Analysis of Research Progress on Agricultural Eco-Efficiency: Postprint

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Abstract

Agricultural eco-efficiency constitutes a crucial indicator for evaluating the sustainability of agricultural development. Through its assessment, the true value of agricultural ecosystems can be accurately evaluated, enabling efficient utilization of agricultural resources and mitigation of endogenous pollution caused by agricultural waste, thereby fundamentally addressing ecosystem degradation and environmental pollution while laying the foundation for sustainable agricultural development. A systematic review of extant literature reveals several issues in agricultural eco-efficiency research: 1) inconsistent conceptual definitions and convergent evaluation methodologies; 2) insufficient investigation of influencing factors at the macro level, with convergence analysis at the county level urgently requiring enrichment; 3) applications in ecological asset reproduction, ecological agricultural production modes, and ecological agricultural policies urgently requiring strengthening. To this end, this paper analyzes the following aspects that agricultural eco-efficiency research will focus on to promote sustainable agricultural development in China: 1) improving evaluation methodologies for agricultural eco-efficiency; 2) strengthening research on driving factors of agricultural eco-efficiency; 3) promoting application of agricultural eco-efficiency in ecological asset reproduction, transformation of agricultural production modes, and formulation of agricultural policies.

Full Text

Preamble

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Review of Methodology and Application of Agricultural Eco-Efficiency

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Abstract: Agricultural eco-efficiency is a crucial indicator for evaluating agricultural sustainability. Through its assessment, we can accurately evaluate the true value of agricultural ecosystems to achieve efficient utilization of agricultural resources, mitigate endogenous pollution caused by agricultural waste, and fundamentally address ecosystem degradation and environmental pollution, thereby laying a foundation for sustainable agricultural development. A systematic review of existing literature reveals several key problems in agricultural eco-efficiency research: 1) inconsistent conceptual definitions and convergent evaluation methods; 2) insufficient research on macro-level influencing factors and a pressing need for more convergence analyses at the county level; and 3) applications in ecological asset reproduction, eco-agricultural production modes, and eco-agricultural policies that require strengthening. Accordingly, this paper identifies future research priorities for promoting sustainable agricultural development in China: 1) improving evaluation methods for agricultural eco-efficiency; 2) strengthening research on driving factors; and 3) advancing applications in ecological asset reproduction, transformation of agricultural production modes, and policy formulation.

Keywords: Agricultural eco-efficiency; Agricultural ecosystem; Agricultural resources; Environmental pollution; Sustainable development

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Introduction

With rapid population growth and changing consumption demands, agriculture now provides not only food production but also increasingly delivers living functions and ecological services such as recreation, tourism, and landscape values [**?**]. For China, a developing country, agricultural development since rural reforms began over 30 years ago has achieved remarkable success: feeding 22% of the world' s population with only 7% of global cultivated land [**?**]. However, long-term over-reliance on natural resource utilization and chemical inputs has caused severe non-point source pollution and environmental damage. Currently, China' s agricultural sustainability faces dual constraints from resources and the environment. Statistics indicate that in 2015, China' s land area was 9.478 million km^2, but per capita cultivated land was only 0.982 hm^2, a 2% decrease from 2004. During rapid industrialization and urbanization, occupation of high-quality cultivated land has shown a rigid increasing trend, further reducing the proportion of premium farmland. For agricultural water resources, scarcity is becoming increasingly apparent. Data show that agricultural water use has declined from 85% of total national water consumption in the early 1980s to about 65% currently, with decreasing supply guarantee rates, particularly for high-quality water sources. Additionally, land desertification has become increasingly severe, reaching 2.67 million hm^2 and expanding at 2,460 km^2 annually [?]. Degraded, desertified, and salinized grassland accounts for about one-third of total grassland area, increasing at 2 million hm^2 per year. Biodiversity has sharply declined, with 15%–20% of animal and plant species now threatened. All these ecological problems exist extensively in rural areas, posing serious challenges to agricultural sustainability.

