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Changing food nitrogen flow in a food-exporting city

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Introduction: Nitrogen (N) plays a significant role in food systems, but only a fraction of N is effectively utilized and the rest is lost to the environment and negatively affects the ecosystem. So far, there has been relatively little research on N flow associated with the food production and consumption of production-oriented cities in developing countries.

Methods: In this study, we present a comprehensive analysis of N flow in the food production and consumption system of Changchun in China between 1991 and 2014, and define three types of nitrogen use efficiency (NUE) and compare them.

Results: (1) Total new N input into the food system in Changchun increased by 63.75% (240.8 to 394.3 Gg N yr^{-1}) during the study period, mainly attributable to the high volume of food exports(total output from 47.63 to 72.51 Gg N yr^{-1}). (2) Changchun typically exhibited lower apparent NUE and virtual NUE of the food system, while its actual NUE was typically higher, compared to food-importing cities. (3) The consumption of crop food witnessed a decrease from 24.2 Gg N in 1991 to 18.7 Gg N in 2014, whereas the consumption of animal food showed an upward trend from 2.5 Gg N to 7.7 Gg N. Both urban and rural residents consumed less grain food but more fruits and meat. (4) The total N loss has increased from 131.3 Gg N in 1991 to 266.6 Gg N in 2014. The crop production caused 58.1% of the total N loss in 2014, and the atmospheric loss accounted for 40.2% of the total.

Conclusion: The study has revealed the distinctive features, fluctuations, and underlying drivers of N flow in the food-exporting city, setting it apart from food-importing city. These findings provide a valuable point of reference for the implementation of customized and diversified nitrogen management strategies in these specific urban areas.

KEYWORDS
nitrogen flow, nitrogen use efficiency, food system, food-exporting city, nitrogen loss

1. Introduction

Nitrogen (N) is an irreplaceable element in the natural environment. It can be absorbed by crops when it is converted to reactive N (Nr), thus helping to maintain food production. Consequently, it is an essential determinant of the food supply (Galloway et al., 2004; Kanter et al., 2020); indeed, N input mainly originates from agricultural production and energy use (Xing and Zhu, 2002). As the world's population has grown, the food demand has markedly increased, to the point where the naturally occurring N can no longer meet the intensifying demands of food production (Tilman et al., 2011). In response, farmers have begun to rely on artificially synthesized fertilizer (Erisman et al., 2008). As a good "helper" to improve food production, N fertilizer has come to play a significant role in promoting crop growth, expanding crop yields and accelerating agricultural development (Galloway et al., 2003). Yet this anthropogenic N input has impacted the N cycle in both natural and manmade ecosystems (Erisman et al., 2013; Liu et al., 2020), and excessive N lost to the environment can contribute to many environmental problems, such as biodiversity loss, coastal ecosystem degradation, global warming effects and so on (Grimm et al., 2008; Shi et al., 2015; Smith and Siciliano, 2015; Huang et al., 2017). Therefore, how to use N efficiently and rationally is an urgent problem to solve.

As a developing country with an enormous population, China is facing a shortage of resources. With China's rapid population growth and economic development in recent years, massive amounts of N fertilizer have been applied to agricultural production, to satisfy the rising demand for food (Fowler et al., 2013; Bai et al., 2014). China has therefore become a hotspot for exploring N flow in the food system (Bai et al., 2014). For example, Ma et al. used the NUFER (Nutrient flows in Food chains, Environment and Resources use) model to study the N cycle and N utilization efficiency of China in 2005, and their results showed that circulating N only accounted for about 30%, and the nitrogen use efficiency (NUE) in the food chain system was only 8.9% (Ma et al., 2010). Some other researchers have shown more interest in the driving forces of food system N flows. For example, Gao et al. analyzed the *per capita* food N consumption in urban and rural areas in China from 1990 to 2012, and concluded that dietary changes, population growth and urban–rural migration are the main factors affecting N flow in China's food system (Gao et al., 2018). And some studies have linked different subsystems systematically: Gu et al. used the CHANS (Coupled Human and Natural System) model to study the N cycle in China's industrial, agricultural, human, environmental, and natural systems, finding that reasonable management measures could reduce China's environmental pollution by half, based on the supply of food, energy and other necessities (Gu et al., 2015).

Urban areas, with their concentrated consumption of resources and concentrated release of wastes (Zhong et al., 2021), are confronted with serious N pollution problems (Groffman et al., 2004; Hobbie et al., 2017), and the production and consumption activities in cities have become one of the important processes changing the regional and global N cycle. Thus many researchers have focused on small-scale studies of N flow in the food system, an approach more conducive to proposing targeted measures. By taking European cities as study cases, Barles (2007) and Gierlinger (2015) explored the changes of N flows from the food and feed supply to food consumption during the 19th century, and compared the N in the food system under different socio-ecological contexts. Some studies have paid more attention to urban food consumption, by establishing an N balance model (balance of input, storage, and output). Forkes and Faerge studied N loss in Toronto and in Bangkok, respectively, to explore management practices (Faerge et al., 2001; Forkes, 2007). In the study of urban food N flow in developing countries, Ma et al. explored the impact of urban expansion on N flow, pointing out that low N use efficiency is the main problem we are currently facing (Ma et al., 2014). Liu et al. investigated the impact of changes in dietary habits on N flow in Shanghai under rapid urbanization, through questionnaires and interviews, showing that the potential N load from the human diet will continue to increase (Liu et al., 2014). Liao et al. also took Shanghai as a case city, focusing on the N input, output and pollution associated with food production and consumption (Liao et al., 2021). Huang et al. investigated the N flows of the urban food system in a food-importing city (Huang et al., 2020). Dong et al. presented the variations of N flow under anthropogenic disturbance from production and consumption in Guangzhou (Dong et al., 2020). Wang et al. calculated the N balance, NUE and N losses in Ledu County, a typical agricultural and pastoral region on the Qinghai-Tibet Plateau, and proposed five measures to improve N management (Wang et al., 2021). Zhang et al. studied the evolution of food nitrogen in Beijing, during 1979–2019, and investigated the supply hinterlands from a nitrogen perspective (Zhang et al., 2022). On a larger scale, Zhang et al. analyzed the food nitrogen flow of the Yangtze River Delta city cluster (Zhang et al., 2022).

