Analysis of Historical Variation Characteristics of Phosphorus Nutrient Flow in the Food Chain in the Changchun Area (Postprint)

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Abstract

Phosphorus is an essential element for life, and its cycling and transformation play a crucial role in the food chain. This study analyzes the phosphorus flow trend characteristics in the food chain of Changchun region from 1993 to 2013 by collating statistical data and literature, and employing the NUFER model (Nutrient flows in Food chain, Environment and Resources use, NUFER), reveals existing problems and proposes strategies to provide a basis for optimized management of phosphorus in the regional food chain. The results show that the total phosphorus input into the food chain of Changchun region was 32.6 Gg in 1993, increasing to 113.9 Gg by 2013. In terms of food production, phosphorus nutrient production from animal-derived foods increased from 0.7 Gg in 1993 to 2.7 Gg in 2013, while that from plant-derived foods decreased from 16.1 Gg in 1993 to 15.7 Gg in 2013. Regarding food consumption, phosphorus consumption from animal-derived foods increased from 0.5 Gg in 1993 to 1.1 Gg in 2013, while that from plant-derived foods decreased from 5.0 Gg in 1993 to 4.4 Gg in 2013. Over the 20-year period, the amount of phosphorus accumulated in waste form in the food chain of Changchun region increased by 15 percentage points, and phosphorus losses through runoff, leaching, and erosion increased by 17.6 Gg. By 2013, the phosphorus loss rate in the food chain reached 20.2%. The phosphorus utilization efficiency across all segments of the food chain showed a declining trend, with the phosphorus utilization efficiency of crop production and livestock and poultry production systems decreasing from 94.2% and 4.1% to 49.3% and 3.8%, respectively. The phosphorus utilization efficiency of the entire food chain decreased by 20.3 percentage points. Simultaneously, the phosphorus recycling efficiency also gradually decreased. Over the 20-year period, phosphorus flows in the food chain of Changchun region exhibited a pattern characterized by "large input, large accumulation, high loss, low utilization efficiency, and low recycling efficiency." Therefore, phosphorus nutrient input in the regional food chain should be controlled, attention should be paid to the

recycling of phosphorus from waste in livestock and poultry systems, and phosphorus losses should be reduced to improve phosphorus utilization efficiency.

Full Text

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Abstract

Phosphorus is an essential element for life, and its cycling and transformation play critical roles in the food chain. Using statistical data and literature sources, this study investigated the trends and characteristics of phosphorus flows in Changchun' s food chain from 1993 to 2013 employing the NUFER (Nutrient flows in Food chain, Environment and Resources use) model. The research identified existing problems, proposed management strategies, and provided a basis for optimizing phosphorus management in the region' s food chain. Results showed that total phosphorus input to the food chain system increased from 32.6 Gg in 1993 to 113.9 Gg in 2013. In food production, phosphorus in animal-derived foods rose from 0.7 Gg to 2.7 Gg, while phosphorus in plant-derived foods decreased from 16.1 Gg to 15.7 Gg. In food consumption, phosphorus from animal-derived foods increased from 0.5 Gg to 1.1 Gg, whereas phosphorus from plant-derived foods declined from 5.0 Gg to 4.4 Gg. Over the two decades, phosphorus accumulation as waste in the food chain increased by 15 percentage points, and phosphorus losses through runoff, leaching, and erosion increased by 17.6 Gg. By 2013, the phosphorus loss rate in the food chain reached 20.2%. Phosphorus use efficiency across all food chain stages declined, with crop and livestock production system efficiencies dropping from 94.2% and 4.1% to 49.3% and 3.8%, respectively. Overall food chain phosphorus use efficiency decreased by 20.3 percentage points. Simultaneously, phosphorus recycling efficiency gradually declined. During the 20-year period, Changchun' s food chain phosphorus flow exhibited a pattern of "high input, high accumulation, high loss, low efficiency, and low recycling." Therefore, controlling phosphorus inputs, enhancing waste recycling, reducing losses, and improving use efficiency are critical for the region.