Research shows that agricultural non-point source pollution has become a major pollution source in China [?]. The First National Agricultural Pollution Census Report revealed that chemical oxygen demand, total nitrogen, and total phosphorus emissions from agricultural production reached 13.24 million tons, 2.7 million tons, and 280,000 tons respectively, with agricultural pollution accounting for 33%–50% of total national pollution [?]. The Asian Development Bank estimates that annual direct economic losses from resource and environmental damage in Chinese agriculture represent 0.1%–1% of national GDP [?].

As living standards improve and household Engel coefficients decline, consumers increasingly demand high-quality, safe agricultural products, while production faces shortages of premium land and water resources, creating a supply-demand contradiction that may intensify in the short term. Therefore, urgent action is needed to achieve green transformation in agricultural production, prioritizing quality improvement. This requires in-depth research on eco-efficiency in agricultural production to inform policy recommendations for sustainable agricultural development.

In the field of eco-efficiency research, substantial achievements have been made [?]. Specifically for agricultural eco-efficiency, domestic scholars have conducted studies at two scales: 1) national scale, using national and provincial data with various evaluation methods; and 2) provincial, municipal (county), and district scales, examining multi-dimensional (temporal and spatial) agricultural eco-efficiency using regional data. National-scale research continues, with methodological innovations such as DEA dynamic models considering time effects [?] and spatial econometric methods [?]. Research at provincial, municipal, and county levels is abundant but lacks innovation, as reflected in the journals where such studies are published [?]. Since agricultural eco-efficiency research started relatively late in China, many areas require more in-depth investigation. This paper systematically reviews existing literature on agricultural eco-efficiency concepts and research methods, and prospects key issues needing resolution in future research.

1.1 Conceptual Definition of Agricultural Eco-Efficiency

The term "eco-efficiency"is translated from "eco-efficiency,"where "eco-"is the root of both ecology and economy, and "efficiency"denotes efficiency and effectiveness, indicating that the concept encompasses both ecological and economic dimensions [?]. The concept was first proposed by German scholars Schaltegger and Sturm in 1990, defined as the ratio of added value to increased environmental impact [?]. It gained widespread recognition after the World Business Council for Sustainable Development (WBCSD) published *Changing Course: A Global Business Perspective on Development and Environment* in 1992, which defined eco-efficiency as: "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth' s estimated carrying capacity, and simultaneously achieving environmental and social development goals" [?]. This WBCSD definition remains the most widely accepted globally [?], with subsequent elaborations by OECD, BASF Corporation, EFG-IFC, UNCTAD, Australian Government Department of the Environment and Heritage, and Industry Canada.

Agricultural eco-efficiency extends the eco-efficiency concept to agriculture, inheriting its essential connotations but lacking a precise, universally accepted definition. Scholars have defined it from various perspectives, emphasizing particular aspects without general applicability. Zhou Zhenfeng [?] defined it as the input-output ratio based on economic indicators, resource inputs, and environmental impacts, achieved by regulating resource use in agricultural production to minimize resource consumption and waste pollution while meeting food demand and quality of life needs. This definition emphasizes efficient resource utilization but insufficiently addresses environmental impacts. Wu Xiaoqing et al. [?] defined it as minimizing environmental pollution and resource consumption while ensuring agricultural product quantity and quality, promoting a modern eco-agricultural development model based on "appropriate quantity, high quality, pollution reduction, and resource conservation." This view treats agricultural eco-efficiency as merely a scientific development model, underestimating its broader value. Chen Zunyi [?], evaluating Anhui' s agricultural eco-efficiency, defined it as producing maximum output with minimum resources and energy consumption while minimizing environmental impact during crop cultivation, limiting the scope to planting and excluding other agricultural activities. Chen Xingpeng et al. [?] defined it as the relationship between agricultural input, expected economic output, and expected environmental output, considering expected environmental outputs but neglecting unexpected outputs. These varied definitions lack universality, with most studies applying the general eco-efficiency definition directly to agriculture without proper contextualization. Based on eco-efficiency as a comprehensive efficiency comprising economic and environmental components, and considering agricultural production characteristics, we define agricultural eco-efficiency as: **in agricultural production activities, maintaining natural resource consumption and pollu-**

tant treatment capacity within the carrying capacity of agricultural ecosystems, producing greater quantities and higher quality agricultural products or services with fewer natural resources, while minimizing negative impacts on the environment and agricultural product consumption.

