Nitrogen Effects Analysis in Agricultural Land Use Systems Based on Material Flow Analysis: A Case Study of Taojiang County, Hunan Province (Postprint)

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Abstract

To systematically analyze and evaluate the environmental effects of agricultural land use, understand material cycling patterns in agricultural systems, and improve material use efficiency, this study employs material flow analysis methods. By constructing a material flow analysis framework and evaluation indicator system for regional-scale agricultural land use systems, and taking Taojiang County in Hunan Province as a case study area, this paper comprehensively evaluates nitrogen use efficiency and environmental health status in the region's agricultural land use system. The results indicate: (1) From 1980 to 2013, both production input nitrogen and environmental input nitrogen in Taojiang County' s agricultural land use system increased significantly, with increases of 1.2-fold and 0.4-fold in 2013 compared to 1980, respectively; among these, production input represented the primary source of total nitrogen input in Taojiang County, accounting for 77% of the total input in 2013. (2) From 1980 to 2013, total nitrogen output in Taojiang County exhibited a fluctuating annual increase, while product output nitrogen increased only marginally; however, environmental output nitrogen increased by 1.4-fold compared to 1980. (3) Concurrently, nitrogen fertilizer input intensity in Taojiang County' s agricultural land use system increased annually, reaching 328.4 kg · hm 2 by 2013, which exceeds the warning threshold (250.0 kg · hm 2); furthermore, nitrogen material use efficiency in Taojiang County decreased year by year, and material production efficiency remains at a relatively low level, necessitating further measures to adjust agricultural structure and enhance the added value of agricultural products. (4) From 1980 to 2010, the ecological stability and environmental health quality of Taojiang County' s agricultural land use system deteriorated annually; however, from 2010 to 2013, environmental health quality in Taojiang County improved, with its nitrogen nutrient load decreasing from 208.8 kg · hm 2 in 2010 to 154.1 kg ·

hm 2 in 2013.

Full Text

Preamble

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SFA-based Analysis of Nitrogen Effects on Agricultural Land Use Systems: A Case Study of Taojiang County, Hunan Province

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Abstract: Since the reform and opening-up policy launched in 1978, environmental problems have intensified due to unreasonable agricultural land use practices in China. Systematic analysis and evaluation of the environmental effects of agricultural land use, detailed understanding of material cycling mechanisms in agricultural systems, and improvement of material utilization efficiency have thus become key research priorities in land science. Substance Flow Analysis (SFA) is a systematic method for assessing material flows and stocks within a defined system across space and time, comprising three components—sources, pathways, and sinks. It characterizes the pathways of substances entering, exiting, and moving through a system, serving as an effective support tool for resource and environmental management. This paper establishes an indicator system (including material input indicators, material output indicators, stock indicators, material intensity and efficiency indicators, and environmental health indicators) based on the SFA framework for assessing regional-scale agricultural land use systems. The method was applied to evaluate material use efficiency and environmental quality in agricultural land use systems. Using Taojiang County (northern Hunan Province) as a case study, material flows in the SFA framework for agricultural land use systems included productive input, production output, environmental output, and stock. The results indicated that: (1) nitrogen derived from material productive input and environmental input increased sharply from 1980 to 2013, with amounts in 2013 being 1.2 and 0.4 times those in 1980, respectively, with productive input serving as the main nitrogen source in Taojiang County; (2) production output increased slowly during 1980–2013, while environmental output in 2013 approximately doubled that in 1980; (3) nitrogen material input intensity in Taojiang County showed an increasing trend, reaching 328.4 $kg \cdot hm^{-2}$ in 2013, exceeding the critical value of 250.0 $kg \cdot hm^{-2}$, while material use efficiency of nitrogen decreased gradually, and compared with the provincial average, material production efficiency in Taojiang County was lowest in 2013, necessitating government measures to promote agricultural structural adjustment and improve added value of agricultural products; and (4) ecosystem stability and environmental quality declined gradually from 1980 to 2010, but improved during 2010–2013, with nitrogen load decreasing from 208.8 $kg \cdot hm^{-2}$ in 2010 to 154.1 $kg \cdot hm^{-2}$ in 2013. Although SFA analysis contains certain errors due to data limitations and parameterization difficulties, the SFA method proves useful for evaluating material use efficiency and environmental quality in agricultural land use systems.

