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Reducing food-system nitrogen input and emission through circular agriculture in montane and coastal regions

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ABSTRACT

Reducing biogeochemical flows (e.g., reactive nitrogen [Nr]) is essential for a sustainable food system. Previous studies lack tailored strategies for Nr reduction in smaller-scale agricultural production. We developed a framework coupling material flow analysis and system dynamics modeling to establish a pathway for Nr reduction. We applied this framework to Fujian, southeast China, a mountainous and coastal province with fragmented small-scale agricultural and large-scale aquaculture production. Crops, livestock, and aquaculture accounted for 44.03%, 31.11%, and 23.69%, respectively, of Nr input in 2019. Thus, crop and livestock production accounted for approximately 70% of total Nr emissions. Only 8.66% of the total Nr inputs were recycled from livestock to cropland, and the Nr use efficiency of all three food categories was less than 20%. A balanced diet among residents increased (by 15.5%) Nr emissions, whereas minimized food loss and waste partially neutralized (reduced by 17.9%) the increase in Nr emission from dietary changes. By contrast, recycling kitchen waste, manure, and straw would eliminate 39.5% of the regional-food-system Nr emissions. We conclude that a circular agricultural system with Nr recycling is effective to reduce Nr input and emissions through more unified crop and livestock production in montane and coastal regions of Fujian.

1. Introduction

Nitrogen (N) is the primary component of proteins and is essential for the existence of humans and all other living organisms (Galloway et al., 2004). N exists in terrestrial and marine ecosystems in various forms, is affected profoundly by human activities, and is a vital resource for agri-food production (Galloway, Schlesinger, Levy, Michaels, & Schnoor, 1995). However, excessive emissions of reactive nitrogen (Nr) result in enhanced greenhouse effects (Kim & Dale, 2008; Nigussie, Bruun, Kuyper, & de Neergaard, 2017), and lead to water-quality degradation (Deegan et al., 2012; Liu et al., 2013), eutrophication (Canfield, Glazer, & Falkowski, 2010; Deegan et al., 2012), nutrient run-off in marine dead zones (Breitburg et al., 2018; Oschlies, Brandt, Stramma, & Schmidtko, 2018) and loss of soil nutrients (Wang et al., 2021; Wu et al., 2019). These adverse effects further threaten human health and ecological safety.

Food production and consumption are of primary importance for economic stability and sustainable development (Lin & Grimm, 2015). Nitrogenous fertilizers are widely used to meet 48% of the total global food demand (Ibrahim et al., 2019). However, crops are capable of utilizing only 30%–40% of applied nitrogenous fertilizers (Hakeem, Ahmad, Iqbal, Gucel, & Ozturk, 2011). The fertilizer-to-consumer efficiency is only 14% in Flanders (the densest livestock region in Europe) (Coppens, Meers, Boon, Buysse, & Vlaeminck, 2016), 17% globally (Uwizeye et al., 2020),19% in China (Luo, Hu, Chen, & Zhu, 2018), and 42% in Canada (Ontario) (Boh & Clark, 2020), which can be expected that regions with lower livestock density have higher conversion efficiencies, and with the most important losses embedded in the environment. China is the largest nitrogenous fertilizer producer and consumer globally, thus Nr emissions from food production and consumption are a primary source of environmental pollution in the country (Gu et al., 2013; Zhang et al., 2013). Population growth and dietary shifts have further increased food demand as well as Nr inputs and emissions. Furthermore, food production has become increasingly reliant on

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nitrogenous fertilizers and feed, which are associated with environmental and health concerns (Ibrahim et al., 2020).

Previous studies have extensively analyzed the Nr inputs and emissions from human activities and modeled various reduction strategies. Material flow analysis (MFA) is widely used to quantitatively explore urban N flows from source to sink and, in combination with system dynamics (SD), to identify critical emission processes for Nr pollution management (Lin et al., 2016). Previous studies have used MFA as a valuable tool to calculate N flows under different scenarios, including in agricultural soils (Amann et al., 2021; Lederer, Karungi, & Ogwang, 2015), aquaculture rivers (Do, Trinh, & Nishida, 2014; Van Tung et al., 2021), livestock feed (Sporchia, Kebreab, & Caro, 2021), waste management (Guo et al., 2019; Tanzer & Rechberger, 2020), human diet (Thaler et al., 2015), agricultural and household systems in a rural area (Do-Thu et al., 2011), and food production and urban consumption systems in a coastal city (Li et al., 2020). However, despite the direct use of MFA, especially at the urban-rural area scale, few studies have described Nr recycling from food (straw) residue into food production, where urban food Nr emissions accumulate in an area and affect the N balance.

Reduction of food loss and waste (FLW) and improvement of Nr use efficiency would benefit from addressing the environmental predicament (Hu, Su, et al., 2020). For example, halving FLW along the entire food supply chain would reduce environmental impacts by more than 50% (Xue et al., 2021). In addition, if sophisticated technologies, such as energy recovery or anaerobic digestion, are implemented in FLW treatment, an annual reduction of up to 1.56 Mt CO_2eq could be attained in Peru(Vazquez-Rowe, Ziegler-Rodriguez, Margallo, Kahhat, & Aldaco, 2021) or a lightening of 20-80% of Global Warming Potential (GWP) in Spain (Hoehn et al., 2020). Moreover, the adoption of enhanced management practices in fields results in a 14.7%–25% reduction of national Nr use in the Chinese maize system (Cui et al., 2018; Ying et al., 2020). Similarly, advanced fertilizer optimization may reduce Nr emissions by 23% in the food production system in China (Hu, Cui, et al., 2020; Hu, Su, et al., 2020). Simultaneously, the efficiency of the agri-food system has been improved by 3.4%–21% under the recycling of biotic resources (Kuisma & Kahiluoto, 2017). Although these alterations prove that single or independent strategies affect Nr influxes and emissions in multiple ways, dynamic interactions of food production and consumption normally dominate Nr utilization efficiency in the regional food system. Current knowledge of using MFA and SD in combination to explore the dynamic interactions among food waste and recycling in the changes of Nr influxes and fates remains limited.

