Spatiotemporal Characteristics of Nitrogen and Phosphorus Flows and Environmental Losses in the "Soil-Feed-Dairy Cow" System in Beijing: Postprint

Authors: Wei Sha, Bai Zhaohai, Wu Dimei, Jiang Rongfeng, Xia Lijiang, Ma Lin

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Abstract

Analyzing the nutrient flow and environmental emission characteristics of the "soil-feed-dairy cow" farming system in the suburbs of large cities is fundamental for policy formulation regarding reasonable control of farming scale, promotion of agriculture-livestock integration, ecological environment protection, and assurance of livestock product supply. This study selected 28 large-scale dairy farms in the suburbs of Beijing, investigating feed sources and inputs, dairy cow production and manure management, as well as product output. Combining publicly available literature data and Beijing statistical data, the NUFER-animal model was used to conduct a quantitative analysis of the spatiotemporal changes in nutrient flow characteristics, utilization efficiency, and environmental losses in the "soil-feed-dairy cow" production system of large-scale dairy farms in Beijing from 1980 to 2013. The results showed that from 1980 to 2013, nitrogen use efficiency at the individual cow scale (including only lactating cows) increased from 14.9% to 21.2%, and phosphorus use efficiency increased from 13.8% to 27.3%; at the herd scale (including calves, growing cattle, heifers, lactating cows, and dry cows), nitrogen use efficiency increased from 14.5% to 18.2%, and phosphorus use efficiency increased from 15.8% to 24.9%; at the system scale (soil-feed-dairy cow), nitrogen use efficiency increased from 11.3% to 15.8%, and phosphorus use efficiency increased from 13.3% to 22.3%. Nitrogen use efficiency at the individual, herd, and system scales of dairy farming in Beijing decreased before 1985; thereafter, it gradually increased. Phosphorus use efficiency at the individual, herd, and system scales continuously increased. Total nitrogen loss at the system scale increased from 1,516 t in 1980 to 16,973 t in 2013; total phosphorus loss increased from 114 t to 1,763 t. The nitrogen and phosphorus losses per kilogram of nitrogen-phosphorus product both showed a

continuously decreasing trend. The nitrogen and phosphorus flow characteristics in Beijing' s "soil-feed-dairy cow" production system have undergone significant changes, with nutrient use efficiency and total environmental losses continuously increasing. The reasons for these changes include increased livestock numbers, transformation of farming patterns from traditional to intensive systems, and improvements in environmental management measures. Therefore, adjusting dairy farming from quantity-oriented to quality-oriented development, as well as improving feeding techniques and manure management levels, are necessary measures to enhance the sustainable development of urban dairy farming.

Full Text

Temporal and Spatial Characteristics of Nitrogen and Phosphorus Cycling and Environmental Losses in the "Soil-Feed-Dairy" Production System in Beijing

WEI Sha[1,2], BAI Zhaohai[2], WU Dimei[3], JIANG Rongfeng[1], XIA Lijiang[1], MA Lin[2]

[1]Key Laboratory of Plant-Soil Interactions, Ministry of Education / College of Resources and Environment, China Agricultural University, Beijing 100193, China
[2]Key Laboratory of Agricultural Water Resources, Chinese Academy of Sciences / Hebei Key Laboratory of Water-Saving Agriculture / Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050022, China
[3]Beijing Environmental Monitoring Station of Animal Husbandry, Beijing 100083, China