Keywords: Phosphorus; NUFER model; Food chain; Nutrient flow; Phosphorus use efficiency; Phosphorus loss rate; Changchun area

Introduction

Phosphorus is an essential nutrient for the growth and development of plants and animals and constitutes an important nutrient resource within food chain systems [1]. It is also a limiting factor determining water eutrophication and biodiversity [2]. Phosphorus input is a crucial means of maintaining product quality and yield of crops and livestock while meeting global food demands [3]. However, excessive application not only wastes resources but also creates environmental pressures. As a major agricultural country, China ranks first globally in phosphorus fertilizer consumption [4]. Large amounts of phosphorus accumulate in soils and enter water bodies through runoff, leaching, and erosion, causing environmental pollution. Meanwhile, the sustainable development of phosphorus resources has become a hot topic of concern both domestically and internationally. Currently, research on phosphorus nutrient material flows is receiving increasing attention. Smit et al. [5] quantified phosphorus flows in agricultural and non-agricultural subsystems in the Netherlands, finding that half of the total phosphorus surplus in 2005 accumulated in farmland soils, with the remainder lost through various pathways and only a minimal portion recycled to cropland, and discussed strategies for sustainable phosphorus resource use. Suh et al. [6] developed a phosphorus flow framework for food systems and calculated phosphorus use efficiency, revealing that only 15% of phosphorus in food is actually consumed by humans, with the rest lost to the environment, primarily during livestock production and crop cultivation stages, and proposed measures to improve phosphorus use efficiency. Egle et al. [7] attempted to quantify phosphorus flows and stocks in waste and wastewater, using STAN software to construct a model that provided a solid foundation for assessing phosphorus accumulation in Austrian farmland soils and waste, and for developing relevant management plans. Chen et al. [8] demonstrated that excessive phosphorus fertilizer input in cropland systems leads to soil phosphorus accumulation, posing risks to water bodies, while grassland grazing systems face severe phosphorus deficits, causing large-scale grassland degradation. Bai et al. [9] analyzed nitrogen and phosphorus nutrient flows from the perspective of dairy production, pointing out that more efficient utilization of nutrients from livestock excreta in dairy production is essential for improving nutrient use efficiency across the entire system. Ma et al. [10-11] synthesized findings from related studies to establish the NUFER (Nutrient flows in Food chain, Environment and Resources use) model, and based on this model, predicted phosphorus loss scenarios in

China, noting that changes in phosphorus fertilizer use are driven by population growth and dietary structure changes [12]. Zhang Jianjie et al. [13] used the NUFER model to investigate spatial distribution characteristics of phosphorus flows in crop-livestock production systems in Shanxi Province, providing scientific recommendations for nutrient resource management in the province. Analyzing nutrient flow characteristics of a single system alone makes it difficult to regulate and manage nutrients across the entire food chain. Therefore, evaluating phosphorus nutrient management from a food chain perspective has attracted considerable attention, yet few regional studies in China have examined phosphorus flows across the entire food chain. Changchun region, as a typical area with large-scale agricultural and livestock product production and export, currently lacks detailed understanding of its phosphorus nutrient flow characteristics. Therefore, investigating the trends and characteristics of phosphorus flows in Changchun' s food chain can contribute to sustainable phosphorus resource utilization in the region and provide guidance for improving phosphorus use efficiency and reducing environmental risks. This study employs the NUFER model to analyze phosphorus flow patterns in Changchun' s food chain from 1993 to 2013, clarifies the region' s phosphorus flow trend characteristics, reveals existing problems, and provides a comprehensive, systematic basis for optimized nutrient management of phosphorus in the region.

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1. Materials and Methods

1.1 Overview of Changchun Area Changchun City is located in central Jilin Province and features a temperate continental semi-humid monsoon climate with concurrent rainfall and heat. The region covers a land area of 2.06×10 hm^2, with 1.31×10 hm^2 of cultivated land, approximately 30% of which is used for crop cultivation. Situated in the Songliao Plain, one of the world' s three "golden corn belts," Changchun has developed a long-standing agricultural planting pattern dominated by corn. During the five-year period from 2008 to 2013, the region' s average grain output reached 8.47×10 t, with corn production reaching 6.69×10 t, accounting for 29% of Jilin Province's total corn output. The livestock market primarily focuses on pigs, beef cattle, poultry, and their by-products. In recent years, pigs, beef cattle, and poultry have accounted for approximately 37%, 31%, and 27% of total livestock numbers, respectively [14].

1.2 Changchun Food Chain System This study uses Changchun' s administrative boundaries as the system boundary. The Changchun food chain system includes crop production systems, livestock production systems, household consumption systems, and waste materials (such as crop straw, human and animal manure, and domestic waste). The pathways of phosphorus flow and cycling in the food chain are illustrated in Figure 1 [Figure 1: see original paper]. Phosphorus enters the food chain through (1) fertilizers and (2) external feed inputs. Outputs from the food chain include (3) plant-derived products, (4) animal-derived products, and (5) losses through leaching, runoff, and erosion. Additionally, nutrient flows within the system occur through (7) plant-based foods, (8) grains and straw used as feed, (9) animal-based foods, (10) straw, (11) animal excreta, (12) domestic waste such as food residues and human excreta, (13) livestock manure returned to fields, (14) straw reused as feed, (15) straw returned to fields, and (6) phosphorus accumulation in waste between total system inputs and outputs. With increasing population and food consumption, phosphorus deposition in human bodies has also increased; however, this accounts for less than 1% of total phosphorus input to the food chain and is therefore not considered in this study.