However, most research related to N flow has focused on large cities or consumption-oriented cities, and there has been less research on production-oriented cities. By taking Changchun, China's commodity grain base and a typical food-exporting city as a study case, this research presents an overview of an N flow characteristic of the food system. In the following sections, we elaborate in more detail (i) the overall N flow of the food system in Changchun from 1991 to 2014, (ii) the NUE of food systems, (iii) changes in the structure of food production and consumption systems, and (iv) the N loss. This study facilitates a comprehensive understanding of the N flows and their drivers in the food-exporting city, and explores various strategies for N management, which are distinct from those for food-importing cities.

2. Materials and methods

2.1. Profile of the case city

Changchun is one of the nine administration prefectures of Jilin province. It is located in the geographic center of Northeast China, in the flat Songliao Plain, with a temperate monsoon climate (Figure 1). It has a vast territory, rich land resources and fertile soil, resulting in superior farming conditions. The arable land area increased from 11,051 km^2 to 13,066 km^2 during 1991–2014, and great agricultural success has been achieved there. Although the proportion of the primary industry has been declining during 1991 to 2014 (since the secondary industry has developed rapidly), its total amount has shown an upward trend year by year (Supplementary Figure S1). During 1991–2014, the urbanization process in Changchun steadily advanced, with the urbanization rate rising from 37 to 45%. Furthermore, Changchun is a typical food-exporting city; its net export quantity of crop and animal food accounted for approximately 63.25 to 78.27% of its total production output during 1991–2014. The total value of food exports in 1991 was about 2019 million US dollars, and increased to 6,884 million dollars in 2014.

2.2. Model description

By adapting the NUFER model from Ma et al. and the coupled urban and rural N flow model of the Chinese food system from Ma et al. (2014) and Gao et al. (2019), this study constructed a food system N flow model at the city scale. The system boundary of the

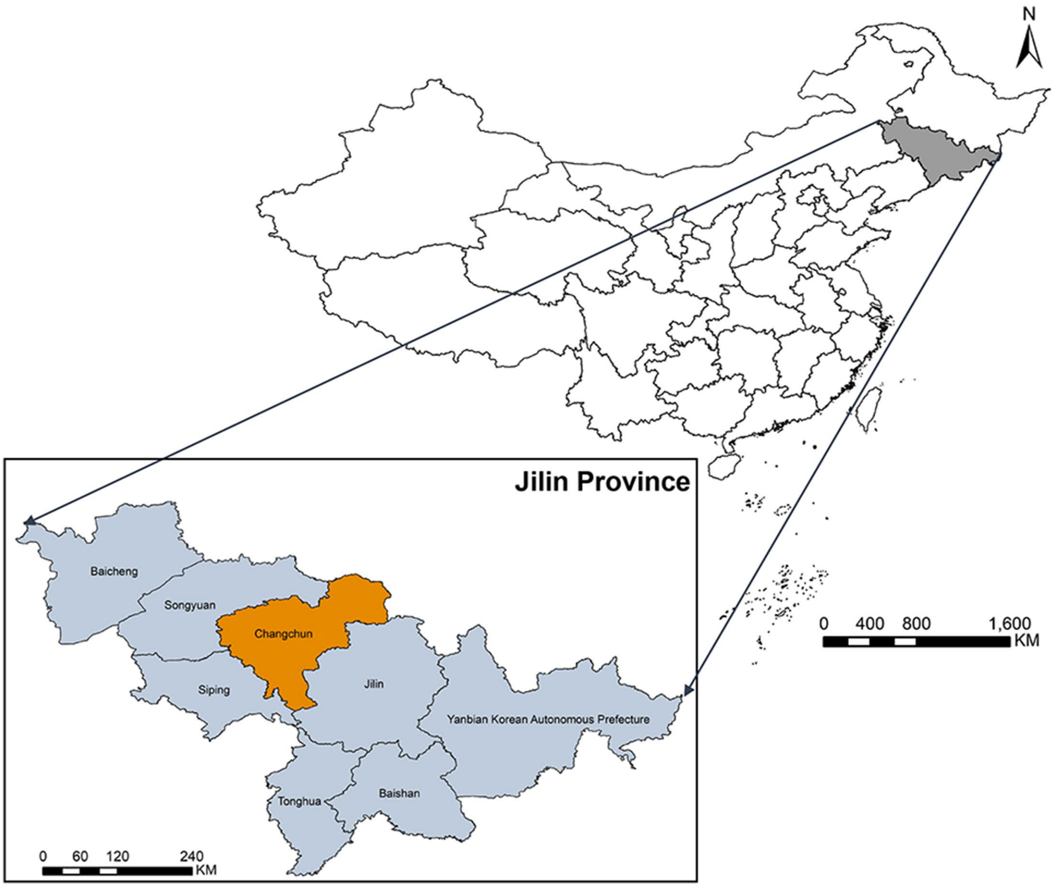

FIGURE 1
The location of Changchun.

model follows the administrative boundary of Changchun, and the whole food system was divided into three parts: crop production (CP), animal production (AP), and household consumption and waste disposal (HC). The CP category included 11 crops (rice, wheat, corn, millet, sorghum, other grains, beans, potatoes, vegetable-oil plants, vegetables, and fruit). The AP category included 11 animals (dairy products, eggs, pork, beef, mutton, poultry, rabbits, horses, donkeys, mules and aquatic products). The HC category included rural and urban household diets. Based on Substance Flow Analysis (N flow = mass of material × N concentration of material) and mass balance calculations ($\sum$inputs = $\sum$outputs + $\sum$accumulations) (Cui et al., 2016), we calculated the total N flow in the food system in Changchun. Details on calculation formulas are presented in the Supporting Information.

