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Performance Evaluation and Stochastic Convergence of Agricultural Carbon Emissions in China: Based on SBM-Undesirable Model and Panel Unit Root Test (Postprint)

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Abstract

Currently, carbon emission performance evaluation and convergence analysis at the global level and from an industrial perspective have become mature, yet research on agricultural carbon emissions remains notably underdeveloped. To supplement existing research and achieve a clearer understanding of regional agricultural carbon emission totals, performance, and their convergence trends, this paper calculates the total agricultural carbon emissions of 30 provinces and municipalities in China from 2000–2014, employs the SBM-Undesirable model to compute agricultural carbon emission performance, and conducts stochastic convergence tests on national and regional agricultural carbon emission totals and performance using panel unit root test methods. The results demonstrate: 1) During 2000–2014, national agricultural carbon emissions exhibited an overall increasing trend, with significant regional disparities. Comparing the annual mean totals of the central region with the national average, as well as the eastern and western regions, the differences in 2000 were 3.3574$×10^{6}$ t, 3.9650$×10^{6}$ t, and 5.9047$×10^{6}$ t, respectively; by 2014, these gaps expanded to 5.2448$×10^{6}$ t, 7.3512$×10^{6}$ t, and 7.6810$×10^{6}$ t, corresponding to growth rates of 56.2%, 85.4%, and 30.0%, respectively. 2) Significant differences exist in agricultural carbon emission performance across regions. The mean performance line chart reveals that the eastern region maintains relatively high average performance, remaining essentially stable around 0.8 over the 15-year period; the western and central regions exhibit lower mean performance, predominantly between 0.3–0.5 in most years, though the western region demonstrates continuous improvement while the central region shows persistent decline. 3) Convergence tests on emission totals indicate that the nation, western region, and central region display evident stochastic divergence, with stochastic convergence occurring only in the eastern region. In performance convergence tests, no stochastic convergence exists at the national level, yet the eastern, central, and western regions each exhibit club stochastic convergence patterns. The stochastic convergence test results suggest that China' s agricultural carbon emission totals and performance will not automatically converge to a steady-state level, necessitating policy interventions to narrow inter-provincial and inter-municipal gaps. This study establishes a foundation for formulating differentiated inter-regional and unified intra-regional agricultural emission reduction policies.

Full Text

Assessment of Agricultural Carbon Emission Performance and Stochastic Convergence in China Using SBM-Undesirable Model and Panel Unit Root Test

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Abstract: While research on carbon emission performance evaluation and convergence analysis at the global and industrial levels has matured, studies on agricultural carbon emissions remain notably underdeveloped. To address this gap and provide clearer insights into regional agricultural carbon emission levels, performance, and convergence trends, this paper first estimates agricultural carbon emissions for 30 Chinese provinces from 2000–2014. It then employs the SBM-Undesirable model to calculate agricultural carbon emission performance and conducts stochastic convergence tests on both emission levels and performance using panel unit root methods. The results reveal: (1) National agricultural carbon emissions exhibited an overall increasing trend during 2000–2014, with significant regional variations. Comparing mean annual emissions between the central region and the national average, as well as eastern and western regions, the gaps widened from 3.3574×10^{6} t, 3.9650×10^{6} t, and 5.9047×10^{6} t in 2000 to 5.2448×10^{6} t, 7.3512×10^{6} t, and 7.6810×10^{6} t by 2014, representing growth rates of 56.2%, 85.4%, and 30.0% respectively. (2) Significant regional disparities exist in agricultural carbon emission performance. Performance mean trend lines show that the eastern region maintained relatively high performance, stabilizing around 0.8 over the 15-year period, while western and central regions exhibited lower mean performance, mostly ranging between 0.3-0.5, though the western region showed gradual improvement while the central region experienced continuous decline. (3) Convergence tests on emission levels indicate stochastic divergence at the national, western, and central levels, with only the eastern region demonstrating stochastic convergence. For performance convergence, no stochastic convergence exists nationally, yet each region—eastern, central, and western—displays club convergence patterns. These findings suggest that neither agricultural carbon emission levels nor performance in China will automatically stabilize; policy intervention is necessary to narrow inter-provincial gaps. This study provides a foundation for formulating differentiated regional policies and unified intra-regional strategies for agricultural carbon reduction.