To address these limitations, in the present study we developed a novel framework coupling the N flow model and SD modeling to analyze Nr input, emission, and mitigation strategies over the full life-cycle of the food system of Fujian Province in China. We chose this region because we aimed to explore effective Nr reduction strategies in the montane and coastal regions that are unsuitable for large-scale and mechanized crop production. This study was designed to achieve the following objectives: (i) to use an N mass-balance approach to estimate dynamic changes of N input and output in the regional food system; (ii) to use MFA and SD in combination to simulate the dynamic flow paths of food-sourced N, including crop planting, livestock breeding, aquaculture, and urban and rural residents' food consumption; and (iii) to predict environmental Nr emission of the regional food system under three mitigation strategies (a balanced diet for residents, minimized FLW, and a recycling food system). The present model covers and integrates all N fluxes in the entire life span of food, track the sources of food production and consumption, quantifies the contributions of the different Nr emission sources, and examines the benefits of three mitigation measures in the food system. The results will be insightful for sustainable agricultural management, and air- and water-quality improvement in montane and coastal regions of Fujian Province, China. The framework developed in this study could be easily applied in other regions.

2. Materials and methods

2.1. Analysis framework

We developed a novel framework coupling MFA and a causal loop diagram that enables analysis of the conceptual causal chain of food-sourced N metabolism and its inputs and outputs, as well as their reciprocity in Supplementary material (SM). The analysis focused on two aspects, namely N emissions inventory and strategies for environmental management. We first tracked environmental emissions from N metabolism in the regional food system in the period 2000–2019, and then focused on the analysis of mitigation strategies. Regional-food-system N metabolism consisted of crop planting, aquaculture, livestock breeding, urban consumption, and rural consumption, which are dominated by human activities. The mitigation strategy analysis simulated future environmental Nr emissions under the variation of a balanced diet for residents, minimized FLW, and recycling food system scenarios.

2.2. Methods

Regional-food-system Nr input simulation

ere, we focused on Nr inputs through the food system, including new Nr input and recycled Nr input. The Nr input was the only source in this metabolism system and was calculated as follows:

$$NCP_{Input} = NCP_{NI} + NCP_{RE} \tag{1}$$

$$NCP_{NI} = NPIC_{AS} + NPIC_{FA} + NPIC_{BF} + NPIC_{IW} + NPIAP_{FB} + NPIL_{LF} + NCP_{IM} \tag{2}$$

$$NCP_{RE} = NPOC_{CC} + NPOC_{CL} + NPOC_{LC} + NCOU_{UC} + NCOR_{RC} + NCOR_{RL} + NCOR_{RL} \tag{3}$$

where NCP_{input} represents the total Nr inputs of the regional food system in a given year; NCP_{NI} and NCP_{RE} represent the new and recycled Nr inputs, respectively; $NPIC_{AS}$, $NPIC_{FA}$, $NPIC_{BF}$, and $NPIC_{IW}$ represent the new Nr from atmospheric sedimentation, fertilizer application, biological fixation, and irrigation water to the crop planting ecosystem, respectively; $NPIAP_{FB}$ is the new Nr within the fish bait of the aquaculture ecosystem; $NPIL_{LF}$ represents the Nr of feed in the livestock breeding ecosystem; NCP_{IM} is import Nr from other areas outside Fujian, including crops, livestock, and aquatic products; NPO_{CC}, $NPOL_{LC}$, $NCOU_{UC}$, and $NCOR_{RC}$ are recycled Nr used for crop planting within straw turnover, livestock excreta, urban kitchen waste composting, and rural human excreta, respectively; and $NPOC_{CL}$ and $NCOU_{RI}$ are recycled Nr from crop straw and kitchen waste used to feed livestock, respectively.

Regional-food-system N output simulation. The N sinks in the regional food system can be classified into two pools. One pool is stored in this system (the human body, food products, and recycled Nr) and the other pool flows out of the system (export to other areas, and loss or release into the air, water, and soil as environmental emissions). Thus, the outputs of the regional food system were expressed as follows:

$$NCP_{Output} = NCOU_{Human} + NCOR_{Human} + NPOL_{LB} + NCP_{EX} + NCP_{LL} + NCP_{Air} + NCP_{Water} + NCP_{Soil} \tag{4}$$

where NCP_{output} represents the total N output from the regional food system in a given year; $NCOU_{Human}$ and $NCOR_{Human}$ represent the product Nr stored in the urban and rural human body through digestion–absorption functions, respectively; $NPOL_{LB}$ is the Nr stored in livestock byproducts, with consideration of byproducts extensively used among different subsystems, such as edible products for residents' consumption and livestock breeding; NCP_{EX} is export Nr of food products from Fujian to other areas, consisting of the crop, livestock, and aquatic products; NCP_{LL} is total Nr loss from production to consumption in the handling, storage, processing, and distribution stages; NCP_{Air}, NCP_{Water}, and NCP_{Soil} represent the total air, water, and soil N emissions, respectively, and can be simulated and calculated as summarized (SM, Table S2). Among them, air N emission comprised 11 categories, which can be grouped into three types, namely nitrogen gas (N_2), nitrogen oxides (NO_x, including nitrous oxide), and ammonia (NH_3), the former belongs to unreactive N, and the latter two belong to Nr emission.