There are two major approaches to describing and assessing the resource efficiency of the system of concern: nitrogen use efficiency (NUE) and N recycling rate. Depending on the differences in system boundaries, application contexts, and management objectives, NUE can be interpreted and defined in three distinctive ways: actual NUE, apparent NUE, and virtual NUE (Ma et al., 2014; Gao et al., 2019). The actual NUE (NUE_{act}), which is defined from the production perspective, refers to the ratio of total N in local agricultural products of a concerned system to total actual N input during the production process. NUE_{act} can be further divided into NUE_c and NUE_a. NUE_c is defined as the ratio of N output in marketed crop products to the total N input into CP, and NUE_a is defined as the ratio of N output in marketed animal products to the total N input into AP (Ma et al., 2012). The apparent and virtual NUE, on the other hand, are both defined from the consumption perspective. Apparent NUE (NUE_{app}) refers to the ratio of total consumed N in the concerned system to total actual N input, which includes both N input into the agricultural production system and imported food N consumed by residents. Virtual NUE (NUE_{vir}), by applying the virtual nitrogen factor (VNF) concept, refers to the ratio of total consumed N in the concerned system to the total N input, regardless of whether it occurs locally or in other areas, to produce the consumed N (Burke et al., 2009). In other words, VNF must be used to trace back all initial N inputs used to produce imported feed and food, and to subtract local N inputs used to produce exported food. In the food system, the N recycling rate is determined by dividing the total amount of recycled nitrogen by the overall quantity of newly introduced nitrogen inputs (Huang et al., 2019).

$$NUE_{act} = \frac{F_{pro}}{I_{a+c} + I_{aqu} + I_{wc} + I_{net-im\,feed}} \tag{1}$$

$$NUE_{app} = \frac{F_{con}}{I_{a+c} + I_{aqu} + I_{wc} + I_{net-im\,feed} + I_{net-im\,food}} \tag{2}$$

$$NUE_{vir} = \frac{F_{con}}{\begin{array}{c} I_{a+c} + I_{aqu} + I_{wc} + I_{VN(net-im\ feed)} \\ + I_{VN(net-im\ food)} - O_{VN(net-ex\ food)} \end{array}} \quad (3)$$

In these equations, I_{a+c} denotes the comprehensive N contribution to crop and animal production systems, which encompasses N originating from chemical fertilizers, atmospheric deposition, irrigation, and forage feed, as well as nitrogen fixation through biological means; I_{aqu} denotes N input from feed in freshwater and seawater cultivation; I_{wc} signifies N encapsulated within wild-caught fish and seafood from aquatic ecosystems; $I_{net\text{-}im\ feed}$ and $I_{net\text{-}im\ food}$, respectively, stand for the N embodied in imported net feed and in food products. In addition, $I_{VN(net\text{-}im\ feed)}$, $I_{VN(net\text{-}im\ food)}$, and $O_{VN(net\text{-}ex\ food)}$ represent virtual N inputs in the course of imported feed and food production processes, as well as virtual N exported through local food exports. Finally, F_{con} and F_{pro} represent overall N in food consumption and food production in urban areas, respectively.

2.3. Data collection

The basic data (Supplementary Table S1) used in this study, such as fertilizer usage, crop residue, crop yields, arable area, feed import, population, and urbanization rates, were mainly taken from Changchun's statistical yearbooks. Another category of data is the parameters used for the calculation of N flow. The N flow parameters can be further divided into fixed and unfixed parameters. The fixed parameters (Supplementary Table S2) are parameters with relatively stable values, such as the N content of compound fertilizer, food N content and crop harvest index, while unfixed parameters (Supplementary Table S3) can vary with location or time, such as N deposition rate and leaching ratio. These parameters were derived from previous research (Ma et al., 2014; Gao et al., 2019).

3. Results and discussion

3.1. N flows of the food system

The total new N input into the food production and consumption systems in Changchun increased by 153.5 Gg N, from 240.8 Gg N to 394.3 Gg N from 1991 to 2014 (see Figure 2 for a more detailed N Flow). During this period, chemical fertilizer was the primary source of N input, reaching 62.7% in both 1991 (151.1 Gg N) and 2014 (247.3 Gg N). The amount of feed import N showed a general increasing trend, from 0 Gg in 1991 to 74.4 Gg in 2014; however, it decreased dramatically in 2010, from 236.7 Gg N in 2009 to 53.2 Gg N in 2010, due to a sharp decrease in animal breeding. The amounts of N from seed, deposition and biological fixation of nitrogen (BNF) remained steady. Total products of the CP and AP subsystems increased from 188.9 Gg N to 336.4 Gg N. The population growth rate and the speed of urbanization in Changchun were not as fast as those of many other cities in China, and the growth rate of local food consumption has been relatively slow. The increase in N flow in Changchun was mainly driven by food production. This is much different from food-importing cities where most of the N in the food system is imported from other areas. For instance, in Shanghai, the N input from nitrogen fertilizer, the major new N input source, decreased significantly, from 149.0 Gg N in 2000 to 37.5 Gg N in 2018 (Liao et al., 2021). In Xiamen, the input of new N into the food system decreased from 30.4 Gg in 1993 to 28.4 Gg in 2012 (Huang et al., 2019). Therefore, decision making on N management needs to consider the different N-flow types of cities. For food-exporting cities with large production capacity, more attention should be paid to reducing new N inputs and loss on the production side. For food-importing cities, altering consumer preferences can serve as a potential strategy to establish a "low nitrogen consumption mode."

Figure 3 shows the N inputs and output of the CP and AP subsystems during 1991–2014. The N input of the CP subsystem (Figure 3A) can be divided into two categories: new N input, including chemical fertilizer, BNF, seed, deposition and irrigation; and circulating N, including manure and crop residue. In 1991, the new N input into the CP subsystem was 240.8 Gg N; in 2014, it rose to 319.6 Gg N. In 1991, the circulating N input into the CP subsystem was 43.7 Gg N; in 2014, it increased to 123.1 Gg N. Apart from a significant decline in manure due to a severe animal flu incident in Changchun in 2010 resulting in a considerable loss of animal life, the overall trend of the N recycling rate demonstrates an upward trajectory. It has surged from 18.13% in 1991 to 38.53% in 2014 (Supplementary Figure S2). As a result, the total N input also increased significantly, from 284.5 Gg N in 1991 to 442.7 Gg N in 2014. As for the N output, crop harvest was the main output of the CP subsystem, with 183.4 Gg N in 1991 and 304.0 Gg N in 2014, showing a slight upward trend. The primary cause of the increase is that Changchun, as a major grain-producing city, increased its crop product supplies to outside the city (net export). Although the population of Changchun increased by 19% from 1991 to 2014, changes in the city's food consumption structure, specifically a reduction in *per capita* grain consumption for rural residents, has resulted in a decline in the city's crop food consumption. Comparing new and circulating N in the CP subsystem, although the ratio of new N input showed a slight downward trend, from 84.5% in 1991 to 72.2% in 2014, it still accounted for the majority of the total N input. In Changchun, there were abundant varieties of straw resources (Fang et al., 2015), but the amount of straw waste was still higher than the amount returned to the field, indicating that there is great potential for better resource utilization of straw.