Keywords: Agricultural carbon emission; Carbon emission performance; SBM-Undesirable model; Panel unit root; Stochastic convergence; Club convergence

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Scientific research indicates that the Earth' s average surface temperature has risen by approximately 0.6°C over the past century, with a potential 5–6°C increase posing catastrophic consequences. Elevated atmospheric concentrations of CO_2 and other greenhouse gases constitute a primary driver of this warming, making carbon emissions a global focus. China has committed to reducing carbon emissions per unit of GDP by 60–65% from 2005 levels by 2030, requiring substantial emission reductions across all sectors. Although secondary and tertiary industries dominate carbon emissions, agricultural contributions cannot be overlooked. Extensive use of diesel fuel and chemical fertilizers and pesticides has pushed agriculture' s share of total emissions to 17%—significantly above the international average—making agricultural carbon control imperative. Under these circumstances, examining convergence in China' s agricultural carbon emissions provides crucial guidance for scientifically formulating and implementing regional agricultural emission reduction policies to achieve sustainable development.

With deepening exploration of low-carbon economies, scholars worldwide have extensively studied carbon emission convergence. Strazicich and List employed IPS panel unit root tests to examine stochastic convergence in per capita carbon emissions across 21 industrialized nations from 1960–1997, finding convergence trends. Westerlund and Basher similarly identified convergence in OECD countries, while Lee et al. found convergence in only four nations. Xu Guangyue used Chinese provincial panel data from 1995–2007 to study per capita carbon emissions, discovering conditional β-convergence and club convergence across eastern, central, and western regions, but no absolute β-convergence—contrasting with Gao Guangkuo et al., who found widespread absolute and conditional convergence without club convergence.

Overall, convergence research has concentrated on global and industrial perspectives, with agricultural carbon emission convergence studies remaining remarkably scarce. Gao Ming et al. analyzed spatial agglomeration and convergence of Chinese agricultural carbon emission performance from 1999–2010 using ML indices, spatial Moran' s I, and three convergence models, finding "club convergence" effects where regions with similar performance levels and external factors converge to uniform steady states. Yang Xiuyu subsequently employed Theil indices to measure regional disparities in agricultural carbon intensity from 1993–2011, finding no σ-convergence or conditional β-convergence—implying inter-regional differences would not diminish over time. Cheng Linlin et al. studied convergence trends, clustering, and club characteristics of agricultural carbon productivity across 31 provinces from 1997–2012 using kernel density functions and spatial econometrics, identifying σ-convergence in eastern and western regions but not nationally.

Existing agricultural carbon emission convergence research has examined performance, intensity, and productivity from different angles, yet divergent conclusions persist due to variations in testing methods, indicator selection, and sample data. Moreover, conventional α, β, and club convergence tests based on cross-sectional and panel regressions have limitations: β-convergence cannot reveal dynamic convergence processes, and cross-sectional tests often suffer from poor size properties, frequently rejecting non-convergence hypotheses and yielding biased results. This paper therefore adopts stochastic convergence testing—an improved method based on panel unit root tests. Panel data offer greater variability and information than time series or cross-sectional data alone, addressing previous research limitations. Building on estimates of agricultural carbon emissions for 30 Chinese provinces (excluding Hong Kong, Macau, Taiwan, and Tibet) from 2000–2014, this study employs the SBM-Undesirable model to calculate agricultural carbon emission performance and conducts stochastic convergence tests on both emissions and performance using panel unit root methods, providing references for rational agricultural carbon reduction policy formulation.

1.1 Agricultural Carbon Emission Calculation

Following established practices in agricultural carbon emission estimation, emission sources are categorized into three components: (1) emissions from agricultural land use, including those from chemical fertilizers, pesticides, and plastic film; diesel consumption by agricultural machinery; soil organic carbon loss from tillage; and indirect fossil fuel consumption for irrigation; (2) methane emissions from rice cultivation; and (3) emissions from ruminant livestock, including enteric fermentation and manure management.

Total agricultural carbon emissions represent the sum of emissions from all sources. lists the carbon emission coefficients for each source.

1.2.1 Model Introduction

Data Envelopment Analysis (DEA) represents the mainstream approach for carbon emission performance measurement, capable of simultaneously evaluating multiple inputs and outputs without prespecified production functions or parameters. DEA generates input-output weights through mathematical programming, eliminating subjective influences and ensuring objective evaluation.

Traditional DEA principles maximize benefits—achieving maximum output with minimum input. However, in a low-carbon society context, agricultural production generates undesirable byproducts like carbon emissions. Tone developed the non-radial, non-oriented SBM model, with the SBM-Undesirable model extending this framework to incorporate both desirable and undesirable outputs.

Since results differ under Variable Returns to Scale (VRS) and Constant Returns to Scale (CRS) assumptions, this study follows Wang Bing et al. and employs the VRS-based SBM-Undesirable model.