Abstract: Analyzing nutrient flows and environmental emissions in peri-urban "soil-feed-dairy" production systems is fundamental for policy-making aimed at rationalizing herd size, promoting crop-livestock integration, protecting ecological environments, and ensuring livestock product supply. This study examined 28 intensive dairy farms in Beijing' s suburbs, investigating feed sources and inputs, dairy production and manure management, and product outputs. Combining published literature data with Beijing municipal statistics, the NUFER-animal model was used to quantify temporal and spatial changes in nutrient flows, use efficiency, and environmental losses in the "soil-feed-dairy" production system of Beijing's intensive dairy farms from 1980 to 2013. Results showed that from 1980 to 2013, nitrogen use efficiency (NUE) at the individual scale (lactating cows only) increased from 14.9% to 21.2%, while phosphorus use efficiency (PUE) increased from 13.8% to 27.3%. At the herd scale (including calves, heifers, dry cows, and lactating cows), NUE increased from 14.5% to 18.2% and PUE from 15.8% to 24.9%. At the system scale (soil-feed-dairy chain), NUE increased from 11.3% to 15.8% and PUE from 13.3% to 22.3%. NUE at all three scales decreased before 1985 but increased thereafter. PUE at all three scales showed continuous improvement. Total nitrogen losses increased from 1,516 t in 1980 to 16,973 t in 2013, while total phosphorus losses increased from 114 t to 1,763 t. However, nitrogen and phosphorus losses per kilogram of product both showed decreasing trends. The nutrient flow characteristics in Beijing' s "soil-feed-dairy" system have changed substantially, with increasing nutrient use efficiency but rising total environmental losses. These changes resulted from increasing herd numbers, transition from traditional to intensive farming systems, and improved environmental management measures. Therefore, adjusting dairy production from quantity-oriented to quality-oriented development, improving feeding and manure management technologies, and enhancing crop-livestock integration are essential for sustainable urban dairy farming development.

Keywords: "Soil-feed-dairy" production system; Nutrient use efficiency; Nitrogen loss; Phosphorus loss; NUFER model

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Introduction

With the development of intensive livestock production, manure pollution has become a global concern. Nitrogen and phosphorus in livestock manure are emitted to the atmosphere as ammonia (NH), nitrous oxide (N O), and other gases, or lost to water bodies through leaching, runoff, and soil erosion, becoming significant sources of PM2.5, greenhouse gas emissions, and non-point source pollution. While Wang et al. analyzed nitrogen and phosphorus inputs and outputs from livestock products at the national scale, their studies lacked analysis of nutrient flows and loss characteristics throughout the entire livestock production chain. Ma et al. established the NUFER (NUtrient flows in Food chains, Environment and Resources) model using a substance flow approach to clarify nutrient use efficiency and losses across the soil-crop-livestock-food processing-household consumption system, providing a more comprehensive analytical method for livestock nutrient flows. Subsequently, Bai established the NUFER-animal model to investigate nutrient utilization and losses in different livestock species and production systems at the national scale. Previous research indicated that regions with high nitrogen and phosphorus emissions per unit of arable land are concentrated around major cities, yet studies on nutrient utilization characteristics and environmental losses in metropolitan livestock production systems remain scarce.

As one of 16 important superior breeds in Beijing' s Seed Industry Development Plan (2010–2015), research on nutrient utilization characteristics and environmental losses of dairy cows in metropolitan environments is urgently needed. This study employs substance flow analysis using the NUFER-animal model to quantify temporal and spatial variations in nitrogen and phosphorus cycling, use efficiency, and environmental emissions in Beijing' s "soil-feed-dairy" production system from 1980 to 2013, providing a theoretical basis for exploring nutrient cycling and mitigation strategies and optimizing livestock layout in metropolitan areas.

1. Materials and Methods

1.1 Study Area Overview

Beijing, China' s capital, is one of the world' s 50 largest metropolitan areas. Located on the eastern edge of the Eurasian continent at the northern tip of the North China Plain (39°28 N–41°5 N, 115°25 E–117°30 E), Beijing covers a total area of 16,800 km² with terrain that slopes from northwest to southeast. The suburban districts (Mentougou, Fangshan, Tongzhou, Shunyi, Changping, Daxing, Huairou, Pinggu, Miyun, and Yanqing) encompass 15,200 km², including 2,209 km² of arable land that accounts for 95% of Beijing' s total farmland. Beijing' s per capita arable land is 0.01 ha, significantly lower than the North China average of 0.093 ha and the national average of 0.18 ha, indicating severe land resource constraints. The dairy herd increased from 20,000 head in 1980 to 151,000 head in 2013, with the production structure rapidly transitioning from traditional to intensive systems. The proportion of intensive farms increased from 0% in 1980 to 72.0% in 2013.

1.2 NUFER Model and System Boundaries

The NUFER model simulates nitrogen and phosphorus flows and use efficiency in "soil-crop-livestock-household consumption" systems, including NH , N , and N O emissions, as well as nitrogen and phosphorus leaching and runoff losses. The NUFER-animal model further analyzes resource requirements, nutrient utilization, and environmental loss pathways for major livestock species (dairy cattle, beef cattle, laying hens, broilers, and pigs) under different production systems (traditional, grazing, specialized households, production zones, and intensive farms).

