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Measuring the Eco-efficiency of Land Use in the "Production-Living-Ecological Space": Coupling Coordination and Influencing Factors

Jiamin Chen

Shenzhen New Urban Planning & Architectural Design Co., Ltd., Shenzhen, Guangdong, 518000, China

Abstract: To examine the utilization efficiency of production, living and ecological territorial spaces and their coordination, this study takes the panel data of 30 provinces in China (excluding Tibet, Hong Kong, Macao and Taiwan) from 2008 to 2025 as a sample, and constructs an index system for land use eco-efficiency in the "production-living-ecological space" covering inputs, desirable outputs and undesirable outputs. A super-efficiency SBM model considering undesirable outputs is employed to measure the efficiency of each subsystem; the entropy weight method is used to synthesize the comprehensive efficiency; a coupling coordination degree model is applied to characterize the coordination level of the three subsystems; and a spatial Durbin model with dual individual and time fixed effects is adopted to identify the influencing factors. The results show that the mean comprehensive efficiency over the study period is 0.499, at a medium-low level, with an "M"-shaped temporal fluctuation. The efficiencies of the production, ecological and living spaces decline in turn, with means of 0.826, 0.517 and 0.333, respectively. The coupling coordination degree of the three subsystems is generally at a mild imbalance level, with a low degree of benign coupling. There is a significant positive spatial spillover in efficiency; economic development has a "U"-shaped relationship with efficiency. Population density, openness, ecological land proportion, and investments in science and technology and governance exert positive effects, while production land expansion and land reclamation exert negative effects, and the effect of land fiscal pressure is not yet significant. The findings can provide a reference for optimizing the territorial spatial layout and improving land use eco-efficiency.

Keywords: Production-living-ecological Space; Land Use Eco-efficiency; Super-efficiency SBM Model; Coupling Coordination Degree; Spatial Durbin Model.

1. Introduction

Territorial space is the spatial carrier of economic and social development, and the coordinated utilization of production, living and ecological functional spaces is an important foundation for advancing ecological civilization construction and high-quality development [1]. With rapid urbanization, problems such as disorderly expansion of construction land, encroachment on cultivated and ecological land, and the superimposition of production and domestic pollution have become increasingly prominent, which calls for a rational evaluation of the input-output efficiency of land use and its coordination level under resource and environmental constraints. Clarifying the efficiency pattern and coupling relationship of various spaces can provide a quantitative basis for identifying weak spaces and matching differentiated regulatory measures. Existing studies mostly measure urban or cultivated land use efficiency from a single functional perspective[2-5], and systematic investigations into the overall efficiency measurement of production, living and ecological spaces, their coupling coordination relationship and spatial association mechanisms remain insufficient. In terms of methods, efficiency measurement incorporating undesirable outputs, coupling coordination and spatial econometric analysis have become important approaches in land use efficiency research[6-8]. Taking 30 provinces of China from 2008 to 2025 as a sample, this paper constructs an efficiency evaluation index considering undesirable outputs, and successively applies the super-efficiency SBM model, entropy weight method, coupling coordination degree model and spatial Durbin model to reveal the spatiotemporal characteristics, coupling coordination pattern and influencing factors of land use Eco-efficiency in the "production-living-ecological space", so as to provide empirical evidence for optimizing the territorial spatial development and protection pattern.

2. Research Design

2.1. Research Methods

(1) Super-efficiency SBM model. Data envelopment analysis (DEA) is a non-parametric evaluation method that requires no production function to be specified; traditional radial and angle models tend to ignore input or output slacks. This paper adopts a super-efficiency SBM model considering undesirable outputs, incorporating the slacks of inputs, desirable outputs and undesirable outputs into the objective function to measure the efficiency of urban and rural production, living and ecological spaces separately, and further ranks the efficient decision-making units; this approach better approximates the real input-output process of land use under resource and environmental constraints.

(2) Synthesis of comprehensive efficiency by the entropy weight method. On the basis of measuring each subsystem efficiency, the entropy weight method is used to determine the weights of the production, living and ecological subsystems and synthesize the comprehensive value of land use Eco-efficiency in the "production-living-ecological space". The formula is:

$$E = \Sigma v_i \cdot E_i \quad (i = 1, 2, 3) \tag{1}$$

where E is the comprehensive efficiency; E_i denotes the

efficiency of the production, living and ecological space subsystems; and v_i is the corresponding subsystem weight.