The model assumes n Decision-Making Units (DMUs), each characterized by three elements: inputs, desirable outputs, and undesirable outputs, denoted as $x \in \mathbb{R}^+$, $y^g \in \mathbb{R}^+$, and $y^b \in \mathbb{R}^+$ respectively. Three matrices are defined: $X = [x_1, \dots, x_n] \in \mathbb{R}^{m\times n}$, $Y^g = [y_1^g, \dots, y_n^g] \in \mathbb{R}^{s_1\times n}$, and $Y^b = [y_1^b, \dots, y_n^b] \in \mathbb{R}^{s_2\times n}$. The production possibility set is:

$$P = \{(x, y^g, y^b) | x \geq X\lambda, y^g \leq Y^g\lambda, y^b \geq Y^b\lambda, \lambda \geq 0\}$$

where λ is a non-negative weight vector in $\mathbb{R}^n_+$. The VRS-based SBM-Undesirable model is formulated as the following linear programming problem:

$$\rho^* = \min_{\lambda, s^-, s^g, s^b} \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{ro}^b}\right)}$$

subject to:

$$\begin{aligned} x_o &= X\lambda + s^- \\ y_o^g &= Y^g\lambda - s^g \\ y_o^b &= Y^b\lambda + s^b \\ s^- \geq 0, s^g &\geq 0, s^b \geq 0, \lambda \geq 0, \sum_{j=1}^{n} \lambda_j = 1 \end{aligned}$$

Here, s^-, s^g, and s^b represent slack variables for inputs, desirable outputs, and undesirable outputs respectively; ρ^* is the objective function value; and λ is the weight vector. The objective function ρ^* is strictly decreasing in s^-, s^g, and s^b, with $0 < \rho^* \leq 1$. When $s^- = 0$, $s^g = 0$, and $s^b = 0$, the DMU is efficient; when $\rho^* < 1$, the DMU is inefficient and requires input-output improvements.

1.2.2 Indicator Selection and Data Processing

All data were sourced from the *China Statistical Yearbook*, *China Rural Statistical Yearbook*, provincial statistical bureau publications, and *Agricultural Statistical Data for Thirty Years of Reform and Opening Up*. Excluding Hong Kong, Macau, Taiwan, and Tibet due to data limitations, the dataset comprises panel data for 30 Chinese provinces from 2000–2014.

Building on existing research and production factor theory, agricultural production inputs are categorized into labor, land, capital, and other inputs, while outputs are divided into desirable and undesirable categories (). Capital input data were unavailable directly; following Wang Jintian et al., this study employs the perpetual inventory method to calculate pure physical capital excluding labor and land:

$$K_{it} = (1 - \delta)K_{i,t-1} + I_{it}$$

where K_{it} represents the current agricultural fixed capital stock for province i, $K_{i,t-1}$ is the previous period' s stock, I_{it} is current agricultural fixed asset investment, and δ is the depreciation rate. Capital input is measured in 100 million yuan. To ensure comparability across years, data were deflated to 2000 constant prices, with the resulting real values serving as the desirable output variable.

1.3 Stochastic Convergence Testing

The stochastic convergence framework follows Evans and Karras. Consider N regions indexed by $i = 1, 2, \ldots, N$. Convergence exists if and only if a common trend a_t and parameters μ_i satisfy:

$$y_{it} = \delta_i + \mu_i a_t + \epsilon_{it}$$

where y_{it} is region i' s carbon emission performance and ϵ_{it} is a stationary disturbance term. Pairwise unit root tests suffer from low power with short time spans. Averaging across regions yields:

$$\bar{y}_t = \frac{1}{N}\sum_{i=1}^{N} y_{it} = \bar{\delta} + \bar{\mu}a_t + \bar{\epsilon}_t$$

Subtracting this from the individual equation eliminates the unobservable common trend a_t:

$$y_{it} - \bar{y}_t = (\delta_i - \bar{\delta}) + (\mu_i - \bar{\mu})a_t + (\epsilon_{it} - \bar{\epsilon}_t)$$

Convergence requires that $k_{it} = y_{it} - \bar{y}_t$ be a stationary series for all i. This is tested through the autoregressive parameter β_i in:

$$k_{it} = \alpha_i + \beta_i k_{i,t-1} + \varphi_i(L)\Delta k_{i,t-1} + u_{it}$$

where i indexes regions, t indexes time, α_i captures regional effects, $\varphi_i(L)$ ensures all roots of the lag polynomial lie outside the unit circle, and L is the lag operator. Assuming no cross-sectional correlation as $N \to \infty$, panel unit root tests on $y_{it} - \bar{y}_t$ determine stochastic convergence. If $\beta_i = 0$, the output gap follows a stationary process, indicating convergence to a common equilibrium level where external shocks are temporary. If $\beta_i \neq 0$, unit root processes cause shocks to accumulate, resulting in stochastic divergence.