Keywords: Substance flow analysis (SFA); Agricultural land use system; Nitrogen cycle; Environmental quality; Material use efficiency

Introduction

Since China' s reform and opening-up, the widespread adoption of high-input intensive agricultural production models has not only satisfied growing food demands but also created conditions for farmers to increase production and income. However, these high-input intensive models have generated serious environmental problems alongside increased agricultural land use benefits, including excessive fertilizer inputs that intensify agricultural non-point source pollution, soil compaction, and ozone layer depletion, severely affecting the sustainability of high-intensity agricultural land use systems [1]. Consequently, systematic analysis and evaluation of agricultural land use environmental effects, understanding material cycling patterns in agricultural systems, and improving material utilization efficiency have become focal research directions in environmental and land sciences. Substance Flow Analysis (SFA) is a systematic method for analyzing material flows and stocks within specific spatiotemporal boundaries, primarily concerning sources, pathways, and sinks of material flows [2]. It is crucial for understanding material cycling patterns in socio-economic systems, improving material use efficiency, identifying environmental problems, and promoting sustainable socio-economic development [3–4]. Currently, two main types of material flow analysis exist: Bulk-Material Flow Analysis (Bulk-MFA) and Substance Flow Analysis (SFA) [5]. Bulk-MFA analyzes flows of mixtures and bulk materials in socio-economic systems, primarily focusing on national economic systems, and has formed a mature research framework widely applied in countries such as Italy, the United Kingdom, and China [6–13]. SFA focuses on specific substance flows, generally chemical elements or compounds [14], and is commonly applied in national material cycle analysis [15–17], watershed nutrient metabolism analysis [18], and environmental risk assessment [19]. SFA offers particular advantages in tracking flows of specific elements or compounds, identifying environmental problems, and improving material utilization rates, and should theoretically be equally applicable for tracking important element flows and analyzing environmental effects in agricultural land use systems.

Agricultural land use systems are natural-ecological-economic composite systems formed during agricultural production activities, comprising natural environments, production factor inputs, land use patterns, land use processes, and various outputs. Current research on agricultural land use systems primarily focuses on applying nutrient balance models to analyze nutrient flows, identify nutrient surplus or deficit conditions, and assess impacts of agricultural inputs on soil fertility, crop production, and water quality. For example, Wang et al. [20] established a nitrogen balance model for China' s farmland ecosystems to estimate nitrogen inputs, outputs, and surpluses across different regions and analyze environmental effects. Chen et al. [21] developed a framework, methodology, and database for apparent nitrogen and phosphorus balance accounting in China's agricultural systems using the OECD model, revealing severe regional imbalances requiring dual management of surplus and deficit. Bao et al. [22] constructed a nutrient balance model to analyze nitrogen loads and water environment impacts in the Yangtze River basin farmland systems from 1980–1990. However, such studies fail to deeply and accurately analyze material use intensity and efficiency or comprehensively evaluate environmental health status of agricultural land use systems. The SFA model addresses these limitations by enabling deeper analysis of material flow patterns, more comprehensive assessment of material use efficiency, and more systematic evaluation of system health status. This study attempts to construct an SFA framework for agricultural land use systems, establish a suitable material flow analysis indicator system for regional agricultural land use processes, comprehensively analyze material use efficiency and environmental health conditions within regional agricultural land use systems, and conduct systematic research using nitrogen effect analysis in Taojiang County, Hunan Province, as a case study.

1.1 SFA Framework for Agricultural Land Use Systems

Based on conceptual models of agricultural land use systems [23], this paper constructs a regional-scale material flow analysis framework. The overall structure includes five categories of material flows [Figure 1: see original paper]: productive input and environmental input (inputs), product output and environmental output (outputs), and net material stock (internal composition).

