Tarim Rim Economic Belt from 2000 to 2020 using a Super-SBM model that accounts for undesirable outputs. Furthermore, we analyze the spatio-temporal evolution characteristics and identify the key influencing factors using the Malmquist-Luenberger (ML) index and the Geodetector model. The results indicate that: (1) The overall CLUEE in the Tarim Rim Economic Belt showed a fluctuating upward trend, though the absolute efficiency remains relatively low, suggesting significant potential for improvement. (2) Spatially, the eco-efficiency exhibits a distribution pattern of "high in the west and low in the east," with significant regional disparities. (3) The ML index analysis reveals that technological progress is the primary driver of efficiency growth, while technical efficiency improvement lags behind. (4) Socio-economic factors, particularly the level of agricultural mechanization and the intensity of land use, are the dominant factors influencing the spatial differentiation of CLUEE. These findings provide a scientific basis for optimizing cultivated land use patterns and promoting green agricultural development in arid regions.

Figure 4

Figure 19: Figure 4

Figure 5

Figure 20: Figure 5

1 Introduction

Cultivated land is the most fundamental resource for human survival and development, serving as the core carrier for food security and ecological stability. In the context of global climate change and accelerating urbanization, the traditional extensive model of cultivated land use has led to serious environmental issues, such as soil degradation, non-point source pollution, and biodiversity loss. Consequently, transitioning toward green and efficient cultivated land use has become a global consensus. Cultivated land use eco-efficiency (CLUEE) is an important indicator that integrates economic output, social benefits, and environmental costs. It reflects the degree to which maximum socio-economic output is achieved with minimum resource input and environmental impact.

The Tarim Rim Economic Belt, located in the southern part of the Xinjiang Uygur Autonomous Region, is a typical arid and semi-arid region. It is characterized by a fragile ecological environment, scarce water resources, and a high dependence on oasis agriculture. The fluctuation range is 0.61 ~ 0.93. The ecological efficiency of cultivated land use in the Kizilsu Kirgiz Autonomous Prefecture and the Kashgar Prefecture exhibits the same range of fluctuation, with identical statistical ranges. The ecological efficiency of cultivated land use in the Aksu region exhibited the most gradual fluctuations, ranging from 0.81 to 0.95. This indicates that the ecological efficiency of land use in this area maintained a high level of stability throughout the study period.

From the perspective of effective states , among the 46 counties (cities), there are ten counties and cities, including Tian County and Aral City, account for 21.74% of the total cultivated land. The average annual value of land-use eco-efficiency exceeds 1, indicating that a breakthrough in efficiency values has been achieved. The DEA efficient state with a value of 1, specifically regarding the Kashgar region and the divisions under the jurisdiction of the Xinjiang Production and Construction Corps. The market share has reached 60%, a phenomenon primarily attributable to the structural differences in agricultural production management systems between the Xinjiang Production and Construction Corps (XPCC) and local

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Figures

Source: ChinaXiv —Machine translation. Verify with original.

Figure 7

Figure 21: Figure 7