Figure 1. Schematic diagram of phosphorus nutrient cycling in food chain

1.3 Data Sources for Food Chain Analysis Basic data and information for the food chain (population, cultivated land area, fertilizer use, crop planting area and yield, livestock numbers, and food consumption) were obtained from the Changchun Statistical Yearbook [13]. Crops were categorized into four types (grains, other crops, vegetables, and fruits), and animals were divided into seven categories (pigs, beef cattle, draft cattle, dairy cattle, sheep, laying poultry, and meat poultry). The Eurostat conversion method was used to estimate and compare livestock numbers [15], with dairy cattle as the standard unit and other livestock converted to corresponding dairy cattle units for comparison. Phosphorus consumption from fertilizers was derived from the pure phosphorus content in phosphate fertilizers and the pure nutrient phosphorus content in compound fertilizers. Phosphorus contents in harvested crops and animal products, phosphorus contents in excreta from each animal type, and the division of edible and non-edible parts in animal products were obtained from literature sources [10-11]. Emission coefficients for phosphorus in crop and livestock production were derived from literature data and survey results [10-11].

1.4 Analysis and Calculation of Phosphorus Flow in the Food Chain [11] The calculation methods for phosphorus nutrients in the food chain are as follows (units: Gg = 10^3 t):

磷素总输入量 = 肥料含磷量 + 饲料外源输入含磷量

磷素总输出量 = 植物性产品含磷量 + 动物性产品含磷量 + 径流、侵蚀、淋洗的磷素损失量 (2)

Where a portion of phosphorus accumulates in waste materials, specifically the phosphorus nutrients present in excreta and household food waste generated during consumption. This is calculated as:

磷素累积量 = 磷素总输入量 磷素总输出量 (3)

磷素养分损失率 (LIR, %)=(磷素损失量/磷素总输入量)×100% (4)

磷素循环再利用率 (RRR, %)=(作物秸秆作为饲料的磷素量 + 动物粪便还田的磷素量)/(秸秆收获的总磷素量 + 畜禽粪便总磷素量)×100% (5)

Phosphorus nutrient use efficiency formulas:

作物生产系统磷素利用效率 (PUEc)=(主要农产品输出/作物生产输入)×100% (6)

畜禽生产系统磷素利用效率 (PUEa)=(畜禽产品输出/畜禽生产输入)×100% (7)

农牧结合系统磷素利用效率 (PUEc+a)=(农牧产品输出/农牧生产输入)×100% (8)

食物链磷素利用效率 (PUEf)=(食品磷素输出/磷素生产总输入)×100% (9)

Other relevant phosphorus nutrient calculation indicators are as follows:

Unit food phosphorus consumption: The amount of phosphorus entering the household consumption system per kilogram of phosphorus from crop and livestock production systems in the food chain.

Animal-derived food consumption proportion in diet (AFER, %): The proportion of phosphorus from animal-derived foods relative to total dietary phosphorus.

Proportion of external phosphorus input (ITR, %): The proportion of phosphorus from foods sourced from other regions relative to total phosphorus input.

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2. Results

2.1 Changes in Total Phosphorus Input and Output in the Food Chain From 1993 to 2013, total phosphorus input in Changchun increased from 32.6 Gg to 113.9 Gg, representing a 2.5-fold increase (Figure 2 [Figure 2: see original paper]). The majority of phosphorus input came from farmland fertilizer application, which rose from 30.2 Gg in 1993 to 87.7 Gg in 2013. With increasing livestock numbers, the proportion of external feed input increased substantially, from an initial 7% to 23%. In terms of nutrient output, most phosphorus accumulated as waste, with accumulation increasing annually from 56% in 1993 to 71% in 2013, reaching 80.6 Gg by 2013.