Productive input refers to materials deliberately introduced through human labor to achieve specific objectives, primarily including seeds, pesticides, chemical fertilizers, and organic fertilizers. Environmental input includes irrigation, dry and wet deposition, biological nitrogen fixation, and human waste from domestic activities entering the agricultural land use system through sewage and garbage pathways. Unlike productive input, environmental input is unintentional and difficult to measure accurately, representing one of the challenges in applying material flow analysis in agriculture. To address this, scholars typically apply coefficient methods for environmental input estimation [20–22].

Product output is divided into agricultural products and by-products. Agricultural products are the primary objectives of land use activities, such as rice, wheat, and corn, while by-products include non-primary outputs like rice straw and wheat straw. Environmental output consists of surface runoff, underground leaching, volatilization (including ammonia volatilization and nitrous oxide emissions), and denitrification. Like environmental input, this component is difficult to measure accurately.

1.2 Indicators for Agricultural Land Use System SFA

The primary objective of material flow analysis is to reduce total material input and final waste emissions, thereby improving resource use efficiency. To achieve this goal, this paper constructs an evaluation indicator system for agricultural land use systems, comprising four major categories and eleven analytical indicators: material input indicators, material output indicators, intensity and efficiency indicators, and environmental health indicators. Calculation formulas for each indicator are shown in Table 1 .

2.1 Study Area Overview

This study uses Taojiang County in Hunan Province as the case area. Located in north-central Hunan along the middle and lower reaches of the Zi River within the Dongting Lake region, Taojiang County has a mid-subtropical continental monsoon humid climate with average annual precipitation of 1,566 mm. The county governs 15 townships with a total population of 867,000 at the end of 2010, including 713,000 agricultural residents. In 2010, Taojiang County had 44,000 hm^2 of cultivated land, 5,273 hm^2 of garden land, 114,720 hm^2 of forest land, and 17,640 hm^2 of other agricultural land. As a typical southern rice cultivation region, rice planting area accounts for 93% of total grain crop area, with a straw return rate of 68%. In 2010, the county averaged 1,107.0 kg of nitrogen fertilizer, 397.5 kg of phosphate fertilizer, and 229.5 kg of potassium fertilizer per hectare of cultivated land, equivalent to 261.0 kg of pure N, 49.5 kg of P_2O_5, and 130.5 kg of K_2O.

2.2 Data Sources and Calculations

Primary data sources, material flow analysis accounting methods, and parameter value bases are detailed in Table 2 . Since nitrogen input through pesticides is minimal, it was neglected in this study [20].

3.1 Nitrogen Input Indicator Analysis

Based on calculation methods in Tables 1 and 2, nitrogen input in Taojiang County' s agricultural land use system from 1980–2013 was obtained (Table 3). Productive nitrogen input showed a steady increasing trend, particularly rapid growth in fertilizer-derived nitrogen from 2005–2010. Literature review [1] indicates that Hunan Province abolished agricultural taxes and implemented four subsidies for grain farmers (direct subsidies, improved variety subsidies, agricultural machinery purchase subsidies, and comprehensive agricultural production material subsidies) starting in 2005, demonstrating these measures significantly influenced farmers' fertilizer input.

The data also reveal that while total environmental nitrogen input increased from 1980-2013, its composition changed: biological nitrogen fixation dominated in 1980, whereas deposition became dominant by 2013. Despite reduced nitrogen input through seeds, nitrogen fixation, and irrigation due to decreasing cultivated land area, rapid growth in nitrogen input through chemical fertilizers, organic fertilizers, and deposition caused total nitrogen input to the agricultural land use system to increase by approximately 100%, rising from 16,887.4 t in 1980 to 32,926.4 t in 2013. Analysis indicates that over the past 30 years, both productive and environmental nitrogen inputs in Taojiang County increased significantly, with productive input—especially through chemical fertilizers—serving as the primary nitrogen source.