(3) Coupling coordination degree model. The standardized values of the three subsystem efficiencies are used to construct a comprehensive index T, and then the coupling degree C and coupling coordination degree D are calculated to characterize the interaction intensity and coordinated development level of the production, living and ecological spaces. The coupling degree reflects the strength of interaction among subsystems, while the coordination degree further measures the degree of benign coupling in the interaction; combining the two avoids judging the coordination level solely by the coupling degree. The core formulas are:

$$D = (C \cdot T)^{(1/2)}, \quad T = \alpha F_1 + \beta F_2 + \gamma F_3, \quad C = \{ F_1F_2F_3 / [(F_1+F_2+F_3)/3]^3 \}^{(1/3)} \tag{2}$$

where F_1, F_2 and F_3 are the standardized efficiency values of the production, living and ecological spaces, respectively; α, β and γ are undetermined coefficients with α+β+γ=1; C is the coupling degree and D is the coupling coordination degree.

(4) Spatial Durbin model. Given the spatial auto-correlation of efficiency, this paper constructs a spatial Durbin model (SDM) with dual individual and time fixed effects. The dependent variable is the comprehensive efficiency, and the explanatory variables include economic development and its quadratic term, industrial structure, population density, openness, land use mode, land reclamation degree, land fiscal pressure, science and technology expenditure, and environmental governance investment; the spatial weight matrix is an economic-geographic nested matrix.

2.2. Index System and Data Sources

According to the functional connotations of production, living and ecological spaces, a measurement index system is constructed from three dimensions—inputs, desirable outputs and undesirable outputs—covering 23 specific indicators; the main indicators are shown in Table 1. The sample consists of 30 provinces of China excluding Tibet, Hong Kong, Macao and Taiwan, over the period 2008—2025. Raw data are obtained from the National Bureau of Statistics of China, China Environmental Statistical Yearbook, China Rural Statistical Yearbook, China Urban Construction Statistical Yearbook, and provincial statistical yearbooks and statistical bulletins; a few missing values are imputed by linear interpolation.

Table 1. Index System for Measuring Land Use Eco-efficiency in the "Production-Living-Ecological Space"

Dimension	Criterion layer	Input indicators	Output indicators (desirable/undesirable)
Production space (urban)	Urban production efficiency	Fixed asset investment, employment in secondary and tertiary industries, urban construction land, urban production water	Desirable: gross output of secondary and tertiary industries, average wage of urban employees, urban green space area; Undesirable: industrial wastewater, industrial SO_2, industrial smoke and dust emissions
Production space (rural)	Rural production efficiency	Total agricultural machinery power, agricultural film use, chemical fertilizer application, employment in primary industry, sown area of crops, agricultural water use	Desirable: primary industry output value, per capita income of rural residents, afforestation area; Undesirable: agricultural carbon emissions
Living space (urban/rural)	Living space efficiency	Total domestic water use, residential building area	Desirable: human well-being index; Undesirable: domestic garbage removal volume, domestic wastewater discharge
Ecological space	Ecological space efficiency	Ecological water use, ecological land	Desirable: ecosystem service value

Note: Undesirable outputs reflect resource and environmental constraints

3. Measurement Results and Spatiotemporal Characteristics

3.1. Temporal Variation

The results show that the mean comprehensive value of land use Eco-efficiency in China from 2008 to 2025 is 0.499, at a medium-low level overall; the trend shows an "M"-shaped fluctuation with a large amplitude, leaving considerable room for improvement. The comprehensive efficiency reached its lowest level in 2024 (0.174) and its highest in 2011 (1.140), about 6.6 times that in the lowest year. The three subsystems rank from high to low as production space, ecological space and living space, with means of 0.826, 0.517 and 0.333, respectively (Table 2). Production space efficiency remains at a relatively high level overall; living space efficiency shows a continuous declining trend, falling from 0.605 in 2008 to 0.162 in 2025, a decrease of about 73.2%; ecological space efficiency fluctuates slightly and reached its stage maximum in 2023. The efficiency gap among the three subsystems reflects that living space upgrading and ecological space protection remain relatively weak links in current territorial land use.

At the regional level, the comprehensive efficiency of the seven geographical regions fluctuates between 0.4 and 0.6, at a medium level overall. Production space efficiency ranks from high to low as North China, South China, Northwest China, Southwest China, East China, Northeast China and Central China; North China and South China reach full efficiency. Living space efficiency declines across all regions; ecological space shows significant regional differences, with South China leading owing to high vegetation coverage and

high ecosystem service value. From the urban-rural perspective, both urban production and living space efficiencies are higher than those in rural areas; the mean rural production space efficiency is 0.656, at a medium-high level.