Figure 2. Input and output of phosphorus in food chain system in Changchun area from 1993 to 2013

2.2 Changes in Food Phosphorus Production and Consumption Changes in phosphorus production, consumption, and export to other regions in Changchun' s food chain from 1993 to 2013 are shown in Figure 3 [Figure 3: see original paper]. Agricultural and livestock products in Changchun have long been in surplus, resulting in substantial phosphorus nutrient exports to other regions. Over the 20-year period, production was dominated by plant-derived foods, with plant-derived food phosphorus production experiencing temporary declines during 1998–2000 and 2006–2009. Animal-derived food phosphorus production showed rapid growth before 2009, dropped sharply in 2010 due to livestock epidemics, and subsequently entered a recovery phase (Figure 3). Plant-derived food phosphorus consumption remained relatively stable, reaching 4.4 Gg by 2013, while animal-derived food phosphorus consumption increased modestly, with 2013 consumption 2.2 times that of 1993. The proportion of animal-derived food phosphorus in consumption also increased gradually, rising from 8.3% to 17.9% (Figure 4 [Figure 4: see original paper]). Exports of phosphorus in plant- and animal-derived foods fluctuated with production, with export proportions reaching 72% and 60%, respectively, in 2013. Overall, the production input cost per unit of food in the food chain increased substantially, with unit food phosphorus consumption rising from 3.6 kg · kg ¹ to 18.5 kg · kg ¹.

Figure 3. Changes of phosphorus production, consumption and export of plant and animal foods in Changchun area from 1993 to 2013

Figure 4. Phosphorus cost of unit food in the food chain system in Changchun area from 1993 to 2013. APFR: proportion of animal food in food consumption.

2.3 Phosphorus Losses in the Food Chain From 1993 to 2013, the amount of available organic phosphorus nutrients (straw, animal excreta) in Changchun' s food chain increased from 18.4 Gg to 52.5 Gg (Figure 5 [Figure 5: see original paper]), but the recycling efficiency of phosphorus nutrients was not optimistic. Although there was a slight increase before 2000, it subsequently showed a continuous declining trend. By 2013, phosphorus recycling and reuse efficiency had dropped to 55%. Phosphorus losses through leaching, runoff, and erosion increased significantly, with the overall loss rate rising from 14.3% in 1993 to 21.7% in 2009, before declining slightly to 20.5% in 2013 (Figure 5).

Figure 5. Phosphorus loss and recycling of food chain system in Changchun area from 1993 to 2013

2.4 Phosphorus Use Efficiency in the Food Chain In the crop production system, phosphorus use efficiency (PUEc) declined from 94.2% in 1993 to 37.6% in 2009, then recovered to 49.3% in 2013. In the livestock production system, phosphorus use efficiency (PUEa) was relatively low, decreasing slowly from 4.1% to 3.8%. Over the 20-year period, the overall nutrient use efficiency of phosphorus in Changchun's food chain (PUEf) decreased continuously, dropping from 25.7% in 1993 to 5.4% in 2013—a substantial decline of 4.8-fold (Figure 6 [Figure 6: see original paper]).

Figure 6. Variation trends of phosphorus utilization efficiency in different systems of the food chain system in Changchun area from 1993 to 2013. PUEc: phosphorus utilization efficiency of crop production system; PUEa: phosphorus utilization efficiency of animal production system; PUEc+a: phosphorus utilization efficiency of farming-grazing system; PUEf: phosphorus utilization

efficiency of food chain system.

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3. Conclusions and Discussion

Between 1993 and 2013, Changchun' s population increased rapidly, with the urbanization rate rising by 6.6 percentage points. To meet growing food demands and maintain long-term supply of agricultural and livestock products to other regions, substantial phosphorus nutrient inputs were made to the food chain. Simultaneously, dietary structure shifted, with rapid increases in animal-derived food consumption, which in turn affected nutrient flow trends and use efficiency.

Research results show that phosphorus use efficiency in Changchun' s food chain crop production system decreased by 44.9% from 1993 to 2013. Phosphorus enters the crop production system primarily as phosphate fertilizer, which has low utilization efficiency—typically only 5–25% is directly utilized by crops [16]. In farmland management, farmers in Changchun habitually apply chemical fertilizers in a single application, and phosphorus fertilizer application rates are generally excessive in the region [17]. Long-term over-application of phosphorus fertilizers has led to continuously rising soil phosphorus surpluses, with phosphorus losses through surface runoff and subsurface drainage causing environmental problems such as water eutrophication. Additionally, large quantities of straw harvested in crop production are not utilized rationally; farmers often burn crop straw in the open to facilitate cultivation and reduce costs, resulting in losses of phosphorus nutrients. Therefore, improving farmers' awareness, applying phosphorus fertilizers rationally, and utilizing phosphorus resources efficiently are direct and effective approaches to enhancing phosphorus use efficiency in crop production systems. Currently, soil testing and formula fertilization technologies being implemented in China [18] can increase yields while reducing fertilizer application rates; however, further research and widespread application of these technologies are needed. Simultaneously, attention should be paid to increasing straw returned to fields to improve phosphorus nutrient recycling efficiency.