3.2 Nitrogen Output Indicator Analysis

Nitrogen output results for Taojiang County' s agricultural land use system are shown in Table 4 . From 1980-2013, nitrogen output through products fluctuated with grain yields: rapid grain production growth from 1980-1990 due to reform and opening-up policies and the household responsibility system increased nitrogen output through seeds from 7,806.3 t in 1980 to 9,976.9 t in 1990 (a 27.8% increase). However, from 1990-2005, rapid cultivated land reduction caused nitrogen output through seeds to decline to 7,420.6 t by 2005. Subsequently, strict farmland protection policies and grain subsidies increased chemical and organic fertilizer application, boosting grain production and causing nitrogen output through seeds to rebound rapidly to 10,743.9 t by 2013.

Meanwhile, environmental nitrogen output increased continuously from 1980-2013: although growth was slow from 1980-1995 (increasing by only 2,234.0 t), massive nitrogen and organic fertilizer application from 1995-2013 caused rapid nitrogen loss through volatilization, accelerating environmental output growth to 13,072.5 t by 2013—2.4 times the 1980 level. Due to cultivated land area changes, nitrogen loss through runoff and leaching first decreased then increased. Total nitrogen output, heavily influenced by product output, followed a pattern of increase-decrease-increase, reaching 26,138.3 t by 2013.

3.3 Nitrogen Use Intensity and Efficiency Indicators

These indicators measure nitrogen input and output per unit cultivated area in specific regions during defined periods, playing an important role in evaluating regional nitrogen use intensity and efficiency.

3.3.1 Nitrogen Input Intensity

Nitrogen input intensity evaluates nitrogen input per unit cultivated area through productive inputs, calculated as the ratio of total productive nitrogen input to total cultivated land area. For comparison purposes, this paper introduces the concept of nitrogen fertilizer input intensity—nitrogen input per unit cultivated area from chemical fertilizers. Results show nitrogen input intensity in Taojiang County increased annually [Figure 2: see original paper], from 267.8 $kg \cdot hm^{-2}$ in 1980 (with nitrogen fertilizer intensity of 147.2 $kg \cdot hm^{-2}$) to 492.5 $kg \cdot hm^{-2}$ in 2005 (with chemical fertilizer nitrogen of 258.8 $kg \cdot hm^{-2}$), representing increases of 84.34% and 75.76%, respectively. According to Lu et al. [32], nitrogen fertilizer input intensity exceeding 250.0 $kg \cdot hm^{-2}$ indicates excessive application and high pollution risk. By this standard, Taojiang County had already exceeded safe levels.

However, after 2005, despite some cultivated land area increase, rapid growth in chemical and organic fertilizer application prevented effective control of nitrogen input per unit area. Nitrogen input intensity and nitrogen fertilizer input intensity continued growing rapidly, reaching 579.2 $kg \cdot hm^{-2}$ and 328.4 $kg \cdot hm^{-2}$, respectively, by 2013, with nitrogen fertilizer input intensity far exceeding the 250.0 $kg \cdot hm^{-2}$ standard, indicating increasing agricultural environmental risk probability.

3.3.2 Nitrogen Input-Output Ratio

The nitrogen input-output ratio, calculated as total productive nitrogen input divided by total product nitrogen output, characterizes nitrogen use efficiency. Since productive input includes seeds, chemical fertilizers, and organic fertilizers, while product output includes seeds and straw, their ratio directly reflects material use efficiency changes in agricultural land use systems. Figure 2 shows the nitrogen input-output ratio in Taojiang County increased annually from 1980–2005, indicating decreasing nitrogen use efficiency. After 2005, the ratio began declining annually, which field investigations attributed to the Taojiang County Agricultural Bureau' s vigorous promotion of soil testing and formula fertilization starting in 2005, which improved fertilizer use efficiency.