This study applied the NUFER-animal model to analyze nitrogen and phosphorus flows, use efficiency, and environmental losses in Beijing' s dairy production system. Three scales were examined: (1) individual scale (lactating cows only), (2) herd scale (including calves, heifers, dry cows, and lactating cows), and (3) system scale (soil-feed-dairy system), incorporating feed production, manure storage, and land application. System boundaries and nutrient flows at different scales are illustrated in [Figure 1: see original paper].

1.3 Calculation Methods

This study employed the NUFER-animal model methodology to calculate feed inputs, nutrient flows, use efficiency, and environmental losses.

The feed conversion rate (FCR) at the individual scale was calculated as:

$$\text{FCR} = \frac{I_{\text{lactating cow}}}{O_{\text{milk}}}$$

where I represents input, O represents output, $I_{\text{lactating cow}}$ is feed input for lactating cows (kg), and O_{milk} is milk output (kg).

Nutrient use efficiency formulas for nitrogen/phosphorus at individual, herd, and system scales were:

$$\text{N(P)UE}_{\text{animal}} = \frac{\text{N(P)}O_{\text{animal}}}{\text{N(P)}I_{\text{animal}}}$$

$$\text{N(P)UE}_{\text{herd}} = \frac{\text{N(P)}O_{\text{herd}}}{\text{N(P)}I_{\text{herd}}}$$

$$\text{N(P)UE}_{\text{system}} = \frac{\text{N(P)}O_{\text{herd}}}{\text{N(P)}I_{\text{feed}} + \text{N(P)}I_{\text{FI}} + \text{NI}_{\text{BNF}} + \text{NI}_{\text{dep}}}$$

where N(P)UE_animal, N(P)UE_herd, and N(P)UE_system represent nitrogen or phosphorus use efficiency at individual, herd, and system scales, respectively. N(P)O_animal denotes nitrogen or phosphorus output in milk from lactating cows; N(P)I_animal denotes nitrogen or phosphorus input in feed for lactating cows; N(P)O_herd denotes nitrogen or phosphorus output from all cattle categories (calves, heifers, dry cows, and lactating cows); N(P)I_herd denotes nitrogen or phosphorus input in feed for all cattle categories; N(P)I_fer, N(P)I_FI, NI_BNF, and NI_dep represent nitrogen or phosphorus inputs from chemical fertilizers, imported feed (purchased from outside Beijing, such as fishmeal, soybean meal, and forage), biological nitrogen fixation, and atmospheric nitrogen deposition, respectively. Byproduct feeds were excluded from system efficiency calculations as they represent internal cycling.

Based on mass balance principles, manure nitrogen/phosphorus excretion equals the difference between animal feed input and product output:

$$\text{N(P)}_{\text{manure}} = \text{N(P)}I_{\text{feed}} - \text{N(P)}O_{\text{animal}} \tag{5}$$

Post-excretion nutrient fate includes three pathways: gaseous emissions, unregulated discharge, and sales. Total environmental losses comprise: (1) on-farm gaseous emissions, (2) on-farm leaching and runoff, and (3) off-farm discharge to water bodies. Manure sales and unregulated discharge ratios were obtained from farm surveys. Gaseous emissions (NH , N O, and N) occur during three manure management stages: housing, storage, and treatment. Calculations were performed as follows:

$$\text{N(P)}_{\text{manure}} = \text{N(P)}_{\text{GEN}} + \text{N(P)}_{\text{discharge}} + \text{N(P)}_{\text{leaching}} + \text{N(P)}_{\text{sold}}$$

where N(P)_manure is nitrogen or phosphorus entering manure management systems; N(P)_GEN is gaseous nitrogen emission (including NH , N O, and N losses during housing, storage, and treatment); N(P)_discharge is unregulated nitrogen or phosphorus discharge; N(P)_leaching is nitrogen or phosphorus leaching loss; and N(P)_sold is nitrogen or phosphorus in sold manure (obtained from surveys). All manure management results are expressed in kg(N) · kg ¹ (nitrogen product) or kg(P) · kg ¹ (phosphorus product).