In livestock production, as residents' dietary structure changed, the proportion of animal-derived food consumption in Changchun increased by 9.6%, yet phosphorus use efficiency in the livestock production system decreased by 0.3%. In contrast, in Beijing, phosphorus use efficiency in the livestock production system increased by 5% between 1978 and 2008 as the proportion of animal-derived foods rose [19]. In 2013, Changchun' s livestock production system phosphorus use efficiency was only 3.8%, far below the national average of 17% [4]. Further comparative analysis reveals that from 1993 to 2013, Changchun residents' dietary structure shifted from plant-based to animal-based foods, driving rapid development of the livestock industry and substantially increasing external feed input. Meanwhile, as livestock production became more intensive and large-scale, substantial manure resources were generated. However, Changchun' s large-scale farming systems remain inadequate, with livestock manure not being centrally processed and utilized in a timely manner, resulting in low conversion and utilization efficiency of phosphorus nutrients at each stage. Additionally, farmers increasingly rely on chemical fertilizers to boost grain yields and are unwilling to spend time and effort collecting and applying manure, preventing its timely return to fields. Therefore, in Changchun' s livestock production sector, greater use of straw and other materials for feed processing is needed to reduce external feed input and narrow nutrient input volumes, while strengthening attention to livestock manure management.

In household consumption, with Changchun' s urban development and rising living standards, food waste has become widespread. Urgent measures are needed to raise public awareness and eliminate food waste to improve phosphorus nutrient use efficiency in the food chain.

From 1993 to 2013, total phosphorus nutrient input to Changchun' s food chain increased substantially, adding 81.3 Gg. Phosphorus in waste accumulation increased by 62.2 Gg, phosphorus lost through leaching, runoff, and erosion increased by 17.6 Gg, yet overall phosphorus recycling efficiency decreased by 5.3% and overall use efficiency declined by 20.3%. The overall phosphorus flow trend is similar to our research findings on nitrogen [20], but phosphorus loss rates are significantly higher than nitrogen, primarily due to higher phosphorus content in livestock excreta. In Changchun, phosphorus nutrients flow out in large quantities through exports of agricultural and livestock products, while waste generated during production accumulates within the local food chain, resulting in low nutrient use efficiency. Therefore, nutrients in waste can be utilized to improve efficiency. In addition to phosphate fertilizers, animal manure, crop straw, sewage, and sludge are all relatively common phosphorus resources available for crops [21]. Regarding phosphorus resource management, on one hand, waste can be utilized systematically to turn it into a valuable resource. Large-scale farms can centrally process manure for field application, and domestic waste and sewage can be treated before discharge to reduce water eutrophication caused by surface runoff. On the other hand, relevant policies and planning management can be established, drawing on successful experiences from European and American countries, providing appropriate compensation to farmers, and formulating policies to control phosphorus fertilizer inputs while supervising straw return and other recycling practices.

As macro-level data sources, statistical data have uncertainties that can affect research estimates. This study collected basic data from the Changchun Statistical Yearbook (1994–2013) to ensure authenticity and reliability as much as possible. Other parameters involved in the research were based on a mature set of parameters summarized by Ma et al. [19], with some adjustments made according to Changchun' s actual conditions [20] to minimize deviations in research results. Additionally, to facilitate understanding of livestock structure, livestock numbers were estimated and compared using the Eurostat conversion method, a commonly used evaluation standard in Europe and America, which may have slight effects on results. With continuous advancement in regional nutrient management research, more accurate and authoritative parameter systems and evaluation standards should be established in the future to further correct regional differences and improve research outcomes.

As a region with large-scale agricultural and livestock product exports, Changchun' s food chain phosphorus flow characteristics exhibit a "three highs and two lows" pattern: high input, high accumulation, high loss, low efficiency, and low recycling. Therefore, future phosphorus management in Changchun' s food chain should: (1) promote rational fertilization and nutrient recycling, reduce straw burning, increase straw returned to fields, and reduce nutrient losses, while simultaneously processing livestock manure for timely field application; (2) establish rational and standardized farming systems to reduce nutrient losses at each stage, utilizing crop straw and other materials for feed processing to reduce external feed input; and (3) adjust food consumption structure according to regional characteristics and eliminate food waste to reduce nutrient losses in household consumption systems. Strengthening coordinated phosphorus nutrient management across all systems in Changchun' s food chain will be essential for achieving sustainable regional phosphorus nutrient development.

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