Table 2. Mean Land Use Eco-efficiency at National and Subsystem Levels (2008—2025)

Efficiency category	Mean	Level judgment	Main temporal characteristics
Comprehensive efficiency	0.499	Medium-low level	"M"-shaped fluctuation with large room for improvement
Production space	0.826	High level	Small fluctuation, maintaining high efficiency overall; urban production space entered a super-efficiency state after 2015
Ecological space	0.517	Medium-high level	Small variation, reaching stage maximum in 2023
Living space	0.333	Low level	Continuous decline, from 0.605 in 2008 to 0.162 in 2025

Note: The mean rural production space efficiency is 0.656, at a medium-high level

3.2. Spatial Agglomeration

The global and local Moran's I indices indicate obvious spatial differences in inter-provincial land use Eco-efficiency. The Moran's I of production space efficiency remains above 0 throughout the study period, at 0.150, 0.123, 0.088 and 0.094 in 2010, 2015, 2020 and 2025, respectively; most provinces fall in the high-high (H-H) and low-low (L-L) quadrants, showing significant spatial agglomeration. Living space efficiency also shows positive agglomeration from 2010 to 2020, while its Moran's I turns negative in 2025, indicating weakened spatial correlation. Ecological space efficiency has no significant spatial correlation, which is related to the fixed total provincial land area and the weak cross-provincial spillover of ecosystem service value.

4. Coupling Coordination Analysis of the "Production-Living-Ecological Space"

The coupling coordination degree is calculated based on the three subsystem efficiencies and divided into five grades: severe imbalance (0—0.199), mild imbalance (0.200—0.399), basic coupling coordination (0.400—0.599), moderate coupling coordination (0.600—0.799) and high coupling coordination (0.800—1.000). Table 3 presents the coupling coordination degrees of representative provinces in 2008, 2011, 2014, 2017, 2020, 2023 and 2025.

Table 3. Coupling Coordination Degree of Representative Provinces

Region	2008	2011	2014	2017	2020	2023	2025
Beijing	0.468	0.475	0.390	0.380	0.339	0.356	0.310
Tianjin	0.544	0.551	0.449	0.476	0.350	0.613	0.353
Shanghai	0.403	0.456	0.424	0.510	0.530	0.522	0.530
Jiangsu	0.236	0.281	0.356	0.275	0.275	0.268	0.226
Zhejiang	0.242	0.253	0.249	0.296	0.271	0.255	0.234
Fujian	0.377	0.384	0.355	0.322	0.407	0.416	0.407
Shandong	0.395	0.416	0.382	0.375	0.366	0.368	0.360
Guangdong	0.294	0.302	0.403	0.368	0.350	0.303	0.339
Guangxi	0.439	0.512	0.471	0.441	0.437	0.421	0.498
Hainan	0.366	0.483	0.509	0.469	0.588	0.413	0.480
Henan	0.160	0.213	0.301	0.232	0.230	0.212	0.217
Sichuan	0.265	0.264	0.374	0.279	0.261	0.282	0.273
Qinghai	0.358	0.366	0.433	0.400	0.365	0.378	0.379
Ningxia	0.442	0.428	0.372	0.475	0.387	0.372	0.372

Note: Only representative provinces are listed.

Overall, the coupling coordination degree of production, living and ecological space efficiency is at a mild imbalance level. The results show that the coupling degree of the three subsystems is high, indicating strong interaction among them, but the coordination degree is low, meaning the benign coupling within the interaction is weak. In the process of economic development, production space keeps expanding, living and ecological spaces are encroached upon, and domestic pollution further adds to the burden on ecological space, restricting the benign coordination of the three. Regionally, Shanghai, which is dominated by the tertiary industry, Ningxia and Qinghai, which are less developed, and Guangxi and Hainan, which are endowed with favorable ecological and tourism resources, are generally at a basic coupling coordination level; energy-based and densely populated expanding provinces have relatively low coordination levels.

5. Spatial Econometric Analysis of Influencing Factors

On the basis of mechanism analysis, 11 variables are selected to characterize factors such as economic development, industrial structure, population scale, openness, land use mode, land reclamation, land fiscal pressure, science and technology level and environmental governance intensity; the variable definitions are given in Table 4. The LM, LR, Hausman and Wald tests all support the spatial Durbin model with dual individual and time fixed effects; the regression results are shown in Table 5.