Regional-food-system N flow simulation. We concentrated on advertent N metabolism to explore the environmental emissions inventory of the regional food system, but excluding inter-regional trade. The overall regional-food-system N metabolism is shown in SM (Fig. S1). The N flow starts from new Nr input into the production subsystem from outside and ends with Nr loss or emissions into the environment, or export of food products to beyond the province boundary. In addition, we calculated the Nr utilization efficiency of three types of food (NUE_C, NUE_L, and NUE_A) in SM, (A.18-20), that is, the ratio of Nr content of food products to its Nr inputs (Ma et al., 2010), to characterize the utilization ratio of the regional food system. Therefore, the chain is dynamic based on differential equations describing changes in N stocks and flows (Li et al., 2020). The calculation methods and parameters of each path are shown in SM (Methods and Tables S2–S8). Here, we adopt distinct emission factors for different Nr input and processes, for the sake of more closely conforming to the actual N material flow analysis, as well as better reflecting the effects under mitigation strategies.

Regional-food-system Nr mitigation strategies. System dynamics is an independent discipline based on system thinking and integrated into computer simulation (Forrester, 1958). The method not only allows analysis of the information feedback system, but also helps to solve the system problems, and has been widely used in regional development. This method facilitates the dynamic modeling of interactions between mitigation measures and Nr emissions. With regard to mitigation strategies, this study adopted three mitigation strategies, namely a balanced diet for residents, minimized FLW, and recycling food systems. For all three scenarios, population data, the output of crop, livestock, and aquatic products, and other data were sourced from the Fujian Bureau of Statistics in 2020.

Scenario I: Balanced diet for residents. Here, we simulated the changes in food-sourced Nr metabolism and environmental emissions caused by changes in diet and associated food production and Nr inputs. The urban and rural residents' food consumption structure was consistent with the national guidelines, but FLW remained unchanged. The national guidelines refer to Chinese residents' dietary guidance recommendations based on their nutrition and health status in the " Chinese Residents Dietary Guidelines (2021)" (Society, 2021) (Guidelines). Food intake per capita in the Guidelines, and urban and rural residents' food consumption status in 2019 (Statistics, 2021) are summarized in Table 1. If the residents' dietary status is not modified within the Guidelines, the excessive and deficient parts should change according to the closest standard, that is, the maximum or minimum value, of the dynamic causal chains as shown in SM (Fig.S2).

Scenario II: Minimized FLW. In the context of minimized FLW, the policy "Implementation Opinions on Strict Economy and Opposing Food Waste" (Implementation), issued by the Fujian Provincial Government was modeled. The Implementation proposes to "promote 'Clean Plate Campaign' action and eliminate food waste". In the present study, we not only assumed that food loss from food production to consumption will be halved in accordance with the Sustainable Development Goals (SDGs) in 2030, but also simulated the scenario that table waste of the edible portion is less than 10% of the "Chinese Food Composition Table 2018 (Standard Edition)" (Institute of nutrition and food safety, 2018) (Table 2), to reduce food demand (SM, Fig. S3).

Scenario III: Recycling food system. On the basis of the prospects for livestock breeding and aquaculture production in the Fujian Economic and Social Development Fourteenth Five-Year Plan and Outline of Long-Term Goals for 2035 with measures adjusted to local conditions, we assumed that the recycling rate of straw application, livestock excreta, and aquaculture residue (reused in the following several years) is 80% and that chemical fertilizer application will be reduced. Kitchen waste was based on the practice in Xiamen City and 90% of which can be "turned into treasure". In addition, the percentage of garbage disposal as standard and sewage disposal in the cities of Fujian is 100%, based on 100% and 92.8% respectively in 2019 (Statistics, 2021). It was worth noting that standard waste disposal mainly included sanitary landfill and incineration of Fujian in 2019, accounting for 64.8% and 31.3% respectively (China, 2020), and the rest were others, mainly composting (Wei et al., 2018), accounting for 3.9%. Meanwhile, standard sewage disposal refers to the percentage of sewage collection disposal in the factory of the city (Statistics, 2021). With regard to the problem of human excreta treatment, if an "eco-friendly toilet" is installed, the solid portion of the feces is degraded by 95% of the in-situ treatment volume, and 85.5% of total Nr becomes biomass yield (Li, Wang, Gao, Zhao, & Zhou, 2018). If the urine is processed, it can be recycled for use in flush toilets or for irrigation. The dynamic causal chains are shown in Figure 1.

2.3. Study area and data collection

Fujian is a coastal province in southeast China, and faces Taiwan Province across the Taiwan Straits. Its land and sea areas are 124,000 km^2 and 136,000 km^2, respectively, and the coastline length is 3751.5 km, ranking second among provinces in China. Fujian is famous for its geographical features of almost 80% of the land is mountainous and hilly, which limits the areas of paddy fields and dry land, and is unsuitable for large-scale crop and livestock production (SM, Fig. S4). Cities have expanded rapidly and the economy has developed substantially in recent decades since China adopted a "reform and opening-up" policy in 1980 (Lin et al., 2016). The urbanization ratio increased rapidly from 42.0% in 2000 to 66.5% in 2019. The urban population comprised 26.42 million individuals and the rural population declined to 13.31 million individuals in 2019 (SM, Fig. S5a). Per capita disposable income of urban and rural households both increased five-fold from 2000 to 2019. Simultaneously, the ratio of per capita food expenditure