2.1 Agricultural Carbon Emission Estimates and Analysis

Using provincial data from 2000–2014, agricultural carbon emission totals were calculated and regional means computed by dividing by the number of provinces in each region. Results appear in .

reveals several patterns: (1) National agricultural carbon emissions increased overall from 2000–2014, with annual growth rates of 0.21% nationally and -0.32%, 0.61%, and 0.32% for eastern, central, and western regions respectively. Only the eastern region showed a gradual decline, while western and central regions experienced growth, with the central region exhibiting the highest growth rates. (2) Growth rates indicate modest emission increases across all three regions during 2000–2003, likely due to reduced agricultural activity as "three rural issues" gained prominence. In 2004, central government agricultural policies stimulated production, increasing emissions from land use and rice cultivation. In 2006, emissions dropped substantially as most provinces reduced ruminant livestock populations (cattle and pig numbers fell 25.5% and 16.9% nationally) and chemical fertilizer use, presumably due to mandatory energy conservation measures during the 11th Five-Year Plan and enhanced environmental awareness. (3) Cross-sectional analysis reveals stark regional differences, with central region emissions far exceeding national, eastern, and western averages. The gaps widened from 3.3574 million t, 3.9650 million t, and 5.9047 million t in 2000 to 5.2448 million t, 7.3512 million t, and 7.6810 million t by 2014 (growth rates of 56.2%, 85.4%, and 30.0%). Eastern emissions fell below the national average while western emissions rose slowly, narrowing the east-west gap, though growth rates suggest they will not converge to identical levels.

2.2 Agricultural Carbon Emission Performance Estimates and Analysis

Building on emission calculations, DEA Solver Pro 5.0 software was used to measure agricultural carbon emission performance under VRS assumptions using the SBM-Undesirable model. Results appear in .

Seven of 30 provinces achieved performance on the production frontier for over half the study period, indicating optimal input-output levels and effective carbon control. Performance was notably high in developed agricultural regions like Shanghai, Beijing, Jiangsu, Zhejiang, and Fujian. Hainan maintained perfect performance (1.000) throughout, while Qinghai achieved 1.000 from 2007 onward. Despite being developing regions, these provinces demonstrated relative efficiency through scale and technology comparisons.

Among the 23 inefficient provinces, Shandong, Hebei, and Liaoning maintained performance values of 0.5–1.0, requiring minor improvements for efficiency. Notably, Shandong stabilized at 1.000 from 2008 onward, demonstrating positive trends. In contrast, Yunnan, Sichuan, Xinjiang, Hubei, Hunan, and Jiangxi exhibited poorer performance, mostly fluctuating between 0.3–0.6, indicating substantial room for improvement. The lowest performers—Ningxia, Shanxi, and Ganshu—showed performance below 0.3 for most years, requiring fundamental input-output restructuring. Averaging 2000–2014 performance values, 12 provinces including Beijing, Tianjin, Hainan, and Qinghai exceeded the national average, while 18 provinces including Sichuan, Guizhou, Yunnan, Shaanxi, Jilin, and Heilongjiang fell below. High-performance provinces cluster in the east, while low-performance provinces predominantly belong to central and western regions.

To visualize regional performance differences, [Figure 1: see original paper] plots mean performance trends for the three regions and the nation. Eastern performance remained stable around 0.8, while western and central performance showed opposite trajectories. Despite starting lowest, the western region improved gradually, whereas the central region, initially intermediate, fell to last place by 2014. Eastern regions benefit from advanced technology and substantial investment, promoting carbon reduction and sustainable development. Central and western regions, constrained by topography and technological limitations, employ extensive agricultural practices, resulting in high emissions, low performance, and severe resource depletion and environmental degradation, particularly in the central region.

2.3 Stochastic Convergence Testing

Given significant regional disparities in both emission levels and performance, this section examines whether these gaps widen or narrow over time using LLC, ADF-Fisher, and PP-Fisher panel unit root tests.

For emission level convergence, the testing procedure follows Carlino et al.: (1) Create a panel of differences between provincial emissions and the national average, then apply panel unit root tests for national-level convergence; (2) Conduct club convergence within each region by subtracting regional averages from provincial emissions and testing the three resulting panels.

For performance convergence, the same procedure applies. Results appear in and .