Table 4. Description of Influencing Factor Variables

Variable	Variable name	Measurement
x1	Economic development (linear term)	Per capita GDP, log-transformed
x2	Economic development (quadratic term)	Quadratic term of per capita GDP, log-transformed
x3	Industrial structure	Value-added of tertiary industry / value-added of secondary industry
x4	Population density	Total population / total area
x5	Openness level	Actually utilized foreign capital, log-transformed
x6	Production land proportion	Production land area / total area
x7	Ecological land proportion	Ecological land area / total area
x8	Land reclamation degree	Total sown area / total area
x9	Land fiscal pressure	Public fiscal expenditure / land transfer income
x10	Science and technology level	Science and technology expenditure, log-transformed
x11	Environmental governance intensity	Investment in environmental pollution control, log-transformed

Table 5. Regression Results of the Spatial Durbin Model

Variable	Regression coefficient	T-statistic	Spatial lag term Wx	T-statistic
x1	-2.444*	-1.711	-2.828	-0.301
x2	0.117*	1.664	0.136	0.297
x3	0.078	0.497	-1.507	1.588
x4	1.857***	2.835	13.758***	2.951
x5	0.021**	1.992	-0.011**	-2.111
x6	-0.001**	-2.321	0.007***	3.347
x7	0.030**	1.972	-0.002*	-1.942
x8	-0.034***	-2.808	-0.044	-0.573
x9	0.037	1.396	0.179	0.846
x10	0.014	0.353	0.686**	2.182
x11	0.024*	1.658	0.260	1.610

Note: ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively

The regression results show that the spatial lag coefficient is significantly positive, indicating a positive spatial spillover from efficiency improvement in a province to its neighboring provinces. The linear term of economic development is negative and the quadratic term positive, significant at the 10% level, showing a "U"-shaped relationship. Industrial structure, population density (significant at 5%) and openness (significant at 5%) have positive coefficients; the scale effect and inward investment spillover help improve efficiency, though pollution transfer warrants attention. The production land proportion is significantly negative at the 5% level, as disorderly expansion squeezes ecological space; the ecological land proportion coefficient is positive, highlighting the importance of protecting ecological land. Land reclamation degree is significantly negative at the 1% level. The land fiscal pressure coefficient is positive but fails the significance test, and its effect remains unclear. The coefficients of science and technology level and environmental governance investment are positive; technological progress and pollution control can mitigate the negative effects of production and domestic pollution. After replacing the weights with a 0-1 adjacency matrix, inverse geographic matrix and economic distance matrix, the core results remain basically stable, indicating robust conclusions.

6. Conclusion

This paper constructs an evaluation index system for land use Eco-efficiency in the "production-living-ecological space", and applies the super-efficiency SBM model, entropy weight method, coupling coordination degree model and spatial Durbin model to empirically analyze the efficiency level, coupling coordination pattern and influencing factors of 30 provinces in China from 2008 to 2025. The main conclusions are as follows:

First, the mean comprehensive land use Eco-efficiency over the study period is 0.499, at a medium-low level, with an "M"-shaped temporal fluctuation; production, ecological and living space efficiencies decline in turn, with means of 0.826, 0.517 and 0.333, and living space efficiency declines most sharply. Regionally, the comprehensive efficiency of the seven geographical regions fluctuates between 0.4 and 0.6; production space is highest in North China and lowest in Central China, while ecological space leads markedly in South China. Second, inter-provincial efficiency shows clear spatial differences: production and living space efficiencies exhibit high-high and low-low agglomeration, while ecological space has no significant spatial correlation. Third, the coupling coordination degree of the three subsystems is generally at a mild imbalance level, with high coupling degree but low coordination degree and insufficient benign coupling. Fourth, there is a significant positive spatial spillover in efficiency; economic development has a "U"-shaped relationship with efficiency; population density, openness, ecological land proportion and investments in science, technology and governance exert positive effects; production land expansion and land reclamation exert negative effects, while the effect of land fiscal pressure is not yet significant.

Based on these conclusions, three aspects should be pursued in the future: first, optimize the utilization path of production space, control the extensive input of urban

production land, improve the three-dimensional land use efficiency, and strengthen the ecological agriculture compensation mechanism to release the potential productivity of rural areas; second, optimize the territorial spatial layout, increase the proportion of living and ecological land, and curb the disorderly encroachment of production space on living and ecological spaces; third, allocate production factors rationally in low-efficiency provinces and promote intensive and green land use through technological progress and environmental governance investment. Meanwhile, inter-provincial spatial linkage should be strengthened, and the positive spatial spillover of efficiency should be leveraged to drive coordinated improvement in low-efficiency provinces. Limited by the sample period and index caliber, this paper has not fully characterized the heterogeneous effects of urban-rural factor mobility and policy shocks; further research can examine the underlying mechanisms of efficiency evolution over a longer period and at a finer scale with multi-source data.

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