Specific emission calculations:

$$\mathrm{N(P)}_{\mathrm{GEN}} = \mathrm{N(P)}_{\mathrm{housing}} \times \mathrm{Ef}_{1i} + \mathrm{N(P)}_{\mathrm{storage}} \times \mathrm{Ef}_{2i} + \mathrm{N(P)}_{\mathrm{treatment}} \times \mathrm{Ef}_{3i}$$

$$\mathrm{N(P)}_{\mathrm{leaching}} = \mathrm{N(P)}_{\mathrm{housing}} \times \mathrm{Ef}_{a} + \mathrm{N(P)}_{\mathrm{storage}} \times \mathrm{Ef}_{b} + \mathrm{N(P)}_{\mathrm{treatment}} \times \mathrm{Ef}_{c}$$

$$\mathrm{N(P)}_{\mathrm{storage}} = \mathrm{N(P)}_{\mathrm{manure}} \times \mathrm{EF}_{1j}$$

$$\mathrm{N(P)}_{\mathrm{treatment}} = \mathrm{N(P)}_{\mathrm{manure}} \times \mathrm{EF}_{2j}$$

where N(P)_housing, N(P)_storage, and N(P)_treatment represent nitrogen or phosphorus quantities in housing, storage, and treatment stages, respectively; Ef is the emission factor for gas type i during housing; Ef and Ef are emission factors for gas type i during storage and treatment; Ef , Ef_b, and Ef_c are leaching coefficients for housing, storage, and treatment stages; EF and EF are the proportions of manure nitrogen or phosphorus entering storage and treatment stages, obtained from farm surveys.

1.4 Data Sources

Data were obtained from three sources: survey data, statistical data, and literature data.

1.4.1 Survey Data

During 2012-2013, farm data were collected through face-to-face questionnaires with farm personnel. Survey samples were selected based on environmental emission registrations and recommendations from livestock department staff. The survey included 28 dairy farms, representing 12% of Beijing' s intensive dairy farms (>200 head). Small-scale farms (<200 head) were excluded due to low economic viability and anticipated future disappearance. Survey content included farm inputs, outputs, production management, and manure management (see).

1.4.2 Statistical Data

Dairy inventory data were obtained from the Beijing Statistical Yearbook. Data on the proportion of intensive dairy farming from 1998–2013 came from the China Livestock Yearbook. Proportions for 1980–1997 were estimated from historical changes in livestock intensification in Beijing and expert assessment. Activity level data for manure management were derived from expert evaluation.

1.4.3 Literature Data

Feed intake and composition for 1980–2005 were based on Bai' s simulated feed structure according to animal energy requirements and feed resources. Feed formulas, intake, feeding days, and mortality rates for 2013 were obtained from survey data. Nitrogen and phosphorus contents in feeds and dairy products used NUFER model parameters. N O and N emission coefficients for manure management came from the NUFER model. NH emission coefficients for housing were from Liu Dong, while storage and treatment coefficients were from Jia Wei and Liu Dong (see). Backfilled manure treated with high-temperature drying was assumed to have no environmental emissions based on expert assessment.

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2. Results and Analysis

2.1 Nitrogen Flow Characteristics and Historical Changes in the "Soil-Feed-Dairy" System

Nitrogen flow accounts for Beijing' s dairy production in 1980 and 2013 are shown in [Figure 2: see original paper]. In 2013, system-scale nitrogen inputs included imported feed (from outside Beijing, such as silage corn, soybean meal, and forage), byproduct feed, and locally produced feed, with inputs of 16,828 t, 1,970 t, and 2,212 t, respectively. Imported feed was the primary nitrogen source, accounting for 80.0% of total feed nitrogen input, followed by locally produced feed (11.0%) and byproduct feed (9.0%). In contrast, 1980 inputs were 773 t, 331 t, and 327 t, respectively, with imported feed comprising 54.0% of feed nitrogen, and byproduct and locally produced feeds each accounting for 23.0%. The proportion of imported feed increased rapidly from 1980 to 2013.

In 2013, system-scale nitrogen outputs included 3,821 t in milk and meat products. Manure nitrogen fate included losses (13,284 t), sales (3,464 t), and field application (441 t), with losses accounting for 77.3% of manure nitrogen output, sales for 20.2%, and field application for only 2.6%. In 1980, manure nitrogen outputs were 617 t (losses), 14 t (sales), and 593 t (field application), representing 50.4% losses, 1.1% sales, and 48.4% field application. The proportions of manure sales and field application changed dramatically between 1980 and 2013.