3.3.3 Nitrogen Material Productivity

Material productivity measures the economic value created per unit material input, calculated as the ratio of agricultural GDP to total productive material input [33]. For easier regional comparison, this paper uses nitrogen input through chemical fertilizers to replace total productive nitrogen input. As shown in Figure 3 [Figure 3: see original paper], Taojiang County' s nitrogen material productivity was 17,000 $yuan \cdot t^{-1}$ in 1980, slightly higher than Hunan Province' s average of 16,000 $yuan \cdot t^{-1}$. Subsequently, Taojiang' s nitrogen material productivity increased annually at a rate far exceeding the provincial average, reaching 1.5 times the provincial average by 2000, indicating leading nitrogen use efficiency in the province during 1980–2000. However, after 2000, Hunan Province' s average nitrogen material productivity grew rapidly, catching up with Taojiang by 2005 and surpassing it by 46,000 $yuan \cdot t^{-1}$ by 2013.

Taojiang County' s nitrogen material productivity was only 160,000 yuan · t^{-1} in 2013, placing it at a backward level within the province.

3.4 Environmental Health Indicators

3.4.1 Nitrogen Nutrient Load

Nutrient load refers to the ratio of the difference between total material input and total material output to total cultivated land area in a given year [34]. Taojiang County' s nitrogen nutrient load results are shown in Figure 4 [Figure 4: see original paper]. From 1980-2013, nitrogen nutrient load first increased then decreased. During 1980-1990, load grew slowly from 47.9 kg · hm^{-2} to 61.0 kg · hm^{-2} (a 27% increase). From 1990-2000, rapid growth in productive and environmental nitrogen inputs caused load to increase sharply to 144.0 kg · hm^{-2} by 2000, a 136% increase from 1990 and far exceeding the national average of 87.1 kg · hm^{-2} [20]. However, from 2000-2010, nitrogen nutrient load continued growing uncontrollably, reaching 208.8 kg · hm^{-2} by 2010. Subsequently, load began decreasing, falling to 154.1 kg · hm^{-2} by 2013. Excessive nutrient surplus can cause soil acidification and compaction, affect water quality, and seriously threaten environmental health.

3.4.2 Environmental Material Circulation Rate

To characterize system stability, this paper introduces the concept of environmental material circulation rate—the ratio of total environmental material input to total environmental material output. In a specific agricultural land use system, if the ratio of environmental input to output remains at 1 over long periods, the system exhibits higher ecological stability and lower environmental risk. Figure 4 shows Taojiang County' s nitrogen environmental material circulation rate declined from 0.99 in 1980 to 0.57 in 2013, indicating increasing nitrogen output to the environment. Environmental nitrogen loss occurs through runoff, leaching, volatilization, and denitrification. Nitrogen loss through runoff and leaching is a primary cause of water eutrophication, while nitrogen loss through volatilization and denitrification is a major source of greenhouse gases. These trends demonstrate decreasing ecological stability in Taojiang County' s agricultural land use system.

Discussion

1) Changes in nitrogen input are influenced by multiple factors. First, cultivated land area changes affect nitrogen input. Taojiang County' s cultivated land area first decreased then increased from 1980-2013, inevitably affecting crop sown area. For example, rice sown area decreased 22.4% from 43,168 hm^2 in 1980 to 33,486 hm^2 in 2005, affecting nitrogen input through seeds, chemical fertilizers, organic fertilizers, and irrigation. Second, crop planting structure changes influence nitrogen input. The

large-scale conversion from double-cropping to single-cropping rice in Taojiang County (single-cropping rice area increased from 280 hm^2 in 1980 to 8,066 hm^2 in 2010) caused substantial increases in chemical nitrogen fertilizer input. Finally, increased chemical and organic fertilizer application per unit area also contributed. This study shows the primary nitrogen input pathway is chemical fertilizer, followed by organic fertilizer, deposition, and nitrogen fixation, with irrigation and seeds contributing the least. These findings align with Wang et al. [20] and Li et al. [35], though specific proportions differ. For example, organic fertilizer nitrogen accounted for 18% of total nitrogen input in the middle and lower Yangtze River basin [35], while this study estimates 33%, primarily because Taojiang County has a developed cattle industry (98,000 head in 2013) with nitrogen excretion coefficients far exceeding other livestock. Additionally, this study estimates deposition nitrogen input at 12.2% of total input on average, higher than Wang et al.' s [20] 3.5% because this study considered that nitrogen input through deposition per unit area increases annually with time [30].