2.3.1 Emission Level Convergence Results With LLC and ADF-Fisher tests failing to reject the unit root null hypothesis (p-values of 0.6403 and 0.2638), while only PP-Fisher rejects at 1% significance, the evidence favors no national stochastic convergence, indicating persistent and widening inter-provincial gaps.

Regionally, all three tests reject the unit root hypothesis at 1% significance for the eastern region, confirming stochastic convergence and a relatively stable emission path among eastern provinces. Western region tests (p-values of 0.9731, 0.7682, and 0.7786) cannot reject the null, as rapid emission growth in Yunnan, Gansu, and Xinjiang (increasing from 11.35, 3.55, and 4.17 million t in 2000 to 13.05, 5.68, and 7.29 million t in 2014) diverged from stable emissions in other provinces, preventing stable equilibrium formation. Central region results similarly fail to reject the null at 5% significance, with Shanxi maintaining stable emissions around 3 million t while other provinces, particularly Heilongjiang (growing from 11.62 to 21.33 million t), followed divergent trends that hindered club convergence.

2.3.2 Performance Convergence Results Nationally, LLC (p=0.1479) and ADF-Fisher tests fail to reject the unit root null, while PP-Fisher rejects at 5% significance. Following the majority principle, no national stochastic convergence exists, consistent with [Figure 1: see original paper] showing divergent trends.

For the eastern region, all three tests reject the null hypothesis, indicating stochastic convergence despite minor fluctuations. Western region results show LLC failing to reject while ADF-Fisher and PP-Fisher reject at 1% and 5% respectively, suggesting club convergence. Central region tests unanimously reject the null at 1% significance, confirming stochastic convergence despite occasional outliers (e.g., Sichuan' s performance spike to 1.000 in 2003–2004 and Xinjiang' s in 2010), as provinces returned to stable values, maintaining a stable intra-regional gap path.

2.3.3 Comparative Analysis Convergence results for levels and performance show similarities and differences: (1) Neither national emissions nor performance exhibit stochastic convergence, instead showing persistent divergence due to varying production methods and energy consumption patterns. (2) At the regional level, eastern emissions and performance both converge, forming a high-performance, low-emission club supported by advanced technology and sustainable practices. Central and western emissions diverge, but performance shows club convergence, forming low-performance, high-emission clubs where convergence occurs at low levels. (3) The divergence in emissions versus convergence in performance may stem from traditional regional classifications based on multiple factors (economic conditions, natural environment, industrial structure). While performance, comprising multiple indicators, can converge within regions, emissions—a single indicator—face stricter convergence requirements, preventing stable intra-regional paths.

3 Conclusions and Recommendations

(1) From 2000–2014, national average agricultural carbon emissions increased, with only the eastern region declining while western and central regions grew, particularly the central region with the highest growth rates and emissions far exceeding other regions.

(2) Agricultural carbon emission performance shows clear regional differences. National and eastern performance remained stable around 0.6 and 0.8 respectively, while central and western performance fluctuated between 0.3–0.5. The eastern region consistently led, the western region improved from the lowest starting point, and the central region fell to last place.

(3) Stochastic convergence tests reveal that neither national emissions nor performance converge automatically. Eastern emissions and performance converge, while central and western emissions diverge but performance shows club convergence at low levels.

Based on these findings, we recommend:

(1) Implement differentiated emission control policies tailored to local conditions. High-emission provinces (Hunan, Henan, Sichuan) require strict reduction targets and carbon reduction technologies. Since enteric fermentation and manure management account for over 50% of emissions in some provinces, improved manure management is essential. Plastic film contributions exceed 20% in Gansu and Xinjiang, requiring mechanized film application and removal to reduce residual pollution.

(2) Adopt differentiated production approaches based on regional performance differences. Eastern regions should maintain high performance while optimizing resource allocation. Central and western agricultural provinces can learn from Shandong' s efficient input configuration (performance=1.000). Western provinces like Guizhou, Yunnan, Qinghai, and Gansu face labor redundancy due to slower rural labor transfer. Chemical fertilizers contribute over 30% of emissions in some provinces; transitioning from inorganic to organic fertilizers and improving absorption efficiency can enhance performance.

(3) Use policy intervention to achieve regional stochastic convergence. Natural mechanisms alone cannot close national gaps. While eastern emissions are well-controlled, central and western regions need material and technical support. Given significant resource endowment differences, achieving emission convergence is challenging. However, intra-regional performance differences are smaller, enabling cost-effective, regionally-differentiated but intra-regionally-uniform performance optimization policies through increased funding, advanced technology, and improved resource allocation efficiency.

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