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Emergy Analysis of Specialized Tea Cultivation Agroecosystems: A Case Study of Anxi County, Fujian Province (Postprint)

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Abstract

The global tea consumption boom continuously drives the expansion of tea plantation scale in China' s traditional agriculture, and the development of tea economy receives increasing attention; however, the eco-environmental effects generated by tea cultivation are often overlooked. This study takes Anxi County, Fujian Province—a specialized tea plantation county—as the research object. By integrating three methods—tea plantation area per township, tea plantation location quotient, and concentration coefficient—the specialization levels of tea plantation in each township of Anxi County are classified into five grades: highly specialized, relatively specialized, moderately specialized, less specialized, and no tea plantation. Based on emergy theory analysis methods, an input-output index system for the agricultural ecosystem of Anxi County is constructed, and eight emergy evaluation indicators including emergy input density, environmental loading ratio, and sustainable development index are established to evaluate and analyze agricultural ecosystems with different specialized tea plantation levels. The research results indicate: (1) In the operation process of specialized tea plantation agricultural ecosystems in Anxi County, renewable environmental resource inputs dominate, with environmental contribution rates reaching as high as 0.96~0.99 among different specialization levels, while the emergy investment ratio is only 0.01~0.04; (2) There is a generally positive correlation between tea plantation specialization level and output emergy density. As the specialization level continuously strengthens, the productivity of the agricultural ecosystem continuously improves overall. The output emergy density of highly specialized tea plantation reaches 4.15E+11 sej·m-2, which is 1.32 times that of areas without tea plantation; (3) Specialized tea plantation agricultural ecosystems possess relatively high production efficiency and economic benefits. There is a positive correlation between tea plantation specialization level and net emergy yield ratio. The net emergy yield ratio of highly specialized tea plantation is

1.29, which is 2.86 times that of areas without tea plantation, with an environmental loading ratio of 0.05, demonstrating environmental friendliness; (4) Specialized tea plantation reduces agricultural ecosystem stability. There is a negative correlation between system stability index and tea plantation specialization level. The system stability index of areas without tea plantation is 1.12, which is 1.56 times that of the highly specialized level. Therefore, during the process of specialized tea plantation, emphasis should be placed on constructing compound ecological tea plantations to enhance biodiversity and stability of specialized tea plantation systems, while increasing investment in scientific and technological management and improving agricultural production technology levels, thereby further enhancing the overall economic development level and sustainable development capacity of agricultural systems.

Full Text

Emergy-based Agricultural Ecosystem Analysis for Specialized Tea Planting: A Case Study of Anxi County, Fujian Province

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Abstract
The global surge in tea consumption has continuously driven the expansion of tea plantation scale in China, a traditional agricultural activity, drawing sustained attention to tea economy development. However, the ecological and environmental consequences of tea planting are often overlooked. This study examines Anxi County in Fujian Province, a specialized tea-producing region, and classifies township-level tea planting specialization into five grades—high, sub-high, middle, low, and no tea planting—by integrating three methods: tea planting area, location quotient, and concentration coefficient. Based on emergy theory, we construct input-output indicator systems for Anxi' s agricultural ecosystems and establish eight emergy evaluation indices including emergy input density, environmental load ratio, and sustainability index to assess agricultural ecosystems across different specialization levels. The results indicate: (1) The operation of specialized tea planting agricultural ecosystems in Anxi primarily relies on renewable environmental resource inputs, with environmental contribution ratios reaching 0.96–0.99 across different specialization levels, while emergy investment ratios remain only 0.01–0.04. (2) A positive correlation exists

between tea planting specialization grade and emergy output density. As specialization levels increase, overall agricultural ecosystem productivity improves, with high-specialization tea planting achieving an output density of 4.15E+11 sej · m ², 1.32 times that of non-tea planting areas. (3) Specialized tea planting agricultural ecosystems demonstrate high production efficiency and economic benefits, with a positive correlation between specialization grade and net emergy yield ratio. High-specialization tea planting achieves a net emergy yield ratio of 1.29, 2.86 times that of non-tea planting areas, while maintaining an environmental load ratio of 0.05, indicating environmental friendliness. (4) Specialized tea planting reduces agricultural ecosystem stability, showing a negative correlation between system stability index and specialization grade. The stability index for non-tea planting areas is 1.12, 1.56 times that of high-specialization areas. Therefore, during tea specialization development, emphasis should be placed on constructing compound ecological tea gardens to enhance biodiversity and system stability, while increasing investment in scientific management and agricultural technology to further improve overall economic development and sustainable development capacity.