1.2.1 Three Entry Points for Agricultural Eco-Efficiency Research

The initial focus of agricultural eco-efficiency research was evaluation—the first entry point. This approach uses agricultural products' economic value as output and the impact on ecosystem carrying capacity (including natural resource consumption and environmental pollutant emissions) as resource-environmental input value, employing mathematical methods and economic models to analyze agricultural eco-efficiency of research units and derive policy implications for improvement. Addressing inefficiencies identified in evaluations, some scholars [?] examined the efficiency loss structure of agricultural ecosystems by dividing it into agricultural resource inputs, expected economic outputs, and unexpected environmental damage outputs to identify key issues and propose specific measures for improving agricultural eco-efficiency and achieving coordinated development between agricultural economic and ecological systems—the second entry point. Given significant regional differences in natural resource endowments and economic development levels, spatial-temporal variations in agricultural eco-efficiency naturally exist. Therefore, analyzing agricultural eco-efficiency from temporal and spatial dimensions to explore limiting factors and examine endogenous growth mechanisms and exogenous improvement pathways constitutes the third entry point. Correspondingly, agricultural eco-efficiency research requires three types of work: 1) improving evaluation methods; 2) perfecting legal, regulatory, and policy systems for enhancing agricultural eco-efficiency; and 3) exploring endogenous growth mechanisms and exogenous improvement pathways.

1.2.2 Differences in Research Background Between Domestic and International Studies

The close connection between agriculture and its ecological environment is generally realized through agricultural policies that protect natural resources and the environment [?]. The original purpose of agricultural eco-efficiency research was to evaluate agricultural policy effectiveness to ensure farming practices do not damage agricultural ecosystems. Therefore, developed countries focus on limited natural resources to maximize human welfare and minimize environmental impacts, advocating improved resource utilization efficiency, reduced pollution, and provision of high-quality, safe agricultural products. China' s introduction of eco-efficiency, particularly in agriculture, has a shorter history, with most research concentrating on productivity until resource and environmental problems significantly impacted agricultural sustainability [?]. Consequently, Chinese agricultural eco-efficiency research emphasizes agricultural environmental pollution, particularly negative externalities from chemical fertilizers, pesticides, insecticides, and herbicides, and government/policy failures in addressing these externalities and their impacts on agricultural efficiency, farmer income, and rural ecology. This represents the first difference in research starting points. Developed-country scholars base their research on the premise that ecosystem carrying capacity underpins economic system development [?], believing that resource supply and environmental pollutant absorption within carrying capacity can better promote agricultural economic development [?]. Chinese scholars address the failure of existing economic theories to fully consider ecosystem equality, advocating ecology as the foundation serving economic value maximization to achieve sustainable agricultural development [?]. This constitutes the second difference. After years of research, these differences have largely disappeared, with studies gradually converging.

2.1.1 Ratio Method

Early eco-efficiency evaluation methods primarily used the ratio of economic value to resource-environmental impact. The widely accepted formula was proposed by the WBCSD:

$$\text{Eco-efficiency} = \frac{\text{Product or service value}}{\text{Environmental impact}}$$

Agricultural eco-efficiency ratio methods have special characteristics because agriculture has both negative impacts (pesticide residues, soil compaction, fertility loss) and positive impacts (CO_2 absorption, noise reduction, harmful gas absorption). Therefore, the agricultural eco-efficiency ratio can be expressed as:

$$\text{Agricultural eco-efficiency} = \frac{\text{Economic value of agricultural products}}{\text{Negative environmental effects} - \text{Positive environmental effects}}$$

The ratio method reflects economic development’ s environmental impacts but only considers output while ignoring input, where the root of environmental impact lies. Consequently, this method has gradually fallen out of favor, replaced by other approaches.