The increase of livestock and poultry production in Changchun led to a significant increase, of 368%, in the total N input into the AP subsystem, from 48.5 Gg N in 1991 to 227.5 Gg N in 2014 (Figure 3B). The Changchun government has successively implemented various measures for the development of the animal husbandry industry, such as the "Three-Year Campaign to Accelerate the Development of Animal Husbandry" and the "Four-Year Plan to Enhance Animal Husbandry," which have accelerated the local animal husbandry industry's progress. Several provincial– and municipal–level animal husbandry industrial parks have been established, making Changchun an important national base for animal products, with the development of animal husbandry; this has become one of the leading industries in Changchun, and the feeding requirements have increased accordingly. Since 1995, the locally produced feed has no longer been able to meet the breeding needs, and Changchun has started to import feedstuff. The feed from external sources accounted for 18.6% of the total N input in 1995, increasing to 69.4% in 2009, gradually becoming the main N input

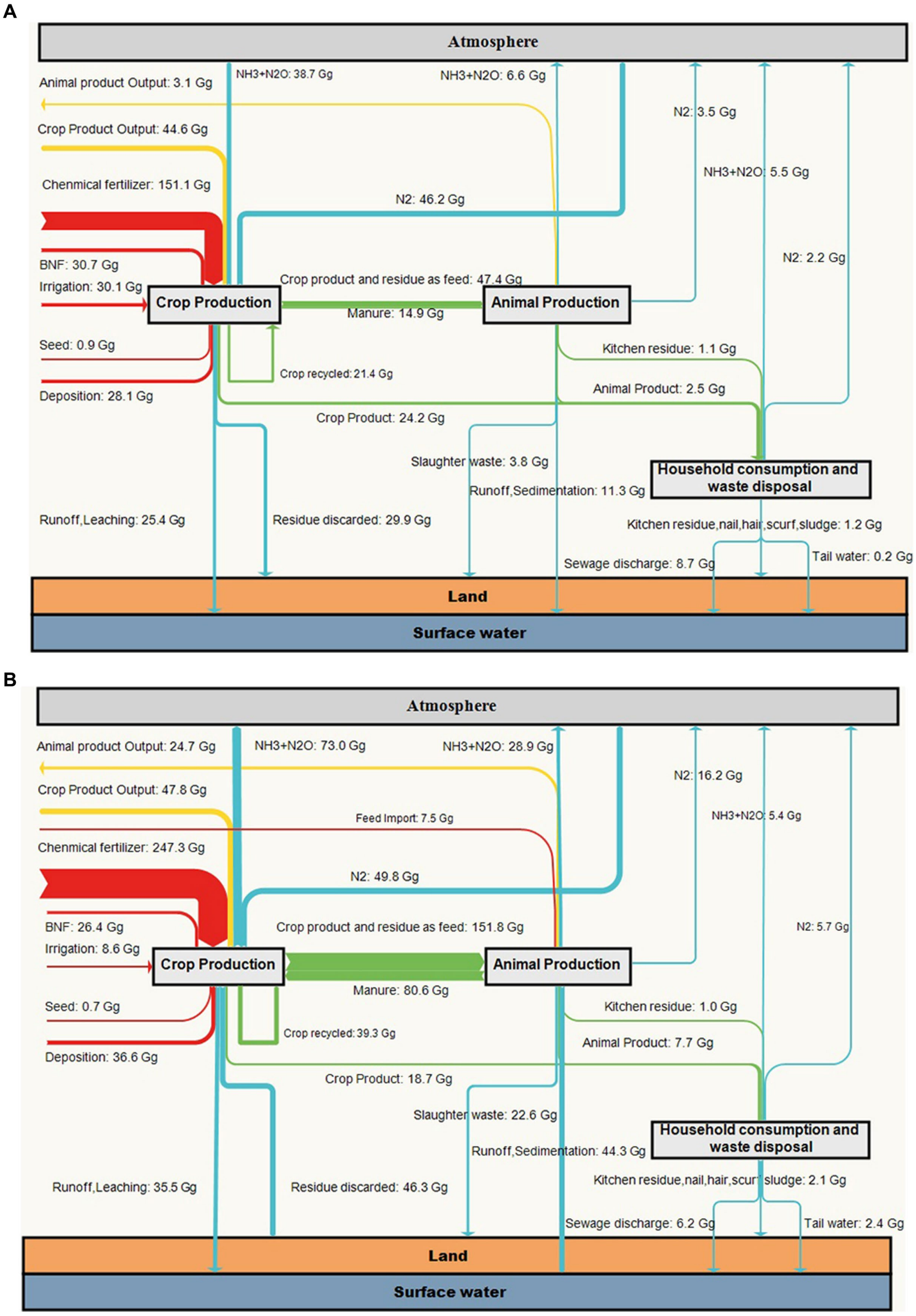

FIGURE 2
N flows of food system in Changchun in **(A)** 1991; **(B)** 2014. Red arrows represent N input flows from external system, green ones represent N internal flows between subsystems, blue ones represent N-loss flows into the environment, and yellow ones represent N output flows to external system.

to the AP subsystem. Due to a severe animal flu incident in Changchun in 2010, though, the number of livestock and poultry decreased significantly, as did the input and output N of the AP subsystem; the N input decreased from 340.8 Gg N in 2009 to 171.8 Gg N in 2010, and the product N decreased from 59.5 Gg N to 25.1 Gg N. After the epidemic was effectively controlled, the N input and output of the AP subsystem staged a recovery in 2011. In general, while the input and output of the AP subsystem were impacted by natural factors during the period from 1991 to 2014, there was an overall upward trend driven by anthropogenic influences.