Keywords: Tea; Specialized planting level; Agricultural ecosystem; Emergy; Anxi County

Introduction

Agricultural ecosystems constitute essential components of terrestrial ecosystems and represent the most fundamental ecosystems for human survival, providing provisioning, regulating, supporting, and cultural services [1]. Human activities significantly influence their structure and function, and their sustainable development critically impacts regional socioeconomic progress. Consequently, examining the ecological effects and sustainability of agricultural ecosystems is particularly important. Tea planting represents a vital part of China' s traditional agricultural activities with a production history spanning thousands of years and occupies a significant position in the nation' s agricultural sector. Expanding tea demand has substantially driven China' s economic development, while the growing scale of tea plantations and the trend toward standardized, scaled, and specialized tea cultivation will inevitably impact agricultural ecosystems. Economic development of these systems must therefore consider the ecological and environmental consequences underlying economic benefits.

Agricultural ecosystems are complex systems. Evaluations using either ecological or economic methods alone can only partially assess certain aspects of their structure and function, failing to comprehensively analyze integrated ecological and economic benefits. In the late 1980s, ecologists led by Odum proposed emergy analysis, providing a new approach for ecological and economic evaluation of agricultural systems. China introduced emergy theory in the early 1990s [2], with Lan Shengfang et al. [3] first applying it to agricultural ecosystem assessment. Emergy analysis employs unified emergy standards, bridging ecology and economics to reveal the true value of natural and socioeconomic systems, with results offering comparability and additivity [4]. Consequently, it has been widely applied to analyze ecological-economic conditions and patterns in agriculture [5-7], forestry [8-10], fisheries [11], industry [12-15], tourism [16-17], land use evaluation [18], and urban ecosystems [19-22] at global, national, watershed, and regional scales, even extending to geochemical studies [23]. Research on energy in China' s agricultural ecosystems started relatively late [24], with emergy analysis primarily used for overall evaluation of agricultural or farmland ecosystems at provincial, municipal, county, or watershed scales. Few studies have examined the impact of specific agricultural elements on ecosystems using emergy methods, and research analyzing tea-dominated agricultural ecosystems and exploring the effects of specialized tea planting remains scarce despite growing global tea consumption.

This study therefore investigates Anxi County, a major tea-producing region known as China' s Tea Capital, to analyze agricultural ecosystems across different specialization grades. By constructing emergy input-output indicator systems for specialized tea planting and establishing eight relevant evaluation indices, we quantitatively analyze the structural and functional characteristics and coordination between ecological and economic benefits of these systems. We examine whether differences exist among agricultural ecosystems at varying specialization levels, whether specialized tea planting imposes significant pressure on ecosystems while generating economic benefits, and what issues require attention to ensure sustainable development of tea-dominated agricultural ecosystems and the tea economy based upon them. The findings aim to provide a basis for implementing management measures for sustainable development of Anxi' s specialized tea planting agricultural ecosystems, offer references for tea economic development in other tea-producing regions of China, and further enrich emergy analysis applications in agricultural evaluation.

1. Study Area Overview

Anxi County, historically known as Qingxi, is located in southeastern coastal Fujian Province, in the northwestern part of the Xiamen-Zhangzhou-Quanzhou "Southern Fujian Golden Triangle" under Quanzhou City' s jurisdiction. The county spans 117°36 -118°17 E and 24°50 -25°26 N, covering a total area of 3,057.28 km^2 with 24 townships, 460 villages, and a population of 1.08 million. Renowned nationwide for its tea industry and hailed as China' s Tea Capital, Anxi is the origin of Tieguanyin, a world-famous tea variety, and is celebrated as the "Hometown of Chinese Oolong Tea." Its tea products hold national certification trademarks, geographical indication protection, and recognition as well-known Chinese trademarks, making the county a leader in China' s tea industry.