Table 1
Chinese residents' dietary guidelines and consumption status in Fujian for different food types (g/person/day)

Items	Guidelines	Urban residents	Rural residents
Grain	250-400	257.7	444.1
Cooking oil	25~30	22.5	27.0
Vegetable	300-500	220.3	247.3
Livestock meat	40-75	76.6	75.5
Fish	40-75	73.3	63.1
Eggs	40-50	24.6	25.3
Fruit	200-350	132.9	106.2
Liquid milk	300	33.6	22.3

Table 2
Proportions of edible food items

Items	Edible part/ (%)	Protein/ (g)	Items	Edible part/ (%)	Protein/ (g)
Grain	98.8	13.14	Sea Shrimp	51	16.8
Cooking oil	100	0	River Prawn	86	16.4
Vegetable	90.2	5.5	Sea Crab	55	13.8
Bovine Meat	100	18.6	River Crab	42	17.5
Mutton Meat	90	19.0	Fish	69.7	20.1
Pig Meat	100	13.2	Eggs	87	12.4
Chicken	66	19.3	Fruit	79.7	0.7
Duck	68	15.5	Milk	100	3.0

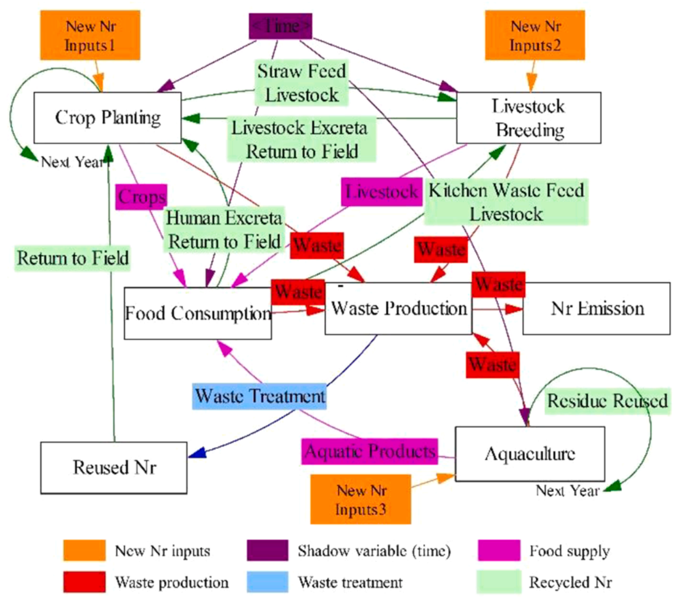

Fig. 1. Causal loop diagram of reactive nitrogen (Nr) flow with recycling food system.

to the disposable income of urban and rural households fell by 38.3% and 18.6%, respectively (SM, Fig. S5b). With the urban population growth, the urban area expanded rapidly from 449.1 km^2 in 2000 to 1, 620.7 km^2 in 2019, whereas the arable land area declined from 2.79 million ha to 1.64 million ha. The aquaculture area varied between 191.6 and 250.1 $\times$ 10^3 ha in the period 2000–2019 (SM, Fig. S5c). As an important component of Nr metabolism, per capita food consumption was 335.7–456.4 kg/year from 2000 to 2019. However, the total food consumption in urban areas increased with the corresponding population growth from 4.92 million tonnes in 2000 to 9.13 million tonnes in 2019, whereas that of rural areas decreased consistently with the rural population decline from 9.02 million tonnes to 5.11 million tonnes (SM, Fig. S5d).

The main farmed crops, livestock, and aquatic products of Fujian from 2000 to 2019 were rice, pork, and fish of seawater, respectively, as shown in Fig S6 in SM. The highest proportion of sown areas and output of grain crops was rice, which was 66.8-79.5% and 74.8-83.6% respectively, and it was decreasing year by year (SM, Fig. S6a and Fig. S6b); at the same time, non-grain crops were vegetables, and the proportion was maintained, at 81.2-88.2% and 97.7-98.5%. In terms of main farmed livestock (SM, Fig. S6c), the proportion of pork in meat showed a trend of increasing first and then decreasing, with a peak of 84.0% in 2010, and a minimum of 41.3% in 2019, which was lower than 56.9% of meat of poultry, and poultry eggs accounted for the highest proportion of milk-eggs, at 65.5-80.4%. Among the main aquatic products (SM, Fig. S6d), the output of seawater was much higher than that of freshwater, the former was about 3-4 times that of the latter, and natural fish accounts for the highest proportion of the output of seawater, 61.0-77.8%; but fish of freshwater culturing accounted for the highest proportion of freshwater products, at 81.8-84.7%.

This study was based on a production-based approach that employs top-down statistics. The data on population, resident consumption, and agriculture were mainly from the "Fujian Statistical Yearbook (2001-2020)" and "China Statistical Yearbook (2001-2020)", see Table S1 in SM. In addition, the data on land use type in Fujian are from the remote sensing monitoring of land use in 2015 in China.

3. Results

3.1. Nr inputs of the regional food system

The Nr inputs of Fujian were 1,316.53–1,572.53 kt N/year from 2000 to 2019. Mean new Nr inputs and recycled Nr inputs were 1,297.45 and 123.09 kt N/year, respectively, accounting for 91.34% and 8.66% of total Nr inputs, respectively. The maximum and minimum new Nr inputs were fertilizer application (mean 558.73 kt N/year) and import livestock (mean 7.88 kt N/year), respectively, the former being 70 times the latter. From 2000 to 2019, fertilizer application and biological fixation decreased by at most 22.53% and 41.97%, respectively. In contrast, livestock feed and fish bait increased dramatically by 120.90% and 72.31%, respectively, with slight increases of 14.53% and 6.95% in irrigation water and atmospheric sedimentation, respectively. The most distinct change in Nr inputs was for imported livestock, from exporting 1.19 kt N/year in 2000 to importing 20.87 kt N/year in 2019 (Figure 2a).