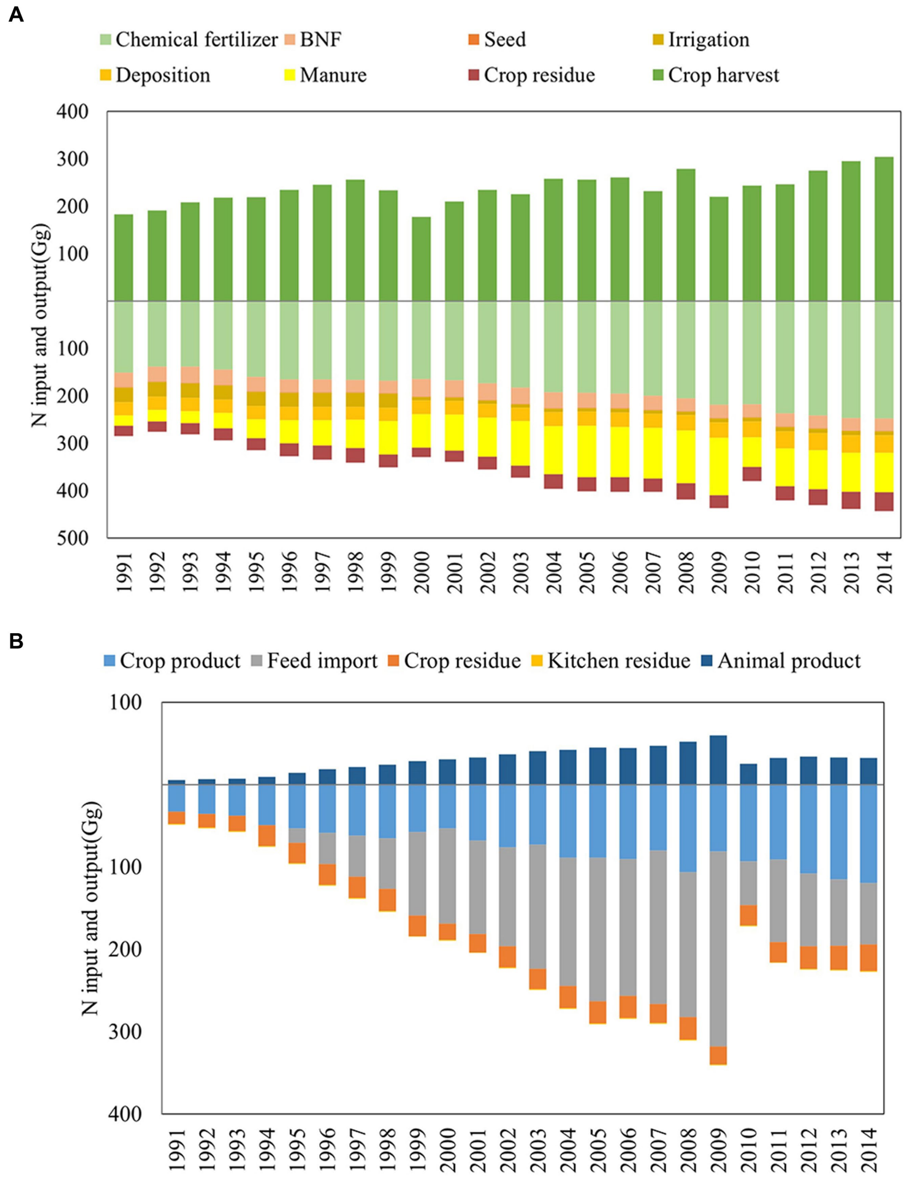

FIGURE 3
N flows of **(A)** crop production subsystem; **(B)** animal production subsystem.

3.2. NUE of food production systems

NUE_c fluctuated from 1991 to 2014. Compared with 1991 (64.5%), the NUE_c increased slightly, to 68.7%, in 2014 (Figure 4A), although NUE_c experienced rapid declines in 2000 and 2009, both due to severe drought conditions, which severely affected the growth of crops, causing a significant reduction in yield. For example, corn production, which represents the highest proportion (42.4–62.1%) of total crop production, experienced declines in yield of 40.6 and 24.5% in 2000 and 2009, respectively. And the NUE_a also rose, from 11.4% in 1991 to 15.3% in 1996, followed by a period of overall stability (Figure 4B), mainly due to the increasing proportion of poultry (from 10.5 to 30.0%, Supplementary Figure S3) in A-food production during the same period. However, there was a slight drop in NUE_a after 2009, which was primarily due to the severe impact of influenza on the production of pork and poultry as well as a severe blow to consumer confidence regarding consumption.

Compared with the CP subsystem, the NUE_a was much lower. The nationwide averages for nitrogen use efficiency in crop production (NUE_c) and animal production (NUE_a) were recorded to be 26 and 16%, respectively in 2005 (Ma et al., 2012). And in Xiamen, a typical food-importing city, the NUE_c in 2014 was 28.8% and the NUE_a was 13.8% (Huang et al., 2019). It can be seen that NUE_c in Changchun was much higher than both the national level and the level in a typical food-importing city, while the NUE_a was equivalent to both the national level and that of a food-importing city. Therefore, improving NUE_a through certain management methods and some techniques are the direction of future efforts. In fact, animal manure has always been an important source of nutrients for crop cultivation (Xia et al., 2017). China's livestock and poultry breeding industry has developed rapidly,