From 2000 to 2014, Anxi' s tea production continuously increased, with tea plantation area expanding overall [Figure 1: see original paper]. In 2014, tea production reached 54,175 tons, accounting for 2.6% of national tea output, while plantation area reached 40,000 hectares, representing 1.5% of the national total. The county currently cultivates six nationally certified tea varieties: Tieguanyin, Huangjingui, Maoxie, Benshan, Dayewulong, and Meizhan, with Tieguanyin comprising over 50% of planted area as the dominant variety. The entire county has become a specialized tea planting region in China, ranking first among national key tea-producing counties for six consecutive years since 2009. As Anxi' s most important livelihood and pillar industry, the tea sector has driven numerous related and supporting industries, benefiting over 800,000 people in the county and playing a pivotal role in both economic development and farmer income growth.

2.1 Classification of Township-level Tea Planting Specialization in Anxi County

To examine the impact and ecological effects of specialized tea planting on agricultural ecosystems, classifying township-level specialization is essential. This study uses 2012 data on township tea planting area, location quotient [25], and concentration coefficient [26] to classify specialization degrees. Tea planting area reflects scale and specialization level, while location quotient (Formula 1) and concentration coefficient (Formula 2) are common specialization metrics, with variables adapted according to available data and research objectives. Considering data availability and scientific rigor of classification results, we integrated calculations from all three methods to classify Anxi' s townships into five specialization grades: high, sub-high, middle, low, and no tea planting . The "no tea planting" grade serves primarily as a reference group for comparison with specialized tea planting.

Where Q represents the location quotient of region i for tea planting, e represents tea production in region i, e represents the sum of crop and tea production in region i, E represents total tea production in Anxi County, and E represents the sum of total crop and tea production in Anxi County.

Where C represents the concentration coefficient of region i for tea planting, a represents tea production in region i, A represents total tea production in Anxi County, m represents population of region i, and M represents total population of Anxi County.

2.2 Emergy Analysis of Specialized Tea Planting Agricultural Ecosystems

Emergy analysis is a quantitative method for analyzing ecological and complex systems [27] that reveals the true value of natural and socioeconomic systems and bridges ecology and economics [28]. This study expresses the inputs and outputs of Anxi' s specialized tea planting agricultural ecosystems in emergy terms, calculates emergy evaluation indices, and analyzes these tea-dominated agricultural ecosystems.

2.2.1 Establishing Input Indicators for Specialized Tea Planting Agricultural Ecosystems

We constructed an input indicator system for Anxi' s agricultural ecosystems comprising five primary categories: renewable environmental resources, non-renewable environmental resources, renewable industrial auxiliary energy, non-renewable industrial auxiliary energy, and organic energy inputs, with 19 secondary measurement indicators . Corresponding emergy transformities and conversion coefficients are provided in the table.

2.2.2 Establishing Output Indicators for Specialized Tea Planting Agricultural Ecosystems

Since this study focuses on the impact of specialized tea planting on agricultural ecosystems and Anxi' s agricultural inputs primarily target planting operations, we calculated agricultural ecosystem outputs based mainly on planting sector outputs. Specific indicators, emergy transformities, and conversion coefficients are listed in .

2.2.3 Establishing Emergy Evaluation Indices for Specialized Tea Planting Agricultural Ecosystems

Based on emergy input-output results, we selected eight evaluation indices: emergy output density, environmental contribution ratio, environmental load ratio, emergy input density, net emergy yield ratio, emergy investment ratio, system stability index, and sustainable development index to assess Anxi' s specialized tea planting agricultural ecosystems .

2.3 Data Sources

While agricultural ecosystem emergy output calculations typically involve four aspects—planting, forestry, animal husbandry, and fisheries—this study focuses specifically on specialized tea planting impacts. Original data for all input and output indicators were obtained from the *Statistical Yearbook of Anxi County 2013* [32]. Emergy transformities and calculation methods primarily reference *Emergy Analysis of Ecological Economic Systems* by Lan Shengfang et al. [4] and other established parameters.

3.2.2 Analysis of Emergy Investment Ratio and Environmental Contribution Ratio

The emergy investment ratio measures agricultural economic development level and environmental load, with higher values indicating greater economic development and less dependence on natural environments [12,34]. Among different specialization levels in Anxi, emergy investment ratios show minimal variation and remain relatively small , indicating low economic development levels, high dependence on natural environments, small auxiliary energy inputs, low economic costs of agricultural production, and consequently low environmental load.