The majority of the recycled Nr input was derived from livestock excreta, which accounted for 50.34% of the total, and showed the highest growth of 82.80% from 2000 to 2019. This might be associated with the implementation of the policy of " fertilizing the farmland with livestock breeding" in Fujian Province in recent years. Over the same period, straw turnover and rural waste accounted for the second-and third-highest proportions, which were 20.82 kt N/year and 17.66 kt N/year, but both decreased by 48.57% and 43.56%, respectively. The remaining three types of recycled Nr, namely straw feed, rural excreta, and urban compost, had also decreased by 49.63%, 43.26%, and 28.28%, respectively (Figure 2b).

3.2. N outputs of the regional food system

Mean N outputs of the regional food system in Fujian were 1,297.45 kt N/year from 2000 to 2019, accounting for 91.34% of the total Nr inputs. Air emissions accounted for the highest proportion of 61.95%, followed by soil and water emissions, which accounted for 10.78% and 9.66%, respectively (Figure 3a). The Nr ultimately digested and absorbed by urban and rural human bodies was only 0.87 kt N/year and 0.77 kt N/year, respectively, and the total proportion did not exceed 1%. From 2000 to 2019, The Nr output of livestock byproducts more than doubled (an increase of 120.47%). The Nr outputs of export crops decreased by 60.19%, whereas aquatic products increased by 57.53%. Air N emissions increased by 24.73% from 2000 to 2015, followed by a slight decrease of 5.97% from 2016 to 2019. Soil and water Nr emissions increased by 31.59% and decreased by 4.88%, respectively.

The mean gaseous N emission was 803.70 kt N/year. Gaseous N emissions comprised 11 categories, which can be grouped into three types, namely nitrogen gas (N_2), nitrogen oxides (NO_x, including nitrous oxide), and ammonia (NH_3), accounting for 47.79%, 29.47%, and 22.74%, respectively (Figure 3b). Gaseous Nr emission was 419.6 kt N/year, including NO_x and NH_3, and excluding inert N_2. Approximately 84.96% of the gaseous Nr emission was derived from crop planting, 12.06% originated from aquaculture, 2% from livestock breeding, and less than 1% was derived from urban and rural residents' food consumption. The soil-deposited Nr from crop planting and direct-discharge Nr of livestock excreta together accounted for more than half of the total soil Nr emissions (26.84%, and 24.31%, respectively). The former decreased year by year, with an average annual decrease of 2.4%, whereas the latter increased by 3.3%. Urban kitchen waste direct discharge was the lowest (2.07%) contributor to soil Nr emission (Figure 3c). In contrast to gaseous and soil Nr emissions, for which the main source was food production, the rural human excreta direct discharge (13.18%–22.54%) exceeded the livestock breeding water loss (8.87%–11.88%), and thus was the third-highest water pollution source after crop planting (30.0%–37.21%) and aquaculture (16.32%–28.34%) (Figure 3d).

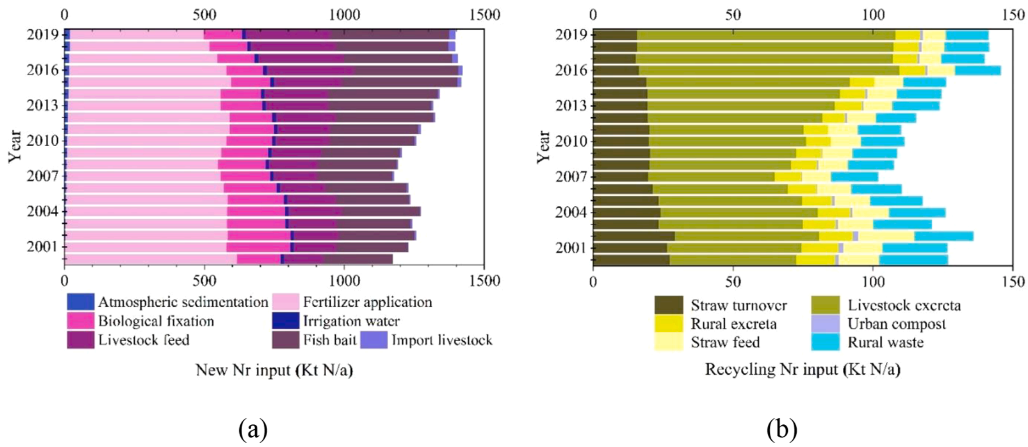

Fig. 2. Reactive nitrogen (Nr) inputs in the regional food system of Fujian from 2000 to 2019. (a) New Nr input; (b) Recycled Nr input.