2.1.2 Life Cycle Assessment Method

Life cycle assessment originated in the 1960s when resource consumption and oil crises significantly impacted society. However, early evaluations were limited to few environmental loads, slowing progress until the 1990s when sustainable development research advanced. The Society of Environmental Toxicology and Chemistry and ISO formally defined life cycle assessment as evaluating energy and resource consumption and waste emissions throughout a product' s entire life cycle (from raw material extraction through disposal) to identify potential environmental impacts and recommend improvements [?]. The earliest quantitative life cycle assessment method was the 1990 Swiss ecological scarcity method [?], calculated as:

$$\text{Ecopoints} = \frac{\text{Emissions}_A}{\text{Emissions}_T}$$

where subscript A denotes actual environmental load and T denotes ideal environmental load. Gu Chengliang et al. [?] empirically analyzed fiscal energy conservation and environmental protection investment impacts on regional eco-efficiency using life cycle assessment. However, this method faces difficulties in boundary determination, complex data selection, strong subjectivity, and questionable credibility, making regional comparisons challenging.

2.1.3 Stochastic Frontier Analysis

Stochastic frontier analysis is a parametric method widely used for efficiency calculation, initially proposed by Farrell [?] in 1957 and independently developed by Aigner et al. [?] and Meeusen and Van Den Broeck [?] in 1977. This method requires specifying a production function, comparing actual output with maximum expected output, and decomposing the error term into inefficiency and random error components. It accounts for random errors' effects on individual efficiency, making it more accurate than DEA. However, it only handles single outputs and produces large errors when input indicators have complex correlations. The basic stochastic frontier production function is:

$$y_{it} = f(x_{it}, t) \cdot \exp(v_{it} - u_{it})$$

where y_{it} is output of unit i in period t, x_{it} represents production factors, t is time dimension, $f(\cdot)$ is the estimated production function, u_{it} is the non-negative inefficiency error term, and v_{it} is the random error term. Lio et al. [?] used stochastic frontier methods to explore relationships between agricultural efficiency and production systems, while Wadud et al. [?] compared farm-level production efficiency in Bangladesh using both stochastic frontier and DEA methods.

2.1.4 Ecological Footprint Analysis

Proposed by Canadian ecologist Rees [?] in the early 1990s and developed by Wackernagel, ecological footprint analysis compares human demand on nature (converted to biologically productive land area) with nature' s supply to determine if regional economic development stays within ecosystem carrying capacity. If human demand is less than regional supply, resources are in ecological surplus; otherwise, they are in ecological deficit. Hong Mingyong et al. [?] analyzed Guizhou' s agricultural sustainability using the ecological footprint model. However, the method has theoretical and practical limitations: lack of actual consumption data for biological resource accounts leads to substitution with production data, causing errors [?]; incomplete account coverage (e.g., omitting underground resources) may underestimate actual carrying capacity [?]; and its emphasis on land productivity and quantity neglects ecological function and quality [?].

2.1.5 Emergy Analysis Method

Developed by renowned ecologist Odum [?] in the 1980s, emergy analysis quantitatively measures "nature-economy-society" complex ecosystems. Using solar emergy as a baseline, it converts different, incomparable energy types into a common standard through emergy transformity to comprehensively analyze ecological flows (material, monetary, information) and evaluate system structure, function, and benefits [?]. Ling Liwen et al. [?] studied ecological efficiency of 67 county agricultural economic systems in Guangdong Province, while Zhu Yulin et al. [?] evaluated Hunan' s 2008 agricultural production using emergy methods. The method involves five steps: 1) collecting original data on resources, environment, and socioeconomics; 2) drawing emergy system diagrams (defining boundaries, inputs/outputs, component processes); 3) compiling emergy analysis tables (raw data, transformity, net emergy yield ratio, environmental loading); 4) constructing comprehensive emergy structure diagrams; and 5) calculating emergy indicators. Emergy analysis incorporates resources, environment, and economic value, overcoming traditional economics' pricing difficulties, but suffers from regional variability in emergy transformity, overly single indicators, and lack of composite metrics.