The environmental contribution ratio reflects the contribution of regional natural resources to agricultural economic development. Differences in environmental contribution ratios across specialization levels are minimal and approach 1 , demonstrating that natural resources contribute substantially to agricultural economic development regardless of specialization grade. Agricultural system operations primarily depend on renewable resources, with relatively low inputs of industrial auxiliary energy such as chemical fertilizers and pesticides.

Tea-dominated agricultural ecosystems rely mainly on natural resources with minimal non-local resource inputs, thus generating fewer negative effects. However, systems primarily dependent on natural resource inputs face certain limitations in overall agricultural economic development due to relatively low industrial auxiliary energy and technology investments.

Emergy output density represents regional agricultural ecosystem productivity [33]. Among different specialization levels in Anxi, specialized tea planting agricultural ecosystems generally exhibit higher output densities than non-tea systems, with tea-involved systems showing greater productivity. Output density increases with specialization grade in the pattern: high > sub-high > middle specialization [Figure 2: see original paper]. Thus, a positive correlation exists between tea planting specialization grade and emergy output density, with system productivity improving as specialization increases.

Both emergy input density and output density show positive correlations with specialized tea planting. However, on a per-unit land area basis, high-specialization tea planting achieves the highest output while maintaining near-minimum inputs, demonstrating that specialized tea planting positively impacts agricultural ecosystem productivity. Higher specialization grades correlate with more standardized garden management and greater resource utilization efficiency.

3.2.3 Analysis of Net Emergy Yield Ratio and Environmental Load Ratio

The net emergy yield ratio, calculated as total system output divided by total auxiliary emergy input, measures system production efficiency. Higher values indicate greater economic benefits and stronger resource utilization efficiency [27]. Across different specialization levels in Anxi, all tea-involved agricultural systems except the low-specialization grade demonstrate higher production efficiency than non-tea systems, with net emergy yield ratio generally increasing with specialization grade . Optimal net emergy yield ratios should range between 1 and 6; values below 1 indicate insufficient output relative to input [35]. Only the high-specialization tea planting system exceeds 1. Compared with other crops, specialized tea planting demonstrates high production efficiency and economic benefits that improve with specialization grade.

The environmental load ratio reflects environmental carrying pressure, with higher values signaling greater environmental stress from economic activities [34] and serving as a warning for economic systems. Anxi' s agricultural ecosystems maintain an environmental load ratio of 0.05 across all specialization levels, demonstrating environmental friendliness. Tea economic activities do not impose greater environmental pressure than conventional crops, and specialized tea planting generates minimal ecological negative effects while delivering positive economic benefits.

3.2.4 Analysis of System Stability Index and Sustainable Development Index

The system stability index reflects system stability magnitude, with higher values indicating more developed emergy flow networks and stronger resistance and resilience [4]. Anxi' s specialized tea planting agricultural ecosystems show stability indices ranging from 0.72 to 1.12, with an overall favorable condition. However, specialization grades follow the pattern: non-tea planting > low > middle > sub-high > high specialization . Non-tea agricultural ecosystems exhibit higher stability than specialized tea systems, with stability indices decreasing as tea planting specialization increases, demonstrating a negative correlation. Thus, specialized tea planting negatively impacts agricultural ecosystem stability.

The sustainable development index measures agricultural ecosystem sustainability. Values between 1 and 10 indicate viable, sustainable systems, while values exceeding 10 signify underdevelopment and values below 1 represent consumptive economic systems [4]. Anxi' s systems show varying sustainability indices across specialization levels, all exceeding 1. However, only non-tea and low-specialization grades fall below 10, while middle, sub-high, and high-specialization grades exceed 10, with the high-specialization grade showing the maximum value . These results suggest specialized tea planting negatively impacts sustainability capacity by reducing system stability and potentially affecting system vitality. Since the sustainability index primarily represents the ratio of net emergy yield ratio to environmental load ratio, and environmental load ratios are identical across specialization levels in this study, the sustainability index has limited applicability for comprehensively evaluating the sustainability of specialized tea planting agricultural ecosystems.