2) Rapid growth in nitrogen and organic fertilizer application significantly increased environmental nitrogen output, particularly nitrogen loss through volatilization, which accounts for 66.5% of total environmental output. Nitrogen volatilization occurs primarily as ammonia volatilization and direct nitrous oxide emissions. Ammonia is a major pollutant causing acid rain and eutrophication, while nitrous oxide is a greenhouse gas with 310 times the global warming potential of CO_2 [36]. Therefore, reducing nitrogen volatilization is key to controlling environmental risk.

3) Few indicators currently exist to evaluate material use efficiency in agricultural land use systems, with input-output ratio being the main metric. However, this ratio is easily affected by natural resource endowments, making regional comparisons difficult. This paper introduces material productivity to measure economic value created per unit material input. Calculations show Taojiang County' s nitrogen material productivity was only 160,000 yuan $\cdot$ t^{-1} in 2013, placing it at a backward level within the province. Therefore, Taojiang County must implement further measures to adjust agricultural structure and improve product added value to enhance nitrogen material productivity.

4) This paper constructs two indicators to evaluate regional agricultural land use system environmental health. Nutrient load indicates material deficit or surplus accumulation per unit cultivated area, allowing comparison with national environmental standards to determine regional environmental health. Comparison with Wei et al. [28] reveals that Taojiang County' s nitrogen load lagged behind national averages from 1980–1995, but increased rapidly from 2000–2005, reaching 45.3% above the national average by 2005. The second indicator, environmental material circulation rate, indicates ecological stability. When environmental nitrogen input

equals output over long periods, human production and living activities have minimal environmental impact and ecological health is higher. Using both indicators provides more comprehensive characterization of agricultural land use system environmental health. Results show both indicators demonstrated deteriorating environmental health in Taojiang County from 1980–2010, with increasing environmental risk probability.

5) Agricultural land use systems are highly complex natural-ecological-economic composite systems, and current research lacks accurate parameters and sufficient statistical data, affecting SFA result precision to some extent. Although mature parameters exist for crop and straw nutrient content, grain-to-straw ratios, and livestock excretion coefficients for national-scale nitrogen flow analysis [35,37], this study selected parameters from regions similar to Taojiang County to ensure accuracy. Additionally, some parameters (e.g., straw and manure return rates) change with socio-economic development and environmental conditions, but were not considered in this study due to lack of relevant research, introducing certain errors. Future research should establish parameter databases for different regions and more accurately record material consumption indicators to facilitate broader SFA application in agricultural land use systems.

Conclusion

This study introduced material flow analysis theory to construct a regional-scale agricultural land use system SFA framework and evaluation indicator system, comprehensively assessing regional material use profiles, efficiency, intensity, and potential environmental health conditions using material input, output, intensity/efficiency, and environmental health indicators. Empirical research in Taojiang County analyzed temporal nitrogen flow patterns in its agricultural land use system, yielding the following conclusions:

1) From 1980–2013, both productive and environmental nitrogen inputs in Taojiang County increased significantly, with productive input—particularly chemical fertilizer—serving as the primary nitrogen source. During the same period, total nitrogen output showed fluctuating growth, while product nitrogen output increased only modestly, but environmental output increased 1.4-fold.

2) From 1980–2013, nitrogen fertilizer input intensity in Taojiang County' s agricultural land use system increased annually, reaching 328.4 kg · hm^{-2} in 2013 (32% above the 250 kg · hm^{-2} standard). Nitrogen material use efficiency decreased annually from 1980–2005, then increased slowly from 2005–2013. Although nitrogen material productivity increased annually, it fell behind the provincial average after 2005, indicating Taojiang County' s agricultural land use system material production efficiency remains at a low level, requiring further measures to adjust agricultural structure and

improve product added value.

3) Environmental health quality and ecological stability of Taojiang County' s agricultural land use system deteriorated annually from 1980-2010. However, after 2010, nitrogen nutrient load began decreasing, indicating recent improvements in environmental health quality.

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