2.1.6 Data Envelopment Analysis (DEA)

DEA, created by Charnes, Cooper, and Rhodes in 1978, is currently the most widely used method for evaluating agricultural eco-efficiency. It assesses relative effectiveness or efficiency of decision-making units with multiple inputs and outputs of the same type, using a non-parametric, probability-based approach [?] without requiring specific model forms or dimensionless data processing. Liu

Feixiang et al. [?] evaluated agricultural eco-efficiency in 17 townships in Wuping County, Fujian using traditional DEA. Wu Xiaoqing et al. [?] applied a preference cone-based DEA model to Wuxi' s agricultural eco-efficiency. Wang Baoyi et al. [?] used the SBM-Undesirable model to assess China' s agricultural eco-efficiency from 1993–2013. Hong Kairong et al. [?] employed network DEA to evaluate agricultural eco-efficiency in 30 Chinese provinces from 2005–2013.

2.1.7 Other Evaluation Methods

Besides the above methods, other approaches include opportunity cost-based economic accounting and system energy flow methods. Opportunity cost methods evaluate capital added value per unit capital input, while system energy flow methods define eco-efficiency as the percentage of usable energy actually utilized between trophic levels. Cheng Cuiyun et al. [?] evaluated China' s agricultural eco-efficiency from 2003–2010 using opportunity cost methods, and Bian Yousheng [?] assessed Beijing' s Liuying eco-agricultural project using system energy flow methods.

In summary, ratio, life cycle assessment, stochastic frontier analysis, ecological footprint, emergy analysis, and DEA methods each have advantages and disadvantages for calculating agricultural eco-efficiency. Method selection must align with specific research objects and purposes, focusing on improving evaluation techniques and optimizing structural parameters to enhance measurement accuracy. DEA' s growing popularity stems from its ability to handle multi-input, multi-output eco-economic systems while avoiding subjective weighting controversies. However, DEA is highly data-dependent, requiring large volumes of reliable, high-quality data [?].

2.2 Research on Influencing Factors of Agricultural Eco-Efficiency

Current research on influencing factors operates at two levels: micro-level studies focus on input redundancy and unexpected output redundancy, while macro-level studies examine agricultural policies (e.g., eco-subsidies, grain-for-green programs) and industrial structure adjustments. Micro-level research is abundant with consistent conclusions: redundancy in chemical inputs (fertilizers, pesticides, insecticides, film) and agricultural pollution are primary causes of efficiency loss. Liu Zhicheng et al. [?] found excessive fertilizer use, high water consumption, and severe pollution were main factors. Wu Xiaoqing et al. [?] showed reduced fertilizer and pesticide use improves eco-efficiency. Zhang Zilong et al. [?] identified unreasonable input structures, imbalanced input-output ratios, and excessive unexpected outputs as causes of low efficiency. Pan Dan et al. [?] found excessive resource consumption and pollutant emissions were primary loss factors.

Macro-level research shows divergent results. Pang et al. [?] found farmers' per capita net income, planting structure, per capita cultivated land, labor education level, urban-rural income ratio, and effective irrigation area had significant negative impacts, while agricultural fixed asset investment, industrial structure, and total population had positive impacts. Hong Kairong et al. [?] found positive correlations with machinery density and per capita agricultural GDP, but negative correlations with agricultural marketization, disaster rates, fiscal agricultural support, and industrialization levels. Cheng Cuiyun et al. [?] found regional resource-environment endowments improved eco-efficiency, while agricultural input and policy support showed significant negative correlations.

These findings indicate that micro-level innovation requires moving beyond conventional input-redundancy perspectives to identify more specific influencing factors, while macro-level research urgently needs deeper investigation in variable selection and theoretical derivation.

2.3 Research on Convergence of Agricultural Eco-Efficiency

Convergence analysis, originating from Ramsey' s regional economic studies, measures whether countries or regions converge or diverge, later extending to consumption, trade, and innovation [?]. Methods include α-convergence, absolute β-convergence, conditional β-convergence, and club convergence [?]. α-convergence examines whether dispersion in agricultural eco-efficiency across units decreases over time, revealing variation degrees. Hong Kairong et al. [?] used α-convergence to test convergence in eastern, central, western, and northeastern China' s agricultural eco-efficiency (economic, social, and ecological systems).