Historical changes in nitrogen flow accounts show that in 2013, individual-scale nitrogen input was 17,624 t (14.2 times higher than 1980), with milk nitrogen output and manure excretion at 3,632 t and 14,000 t (21.7 and 14.1 times higher than 1980, respectively). Herd-scale nitrogen input reached 22,010 t

(14.3 times higher than 1980), with milk output and manure excretion at 3,821 t and 17,189 t (17.5 and 13.2 times higher). System-scale inputs of imported, locally produced, and byproduct feeds increased by 21.8, 7.7, and 5.8 times, respectively. Manure environmental losses and sales increased by 21.5 and 247.4 times, while manure returned to fields decreased by 25.6%, with most manure being sold to surrounding crop growers. In the 2013 crop production stage, chemical nitrogen fertilizer input was 4,782 t (6.8 times higher than 1980), and soil nitrogen accumulation was 5.2 times higher.

2.2 Phosphorus Flow Characteristics and Historical Changes

Phosphorus flow accounts for 1980 and 2013 are shown in [Figure 3: see original paper]. In 2013, system-scale phosphorus inputs included imported feed (2,267 t), byproduct feed (551 t), and locally produced feed (381 t). Imported feed accounted for 70.8% of feed phosphorus input, followed by byproduct feed (17.2%) and locally produced feed (12.0%). In 1980, inputs were 140 t, 87 t, and 61 t, respectively, with imported feed comprising 48.6% (significantly lower than 2013), byproduct feed at 30.2% (significantly higher), and locally produced feed at 21.2%.

In 2013, system-scale phosphorus outputs in manure included losses (1,649 t), sales (635 t), and field application (119 t), with losses accounting for 68.6% of manure phosphorus output, sales for 26.4%, and field application for 5.0%. In 1980, manure phosphorus outputs were 55 t (losses), 3 t (sales), and 184 t (field application), representing 22.7% losses, 1.2% sales, and 76.0% field application. The proportions of field application and sales changed substantially.

Historical changes show that in 2013, individual-scale phosphorus input was 2,536 t (9.9 times higher than 1980), with milk phosphorus output and manure excretion at 692 t and 1,845 t (21.3 and 8.2 times higher). Herd-scale phosphorus input was 3,199 t (10.1 times higher), with milk output and manure excretion at 797 t and 2,402 t (16.7 and 8.9 times higher). System-scale inputs of imported, locally produced, and byproduct feeds increased by 15.2, 5.2, and 5.3 times, respectively. Manure environmental losses and sales increased by 29.0 and 210.7 times, while field application decreased by 35.0%. In the 2013 crop production stage, chemical phosphorus fertilizer input was 761 t (5.7 times higher than 1980), and soil phosphorus accumulation increased by 1.2 times.

2.3 Historical Changes in Environmental Emissions

Changes in nitrogen and phosphorus losses from Beijing’ s dairy production system from 1980 to 2013 are shown in . Nitrogen losses included NH , N O, and N volatilization, unregulated discharge, and leaching/runoff. Phosphorus losses included unregulated discharge and leaching/runoff. In 2013, producing 1 kg of milk nitrogen generated 4.9 kg of nitrogen losses, a 46.2% reduction from 9.1 kg in 1980. Producing 1 kg of milk phosphorus generated 2.7 kg of phosphorus losses, a 29.0% reduction from 3.8 kg in 1980.

However, the reduction in nitrogen environmental losses over three decades occurred in three phases: increasing before 1985, rapidly decreasing and stabilizing after 1985, then rapidly decreasing again after 2000 before stabilizing. As production systems transitioned from household/traditional to intensive models, unregulated discharge losses in 2013 reached 2.6 kg(N)·kg ^{1} (product N), 12 times higher than in 1980, while leaching and runoff losses were 0.3 kg(N)·kg ^{1}, an 88.0% reduction. Phosphorus loss components showed similar trends.