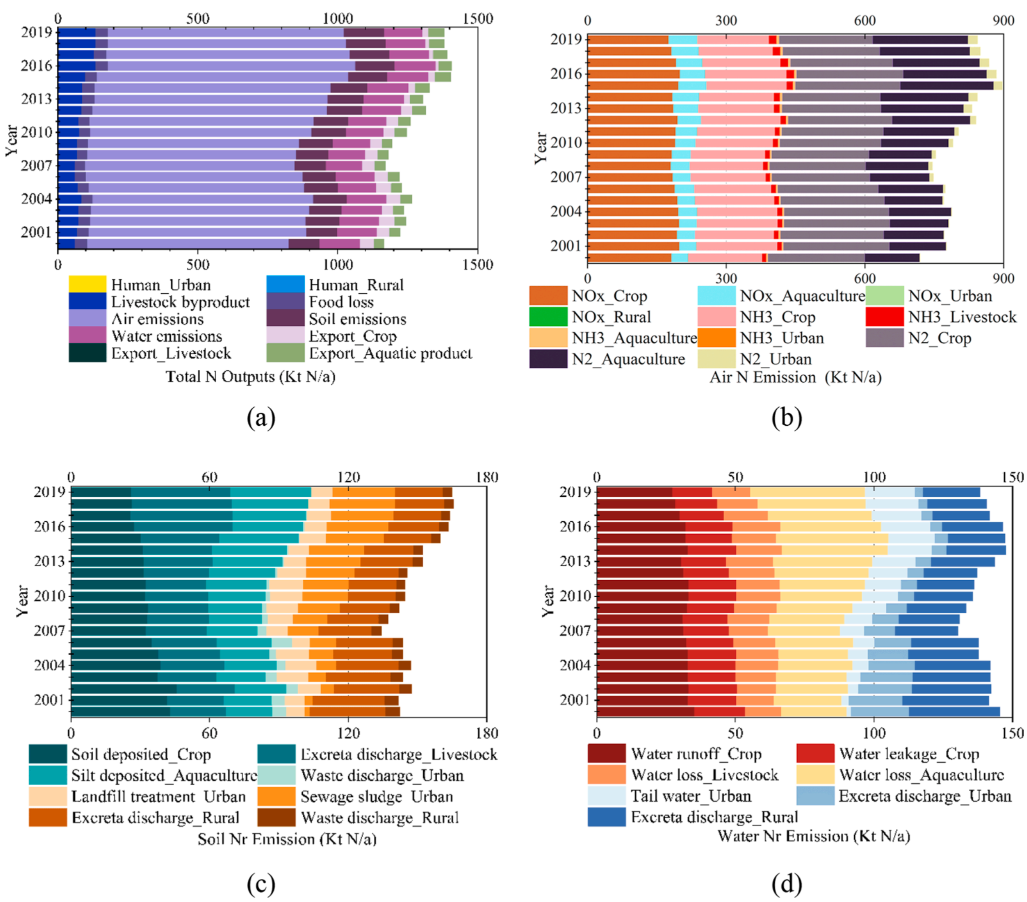

Fig. 3. Nitrogen (N) outputs of the regional food system of Fujian from 2000 to 2019. (a) Total N outputs; (b) Gaseous N emission; (c) Soil Nr emission; (d) Water Nr emission.

3.3. N flows of the regional food system

The mean Nr input of the Fujian food system was 1,420.54 kt N/year between 2000 and 2019. Fertilizer application was the largest Nr input (43.07%), followed by fish bait (24.71%), whereas the recycled Nr of urban compost was the least, accounting for 0.52% (Figure 4a). The majority of new Nr inputs were used for crop planting (mean 853.9 kt N/year) with the proportion gradually decreasing, accounting for 74.79% in 2000 (Figure 4b), 67.08% in 2010 (Figure 4c), and 54.89% in 2019 (Figure 4d). In contrast, the proportions of Nr input from livestock breeding and aquaculture increased, from 219.6 to 245.8 to 350 kt N, and from 246.1 to 302.2 to 424.0 kt N, in 2000, 2010, and 2019, respectively. Recycled Nr was applied for crop planting and livestock breeding. The former accounted for 7.38% of new Nr input in 2000, 6.72% in 2010, and 8.42% in 2019. In the same period, the latter decreased from 3.28% in 2000 to 2.07% in 2010, and 1.69% in 2019. Overall, on average 65.82% of Nr inputs were used for crop planting, followed by 24.71% for aquaculture, and 18.36% for livestock breeding (Figure 4a). These changes in N flows were consistent with changes in the agricultural production mix and indicated that greater mitigation