Absolute β-convergence occurs when units with initially lower eco-efficiency grow faster than high-efficiency units, leading all units to a common steady state, indicating possible long-term convergence. Conditional β-convergence examines convergence to individual steady states, revealing whether inter-unit differences persist long-term. Pang et al. [?] used spatial fixed-effects models to estimate absolute and conditional β-convergence, finding both types exist in China' s agricultural eco-efficiency.

Club convergence examines whether regions with similar initial conditions converge to identical steady states, revealing differences and endogenous change characteristics among similar units. Beyond traditional convergence types, stochastic convergence is emerging in agricultural eco-efficiency analysis. Stochastic convergence occurs when actual eco-efficiency levels align with time-series average levels, predicting whether regional differences will disappear in the short term. Pang et al. [?] found no stochastic convergence in China' s agricultural eco-efficiency, indicating regional differences will persist long-term rather than disappear quickly.

Convergence research remains limited to initial study domains (national and regional levels), with scarce studies at county, sightseeing agriculture, cropping, or livestock levels, requiring enrichment.

2.4 Application Research on Agricultural Eco-Efficiency

Guided by ecological economics rather than human-demand-centered economics, agricultural eco-efficiency research emphasizes sustainable agricultural development under ecosystem constraints [?]. Applications in ecological utilization, protection, construction, and civilization help implement "four-in-one" development. Agricultural eco-efficiency pursues unity between economic and ecosystem optimization, continuous GDP and ecological asset growth, human and ecological security, and harmony among people and between humans and nature, rather than short-term profit or GDP maximization.

This research demands accelerated transformation of agricultural production modes. Future social reproduction will include not only product, capital, and labor reproduction but also ecological asset reproduction, which will become key to agricultural and social reproduction, accelerating integration speed and benefits between agriculture and other industries [?]. It requires designing economic accounting systems suitable for ecological civilization, advancing ecological construction through laws, regulations, assessment mechanisms, and incentive-constraint systems to institutionalize and legalize ecological civilization.

Agricultural eco-efficiency research helps optimize production patterns, form resource-conserving and environmentally protective production modes, implement eco-agricultural policies for protecting cultivated land and water resources, and enhance ecological agricultural product supply capacity. It supports comprehensive prevention and control of water, air, and soil pollution, fosters farmers' awareness of respecting, conforming to, and protecting nature, and cultivates new trends in agricultural environmental protection.

Conclusions and Outlook

This paper reviews and analyzes recent domestic and international agricultural eco-efficiency research. Systematic review reveals that research has achieved certain results, evolving through conceptual exploration, changing entry points, background differences, enriched evaluation methods, factor analysis, convergence analysis, and practical applications. However, problems remain: inconsistent conceptual definitions, convergent evaluation methods, insufficient macro-level factor research, urgent need for county-level convergence analysis, and weak applications in ecological asset reproduction, eco-agricultural production modes, and eco-agricultural policies.

Comprehensive analysis indicates future research should focus on: 1) **Innovative research perspectives**: With agriculture' s multi-functionalities and green transformation, new perspectives are needed for eco-efficiency evaluation. 2) **Methodological innovation**: Accurate assessment requires innovative evaluation methods, improved techniques, and optimized structural parameters to enhance measurement accuracy. 3) **Enriched temporal-spatial dimensions**: Future evaluations should expand spatially (combining macro and micro levels) and temporally (considering long-, medium-, and short-term efficiency). 4) **Improved indicator systems**: Previous studies often used incomplete indicators, focusing only on outputs while ignoring inputs, or using overly single indicators lacking composite metrics, affecting accuracy. Future evaluations should improve indicator systems. 5) **Enhanced applications**: Agricultural eco-efficiency research must ultimately guide practice in ecological asset reproduction, transforming agricultural development modes, and policy formulation.

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Note: Figure translations are in progress. See original paper for figures.