2.4 Historical Changes in Nutrient Use Efficiency

Historical changes in nutrient use efficiency and feed conversion rate at different scales are shown in [Figure 4: see original paper]. In 2013, NUE at the individual, herd, and system scales was 21.2%, 18.2%, and 15.4%, respectively. Average NUE at individual and herd scales decreased before 1985 but increased from 1985 to 2013. While system-scale NUE was lower than herd and individual scales in 1980, it increased continuously as production intensified. In 2013, PUE at individual, herd, and system scales was 27.3%, 24.9%, and 22.3%, respectively, showing continuous improvement from 1980 to 2013. The feed conversion rate in 2013 was 1.1 kg·kg ^{1}, a 62.0% reduction from 1980.

2.5 Spatial Distribution of Nitrogen and Phosphorus Environmental Emissions

Spatial and temporal variations in nitrogen and phosphorus losses are shown in [Figure 5: see original paper]. Compared with 1980, environmental nitrogen losses from dairy production increased rapidly in suburban areas but decreased sharply in urban centers. In 2013, environmental losses in central urban districts (Chaoyang, Fengtai, Shijingshan) were reduced to zero, while suburban losses increased dramatically. In 2013, nitrogen losses per unit of arable land in Huairou, Shunyi, Miyun, and Pinggu were 354.3 kg·hm ^{2}, 69.8 kg·hm ^{2}, 94.4 kg·hm ^{2}, and 27.9 kg·hm ^{2}, respectively–increases of 1,896, 1,308, 758, and 636 times compared with 1980. Phosphorus losses per unit area in these districts were 34.2 kg·hm ^{2}, 6.7 kg·hm ^{2}, 9.1 kg·hm ^{2}, and 2.0 kg·hm ^{2}, respectively –increases of 2,454, 1,688, 977, and 601 times. Regional environmental losses were closely related to dairy herd size and production system distribution.

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3. Discussion

3.1 Temporal Changes in Nutrient Use Efficiency

From 1980 to 2013, nitrogen use efficiency at individual, herd, and system scales showed a "decrease then increase" pattern–declining before 1985, then increasing rapidly after 1985, with a second rapid increase after 2000. Phosphorus use efficiency at all scales increased continuously. Meanwhile, nitrogen and phosphorus losses per kilogram of product showed an "increase then decrease" trend.

These changes were associated with increasing herd numbers, structural changes in production systems, and growing societal attention to environmental issues.

Before the late 1970s, 80% of dairy cattle were raised on state farms. Subsequently, 70% were raised by dispersed households as a supplementary income source rather than a specialized occupation, with low management levels and simple roughage feeding. Consequently, despite rising herd numbers, nutrient use efficiency declined slightly before 1985. Intensive dairy farm construction began gradually in 1986, and with the "Vegetable Basket" project in the late 1990s, Beijing pioneered intensive and scaled dairy production. Since 2000, rapid development increased herd numbers 2.0-fold compared with 1985. System-scale nutrient use efficiency increased continuously, contrasting with trends in pig production, primarily because increases in milk yield per cow far exceeded increases in feed input.

Since 2007, following the State Council's Opinions on Promoting Sustainable and Healthy Dairy Development, Beijing has focused on scaling and standardizing dairy production. The second decline in environmental nitrogen losses after 2000 also correlates with numerous standards, guidelines, and policies issued by the Ministry of Environmental Protection and Ministry of Agriculture regarding livestock farm siting, pollutant discharge, pollution prevention, and harmless treatment.

In 2013, individual-scale NUE in Beijing was 20.5%, higher than China' s 2010 average of 17% but lower than the EU's 2009 level of 26%. This is mainly because Beijing' s dairy feed crude protein content is 16.6%, substantially higher than the US average (13.6%) and EU average (15.8%), due to higher proportions of protein-rich ingredients like soybean meal (22%) and wheat bran (9%). Beijing' s individual-scale PUE of 25.2% exceeds the national average of 17%.

3.2 Spatial Variation in Environmental Emissions Across Beijing Districts

Urbanization has increasingly constrained Beijing' s dairy industry through resource and space limitations, making coordinated intensive production planning urgent during the 13th Five-Year Plan period. Over the past 30 years, environmental losses from livestock production decreased rapidly in urban and peri-urban areas but increased sharply in outer suburbs. Livestock distribution has formed a "three-belt, multi-species" pattern, with cattle production concentrated in Fangshan, Daxing, Tongzhou, Shunyi, Changping, Miyun, and Yanqing—aligning with the spatial distribution of environmental emissions.