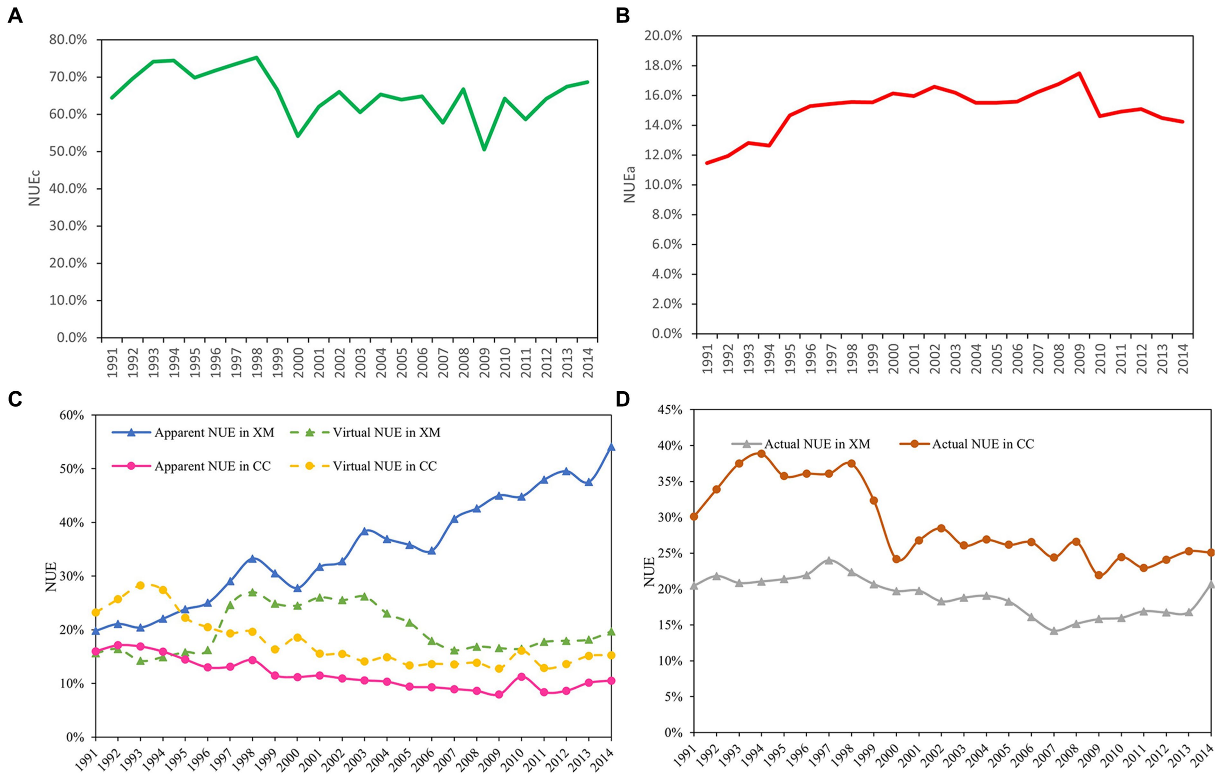

FIGURE 4
(A) NUE in crop production in Changchun; **(B)** NUE in animal production in Changchun; **(C)** apparent and virtual NUEs of food systems in Changchun and Xiamen; **(D)** actual NUE of food system in Changchun. NUE, nitrogen use efficiency; CC, Changchun; XM, Xiamen.

and thus the amount of manure has also increased sharply, showing that China has abundant manure nutrient resources, and has a high potential for replacing chemical fertilizers. However, the current separation of livestock and crop production and improper manure management prevent manure from becoming an effective resource, becoming instead a type of environmental pollution. Studies have confirmed that the proportion of farmers in China who grow crops and also raise livestock has dropped sharply, from 71% in 1986 to 12% in 2017 (Jin et al., 2020), a trend that reduces the potential for recycling manure into farmlands. In Changchun, the proportion of manure and urine in the total N input of the CP subsystem increased from 7.8% in 1991 to 19.0% in 2014, showing that Changchun has developed well in terms of returning manure and urine to fields. It is necessary to further increase the proportion of recycling, strengthen the combination of planting and use, and take full advantage of Changchun's agricultural production.

From the consumption side, between 1991 and 2014, even though there was little fluctuation in either the NUE_{app} or the NUE_{vir} of the food system in Changchun, both showed a basic decreasing trend, and NUE_{app} was clearly lower than NUE_{vir} (Figure 4C). In comparison with Xiamen, a typical food-importing city, it can be discerned that NUE_{app} was overestimated for food-import cities and underestimated for food-exporting cities. From the production viewpoint, the NUE_{act} of Changchun displayed a trend of decrease, followed by stabilization, from 1991 to 2014, consistent with most other Chinese cities (Figure 4D). The NUE_{act} of food-exporting cities is generally higher than that of food-importing cities like Xiamen, partially because of differences in plantation structure and fertilization management. To sum up, NUE_{app} provides the most intuitive understanding of NUE, but it embodies the influence of food trade and is prone to be underestimated or overestimated, causing misperceptions. In contrast, NUE_{vir} can more objectively reflect the resource utilization efficiency and environmental effects at the consumption end. On the other hand, NUE_{act} indicates the resource utilization efficiency and environmental effects of the local food production system. Different NUE metrics, in other words, are applicable to different scenarios and management goals.

3.3. Changes in food production and consumption structure

Crop food (C-food) and animal food (A-food) are the main products of production systems and also two sources of the food consumption subsystem. The C-food produced in Changchun was 67. 0 Gg N in 1991 and 66.5 Gg N in 2014. In 2000, it dropped sharply, from 85.9 Gg N in 1999 to 55.2 Gg N. The amount of A-food production has increased significantly, however, from 5.5 Gg N in 1991 to 32.4 Gg N in 2014, despite a sudden drop in 2010. The consumption of C-food fluctuated from 24.2 Gg N in 1991 to 18.7 Gg N in 2014, while the consumption of A-food increased remarkably, from 2.5 Gg N to 7.7 Gg N. To sum up, C-food consumption N was 9.7 times that of A-food in 1991, while by 2014, the C-food consumption N was only 2.4 times that of A-food. Comparing the data above, it can be easily seen that the food produced in Changchun can not only meet the local demand but also provide a large amount of food for export. The proportion of C-food exported fluctuated during 1991 to 2014, between 63.9 and 76.8%, while the proportion of A-food exported increased from 55.0% in 1991 to 76.2% in 2014 (Figure 5). It can be seen that the demand for A-food increased both in the local region and in other regions. As the NUE of the AP subsystem has been much lower than that of the CP subsystem, an increase in the share of A-food production and consumption will therefore further increase the pressure on N inputs and loads in the region.