4. Discussion and Conclusion

Emergy-based agricultural ecosystem evaluation studies are numerous, with recent results generally showing "deficit" conditions or weakening sustainability due to increased industrial auxiliary energy inputs [5,12,36–37]. In contrast, Anxi' s specialized tea planting agricultural ecosystems depend heavily on natural resources with relatively low inputs of chemical fertilizers and pesticides, imposing minimal environmental pressure and demonstrating strong environmental friendliness and sustainability potential. With identical environmental load ratios across specialization levels, the sustainability index is primarily determined by net emergy yield ratio, which increases with specialization grade. This creates a misleading impression that higher specialization corresponds to declining economic development and weakening sustainability potential. In reality, specialized tea planting achieves high production efficiency and economic benefits without imposing greater environmental burdens, indicating substantial vitality and sustainability potential.

Although the sustainability index has limitations in this study, we retained it as an important evaluation metric. The results reveal its limitations as a composite indicator and caution against one-dimensional interpretation.

The study identifies a key weakness of specialized tea planting agricultural ecosystems: the negative correlation between system stability index and specialization grade. Higher specialization corresponds to lower system stability. Yang et al. [38] demonstrated advantages of rice-fish systems over rice monoculture in solar energy conversion efficiency, emergy investment ratio, environmental load ratio, and system vitality. Biodiversity critically influences system vitality, while specialized tea planting reduces agricultural biodiversity during intensification, diminishing system resistance and stability and consequently reducing sustainability levels. Additionally, Chen et al. [39] showed that downslope tea planting exacerbates soil erosion. As Anxi' s specialized tea planting expands and available cultivated land becomes limited, plantations increasingly encroach on hillside areas, creating soil erosion issues that contribute to declining system stability indices with increasing specialization.

Since 2005, however, the Anxi County government has continuously implemented comprehensive ecological tea garden management, promoting an ecological construction model of "trees + grass + fertilizer + water + roads," launching tea mountain greening projects, conducting "tea-to-forest" conversion on ecologically fragile slopes exceeding 25°, and applying green prevention and control technologies including biological control [40]. With strong government support, specialized tea planting represents not unilateral farmer pursuit of economic benefits but a coordinated "government-enterprise-farmer" agricultural economic activity with management, planning, and guidance, endowing these agricultural ecosystems with strong sustainability potential.

This study evaluated tea-dominated agricultural ecosystems, revealing impacts of specialized tea planting. Emergy analysis involves numerous parameters in system input-output calculations, with values varying across research scales. Most domestic and international studies directly adopt parameters proposed by Odum [27] and Lan Shengfang et al. [4], as does this research. While parameters vary across regions and time periods, direct application of emergy transformities and conversion coefficients without spatiotemporal adjustment inevitably affects calculation accuracy and evaluation authenticity in comparative studies. However, for this study' s purpose of comparing agricultural ecosystems across specialization levels within a single county, result accuracy is sufficient for robust assessment. Future research should address this limitation to enhance rigor and precision. Additionally, as this macro-level study relies on statistical data without specific experiments or monitoring, calculations for topsoil loss and organic fertilizer rely on macro-scale estimation with some error. Nevertheless, these macro-level findings provide important guidance for future meso- and micro-scale research on ecological effect mechanisms in Anxi' s specialized tea planting agricultural ecosystems.

By classifying different specialization grades and applying emergy theory to construct input-output indicators and eight evaluation indices for Anxi' s specialized tea planting agricultural ecosystems, this study yields the following conclusions: (1) Specialized tea planting in Anxi is not unilateral farmer pursuit of economic benefits; tea-dominated agricultural ecosystems primarily operate on renewable environmental resource inputs with substantial sustainability potential. (2) A positive correlation exists between tea planting specialization grade and emergy output density, with overall agricultural ecosystem productivity improving as specialization increases. (3) A positive correlation occurs between specialization grade and net emergy yield ratio, with specialized tea planting agricultural ecosystems demonstrating high production efficiency and economic benefits while generating minimal ecological negative effects. (4) Specialized tea planting reduces agricultural ecosystem stability, with system stability indices decreasing as specialization grades increase. Therefore, during tea specialization development, emphasis should be placed on compound ecological tea garden construction to enhance biodiversity and stability, while increasing investment in scientific management and agricultural technology to improve overall economic development and sustainability capacity.

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