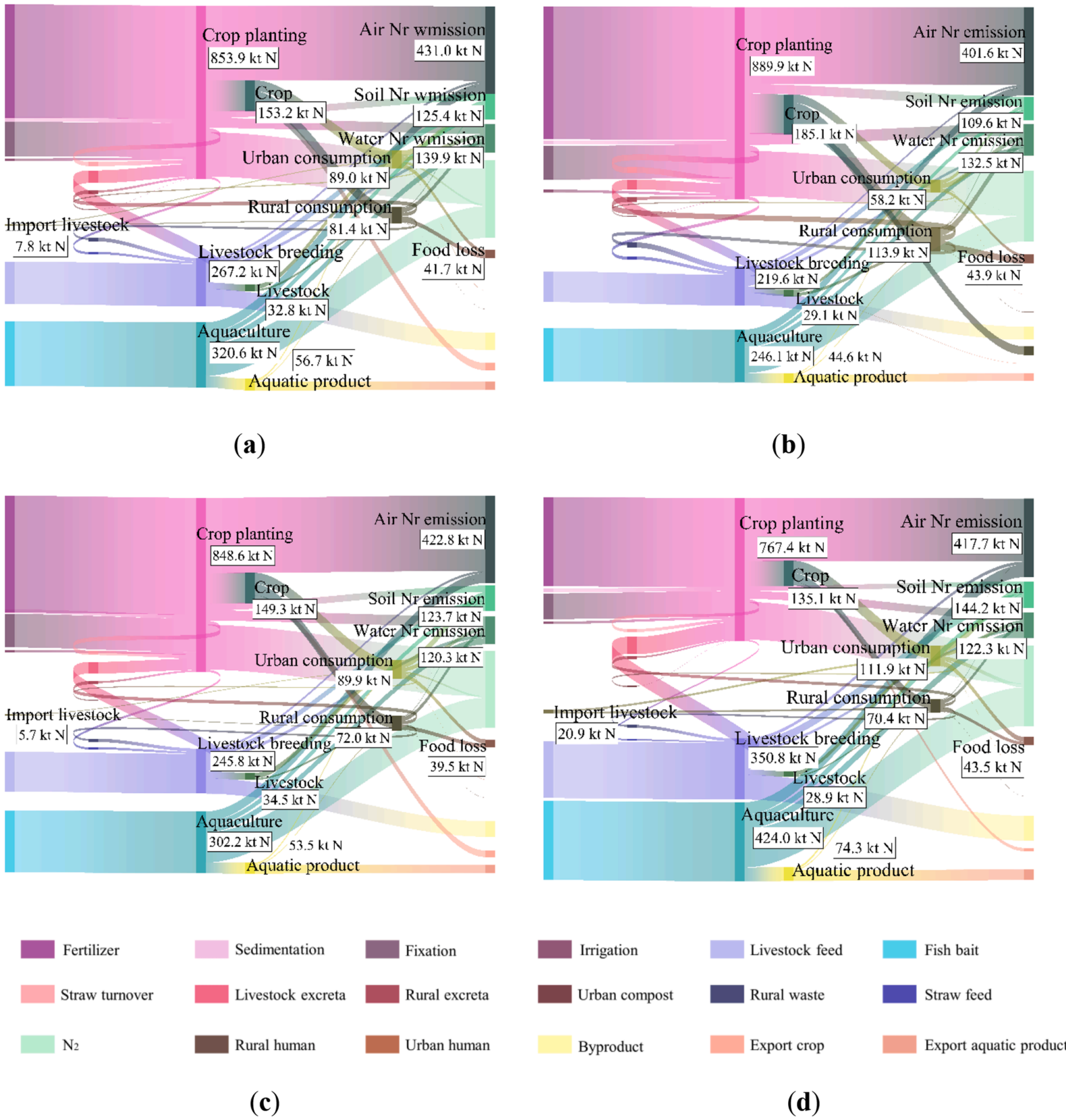

Fig. 4. Regional food system Nitrogen (N) flows of Fujian from 2000 to 2019. (a) Mean N flow from 2000 to 2019; (b) N flow in 2000; (c) N flow in 2010; (d) N flow in 2019.

efforts should be devoted to livestock and aquaculture products.

The intermediate Nr, such as that stored in crop, livestock, and aquatic products, had significantly different Nr inputs and outputs. Crop Nr declined from 185.1 kt N in 2000 to 149.3 kt N in 2010 and 135.1 kt N in 2019. Livestock Nr increased from 29.1 kt N in 2000 to 34.5 kt N in 2010, then decreased to 28.9 kt N in 2019. Aquatic product Nr increased from 44.6 kt N in 2000 to 53.5 kt N in 2010 and 74.3 kt N in 2019. The Nr use efficiency over this period was ranked as follows: NUE_C (17.94%) > NUE_A (17.69%) > NUE_L (12.28%) (Figure 4a). The food system Nr demand of urban residents increased gradually (58.2 kt N in 2000 to 89.9 kt N in 2010 and 111.9 kt N in 2019), with an average annual increase of 3.6%, whereas in rural areas it decreased by 2.2% (113.9 kt N in 2000 to 72.0 kt N in 2010 and 70.4 kt N in 2019). The average food loss was 41 kt N/year. The number of crops, livestock, and aquatic products consumed by urban and rural residents from 2000 to 2019 is shown in SM (Fig. S7). Rural crop consumption was the highest (average 45.67 kt N/year), whereas aquatic product consumption was the lowest (3.71 kt N/year), which was about half of that consumed by urban residents.

On average, 53.28% of N outputs were environmental pollution, that is Nr emission, including 431.0 kt N/year of air, 139.9 kt N/year of water, and 125.4 kt N/year of soil emissions. The majority of the Nr emission was derived from crop planting (64.65%), followed by aquaculture (15.52%), livestock breeding (8.29%), urban (7.48%), and rural (4.06%) residents' food consumption. An average of 85.34% of gaseous Nr emissions was derived from crop planting (Figure 4a). Of water Nr emissions, almost 60% was derived from crop planting (33.96%) and aquaculture (23.88%). Half of the soil Nr emissions were from livestock breeding (29.63%) and urban residents' food consumption (25.24%). The N outputs stored in urban human bodies increased by 65.49%, from 0.05% (2000) to 0.07% (2010) to 0.08% (2019), whereas storage in rural human bodies decreased overall by 46.14% from 0.09% (2000) to 0.05% (2010) to 0.04% (2019). In 2000, export products included crop, livestock, and aquatic products (Figure 4b), whereas in 2010 (Figure 4c) and 2019 (Figure 4d) only crop and aquatic products were exported. The average Nr input from livestock import was 7.8 kt N/year from 2000 to

2019.

3.4. Nr mitigation strategies of the regional food system

Of the total environmental Nr emissions (Figure 5a), crop planting, livestock breeding, and consumption by urban and rural residents increased by 12.8%, 52.8%, 25.6%, and 15.6%, respectively, under a balanced diet for residents scenario. This scenario mainly reflected the initial insufficient consumption of crops (such as vegetables and fruit) and livestock (such as eggs and liquid milk), resulting in a corresponding increase in consumption and production. However, the change in aquaculture was zero owing to the reasonable consumption of aquatic products. Under the minimized FLW scenario, Nr emissions derived from livestock breeding increased by 6.4%, indicating that the reduction of FLW cannot fully offset the effects of a balanced diet for residents scenario. The Nr emissions from aquaculture could be reduced by 12.6% as part of the FLW that might be used for consumption. Under the recycling food system scenario, all subsystems showed a significant reduction in Nr emissions, among which aquaculture showed the highest decrease (79.0%), whereas crop planting showed the lowest (20.8%). These results suggested that the recycling food system scenario may completely counteract the Nr emissions associated with a balanced diet for residents.