We calculated the *per capita* consumption of the main food N of Changchun residents and analyzed the changes in household diets in rural and urban areas (Figure 6). From 1991 to 2014, the *per capita* food N consumption of urban residents increased from 2.7 kg.cap^{-1}.yr.$^{-1}$ in 1991 to 3.8 kg.cap^{-1}.yr.$^{-1}$ in 2014, and reached a peak of 4.35 kg.cap^{-1}.yr.$^{-1}$ in 2003, while *per capita* N consumption of rural residents decreased from 5.0 kg.cap^{-1}.yr.$^{-1}$ in 1991 to 3.2 kg.cap^{-1}.yr.$^{-1}$ in 2014. The *per capita* food N consumption of urban residents gradually came to exceed that of rural residents. Comparing these results with related research, Xian and Ouyang (2016) estimated the food N footprint of urban and rural residents in Beijing from 1980 to 2012, and their results indicated that the N footprint of urban residents showed steady growth, almost reaching the level of developed countries, and the N footprint of rural residents showed a slight decrease, consistent with the results from Changchun. Although Changchun exhibits different trends between urban and rural areas in terms of *per capita* food N consumption, a similar pattern can be observed in *per capita* consumption of C food and A food in both areas. In Changchun, the consumption of C-food represented by vegetables and cereals showed a downward trend. In 1991, urban residents' C-food consumption accounted for 74.8% of total food consumption, falling to 63.4% in 2014; and among rural residents, the proportion of C-food consumption decreased from 95.7% in 1991 to 77.8% in 2014, while consumption of fruits increased slightly (Supplementary Figure S4). The consumption of N in A-food represented by livestock, poultry and aquatic products increased greatly, from 0.7 to 1.4 kg.cap^{-1}.yr.$^{-1}$, and 0.2 to 0.7 kg.cap^{-1}.yr.$^{-1}$ in the urban and rural areas, respectively, and the consumption of eggs and dairy products also increased a great deal. It can be seen that with the improvement of living standards, the food consumption structure of residents in Changchun underwent major changes. People prefer high-N A-food, especially high-quality protein, when they can afford it. Similar trends of diet transition are occurring at the global scale, with traditional diets being replaced by refined-food and meat diets (Godfray et al., 2010; Malik et al., 2013), and one-third of global cropland area is devoted to producing animal feed (Tilman and Clark, 2014), a trend that will greatly affect the environment in negative ways.

3.4. N losses from the food system

China is facing serious N pollution problems (Liu et al., 2011; Zhao et al., 2012). For Changchun, as a result of increasing N input to the food system, the N loss was also steadily increasing during this study period, with a 103.1% increase, from 131.3 Gg N in 1991 to 266.6 Gg N in 2014 (Figure 7), mainly due to the large amount of N input to food production systems caused by the demand for food from other regions. N loss is emitted to the atmosphere *via* NH_3, N_2O and N_2, to the surface water via runoff and leaching, and to the land *via* crop residue, slaughter waste, etc. Most of this N is released into the atmosphere and the water, less to the soil. Between 1991–2014, the amount of N released into the atmosphere accounted for 37.7 to 40.7%

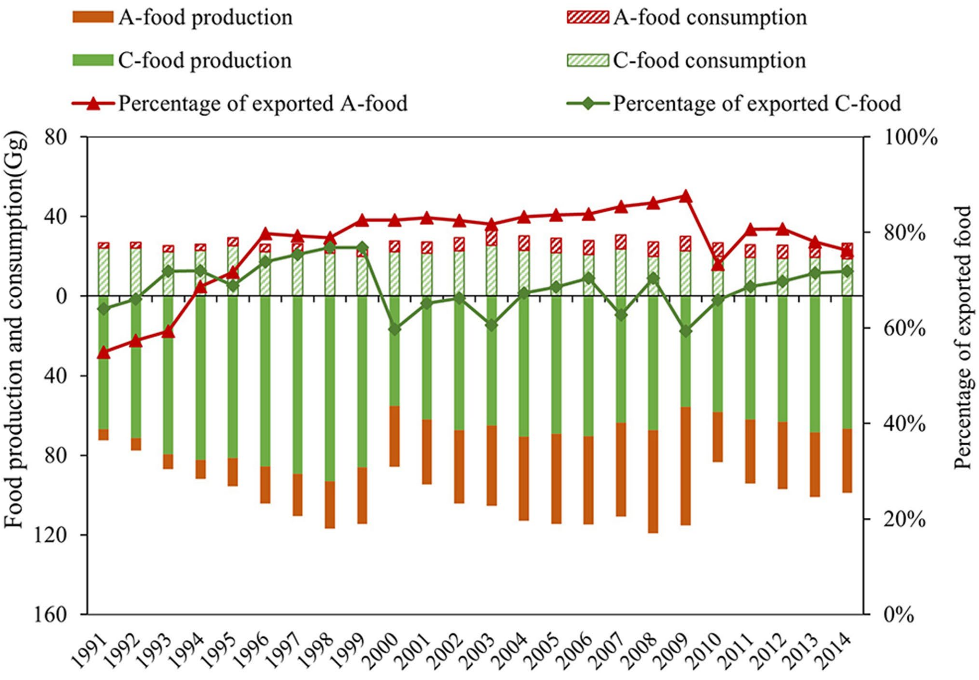

FIGURE 5
Changes in food production and consumption. C-food, Crop food; A-food, animal food.

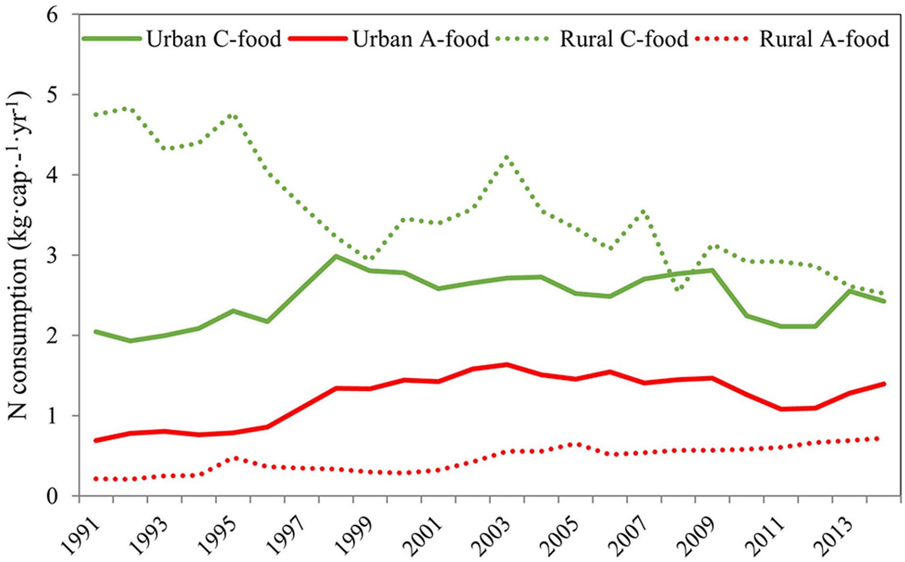

FIGURE 6
Per capita food N consumption of urban and rural residents. C-food, Crop food; A-food, animal food.