Compared with 1980, environmental emissions per unit of arable land increased dramatically in suburban districts, driven by surging herd numbers, rapid intensification, and decreasing farmland. For example, Huairou's dairy herd increased from 30 head in 1980 to 19,438 in 2013 (647-fold increase). Herds in Shunyi, Miyun, and Pinggu increased by 565, 627, and 99 times, respectively. This distribution resulted from both natural and anthropogenic factors. Beijing' s mountainous northwest and northeast regions provide more space and roughage resources for dairy farming, resulting in higher environmental emissions. Additionally, urban functional zoning has altered herd distribution and structure. Beijing' s four functional zones—core capital functional area, urban functional expansion area, new urban development area, and ecological conservation area —have distinct responsibilities. The new urban development area focuses on advanced manufacturing and modern agriculture, while the ecological conservation area serves as an ecological barrier and water source protection zone emphasizing ecological agriculture. Consequently, environmental losses increased most significantly in these two zones, particularly in ecological conservation areas (Huairou, Miyun, Pinggu) and new urban development areas (Shunyi, Daxing). Unlike pig production, dairy environmental emissions increased more markedly in ecological conservation areas because dairy farming requires more land, concentrating in mountainous and hilly regions.

3.3 Optimization Strategies for Nitrogen and Phosphorus Management

Beijing' s dairy industry is typical of metropolitan dairy systems. With accelerating urbanization and decreasing agricultural land, Beijing cannot pursue large-scale farming like resource-based cities. Functional planning changes have created difficulties in site availability and feed supply. Transitioning from quantity-based to quality-based development is paramount. In 2010, medium-sized farms averaged 5,127 $kg \cdot cow^{1} \cdot yr^{1}$ while large farms reached 7,995 $kg \cdot cow^{1} \cdot yr^{1}$, with milk production exceeding consumption by 204,000 t. Achieving production-consumption balance at current maximum production levels could reduce herd size by 25,527 head. Therefore, Beijing should improve nutrient use efficiency through higher per-cow productivity and land resource efficiency to compensate for natural resource limitations.

Promoting moderately scaled farming and crop-livestock integration is essential. Considering environmental capacity, roughage availability, costs, and disease prevention, controlling scale intensity, optimizing feed input, and enhancing crop-livestock integration are necessary. Farmers should be guided to establish dairy production zones and cooperatives to achieve moderate-scale, standardized development. Reducing protein feed input by 2% (from 16.6% to the EU/US average of 14.7%) would decrease gaseous nitrogen losses and economic costs. The government should actively promote "planting-breeding integration" models to achieve "zero-pollution integrated" operations.

Strategic relocation of dairy farming is also recommended. During the 12th Five-Year Plan, Beijing aimed to become a "seed industry capital," leveraging its economic, technological, and human resources to develop superior breeds while combining with Tianjin and Hebei' s natural resource advantages for effective technology-resource integration.

4. Conclusion

This study used the NUFER-animal model to analyze 30 years of nitrogen and phosphorus flows and spatiotemporal changes in Beijing' s "soil-feed-dairy" production system, quantifying nutrient use efficiency and environmental losses.

Nutrient flow characteristics changed substantially. Feed nitrogen and phosphorus inputs remained dominated by imported feed, whose proportion increased over time while byproduct and locally produced feeds decreased, with byproduct feed showing a greater decline. Manure output shifted from primarily on-farm cycling in 1980 to mainly sales to fruit and vegetable growers in 2013, representing a major change in input-output ratios.

Nitrogen use efficiency at individual, herd, and system scales showed a "decrease then increase" trend—declining before 1985 then increasing afterward. Phosphorus use efficiency at all scales increased continuously. Total nitrogen losses increased 10.2-fold from 1,516 t in 1980 to 16,973 t in 2013, while total phosphorus losses increased 14.5-fold from 114 t to 1,763 t. Losses per kilogram of nitrogen and phosphorus product showed an initial increase followed by a decrease. Therefore, adopting precision feeding and manure management technologies from intensive systems while integrating crop and livestock production is essential for improving dairy farming sustainability.

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