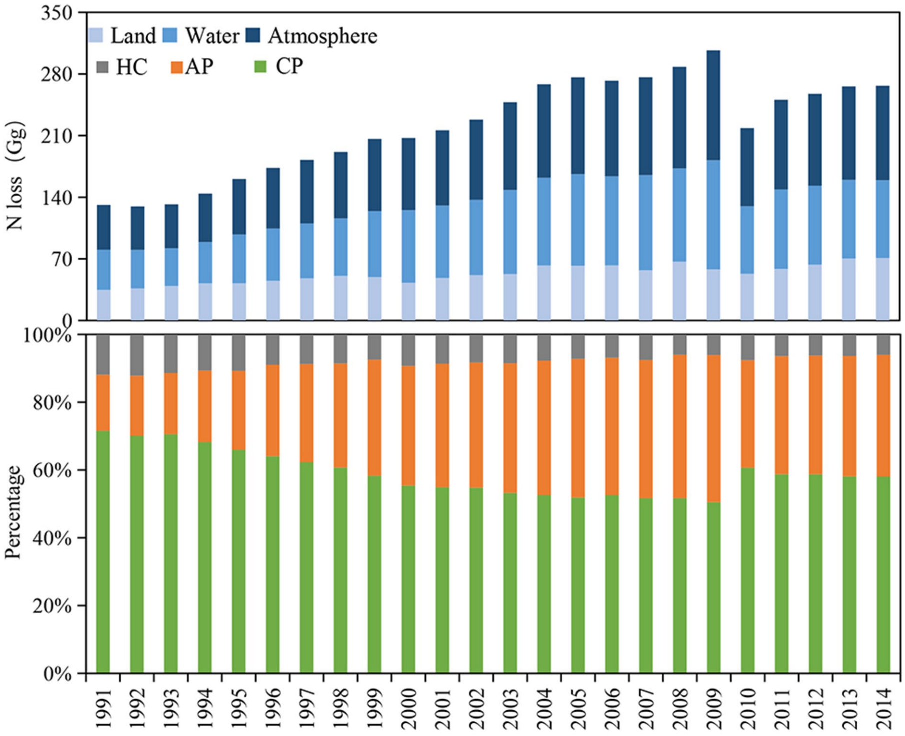

FIGURE 7
N loss to the environment from the food system. CP, crop production; AP, animal production; HC, household consumption and waste disposal.

of the total emissions, and the amount of N discharged into water accounted for 32.5 to 40.4%. From the subsystem viewpoint, the N loss of the CP subsystem was the largest—93.9 Gg N, 71.6% in 1991, and 154.8 Gg N, 58.1% in 2014. The AP subsystem, though, had the fastest growth rate, from 21.7 Gg N, 16.5% in 1991 to 95.8 Gg N, 35.9% in 2014. The ratio of N loss in the HC subsystem decreased from 11.9% in 1991 to 6.0% in 2014, partially due to the increase in sewage treatment rate. The overall structural change is a direct result of the development of the livestock and poultry breeding industry in Changchun, and most of the N loss comes from the production systems, indicating that Changchun is a typical production-oriented city. The N loss can not only result in a waste of resources but can also pollute the environment. Take the AP subsystem, with its increasing N flow, as an example. In 2010, only 33% of animal manure was recycled in China (Bai et al., 2016). In a research on developed countries, Oenema et al. discussed manure management systems in the 27 member states of the European Union, and concluded that the recycling of N still has great potential (Oenema et al., 2007). But there are several obstacles to recycling animal manure, including economic aspects, labor costs, and public acceptance (Yu et al., 2017).

4. Limitations

There are still some limitations worth improving on in this study. First, due to the lack of statistical data, the food processing subsystem was not considered. Real data might be obtained through field surveys of enterprise factories. Second, this study involves a large number of activity-level data and parameters. Some of the acquired data contains uncertainties, and thus has an impact on the accuracy of the research. Therefore, it would be possible to improve the accuracy of the data by performing high-tech measurements. Lastly, in terms of driving forces, we could analyze the separate impact of each N input driving force more accurately in a food-exporting city through quantitative methods.

5. Conclusion

This study presents the historical trend of N flow in the food system of a typical food-exporting city in China. Taking a commodity grain base city, Changchun, as a study case, the research has characterized the dynamics of N flow and N use efficiencies of the food system from 1991 to 2014. The results indicate that the N flow of the food system in a food-exporting city is significantly different from that of other types of cities. Both N input and output of food production were generally on the rise during this time. And the overall trend of the N recycling rate demonstrates an upward trajectory. Both NUE_{app} and NUE_{vir} in Changchun showed a decreasing trend, mainly due to dietary transition. Compared to food-importing cities like Xiamen, it is evident that NUE_{app} is prone to be underestimated for food-source cities while overestimated for food-importing cities. Therefore, NUE_{vir} is better to reflect the resource utilization efficiency and environmental effects from a consumption perspective. Besides, NUE_{act} was higher than that of food-importing cities, partially due to differences in plantation structure and fertilization management. The driving force for increased N input in Changchun was mainly from the production systems, which is a major feature of food-exporting cities. Besides, there were some years of exceptional changes; the droughts in 2000 and in 2009 both caused significant reductions in products, and the flu incident in 2009 seriously affected animal products in the following year. These incidents show that N flow can be influenced by both natural and man-made factors. In addition, we compared the differences in *per capita* N consumption between urban and rural areas, and the results show that urban residents required more A-food and less C-food than rural residents. In terms of N loss, we explored its sources and whereabouts, and noticed that the N loss from the CP system made up the majority, and most of the N was lost to the atmosphere and to surface water.

As one of China's major grain-producing areas, Changchun, while developing its grain-growing industry, had sufficient capacity to further develop its animal husbandry as well. There is clearly sufficient development space for coupling crop production and animal husbandry, so as to enhance NUE. Besides, the *in-situ* collection and processing of feeds can better ensure feed quality, save on transportation costs, and reduce process losses, all of which are friendly to the environment.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WH and SC contributed to the conception and design of the study. QZ, YL, and BG organized the database. QZ, YL, and YH performed the data analysis. QZ wrote the first draft of the manuscript. WH and YL wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1213692/full#supplementary-material

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