Based on the classification of environmental media, the source of gaseous Nr emission from crop planting increased under the balanced diet for residents scenario (13.63%), and decreased under the minimized FLW (13.62%) and recycling food system scenarios (14.71%). Gaseous Nr emissions from livestock breeding only decreased significantly under the recycling food system scenario (18.75%), and those from aquaculture decreased by 12.62% and 77.78% under the balanced diet for residents and recycling food system scenarios, respectively. The gaseous Nr emissions from food consumption of urban residents only increased under the balanced diet for residents scenario (25.55%), whereas that for rural residents decreased markedly under the recycling food system scenario (66.97%) (Figure 5b). The soil Nr emission from the five subsystems only decreased under the recycling food system scenario. Only soil Nr emissions from aquaculture remained unchanged, whereas the remainder increased under the balanced diet for residents scenario, with livestock breeding showing the highest (52.8%) and crop planting the lowest (8.6%) emissions. In contrast, only soil Nr emissions from livestock breeding increased slightly (6.4%), whereas the other subsystems decreased slightly, under the minimized FLW scenario, with crop planting showing the maximum reduction of 30.1% (Figure 5c). The greatest water Nr emissions were from food consumption of urban and rural residents under the minimized FLW scenario, both of which increased. This response was associated with a balanced diet for

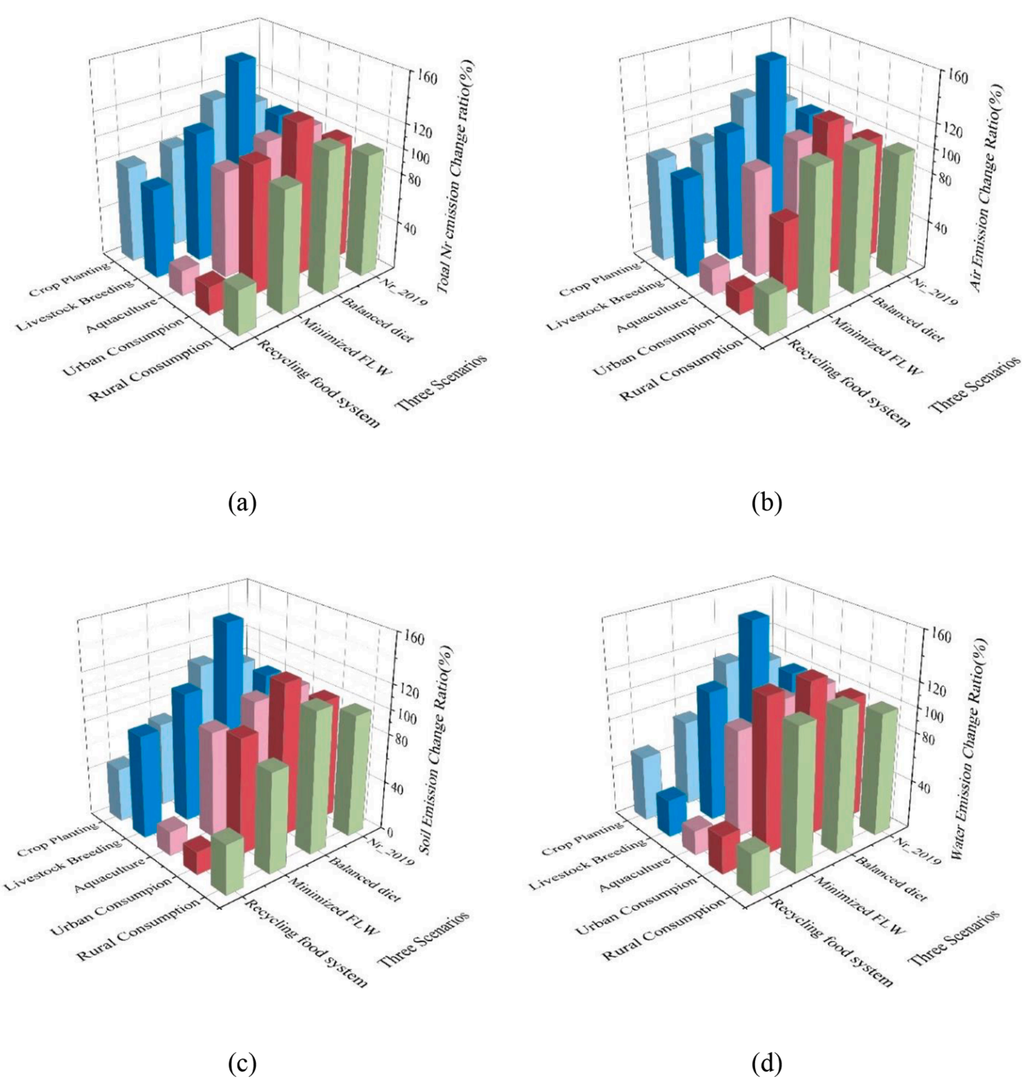

Fig. 5. Changes in reactive nitrogen (Nr) emissions under three mitigation strategies compared with the baseline emissions in 2019 (denoted as 100%). Values are shown as relative change (or change ratio) in comparison with emissions in 2019. (a) Total environmental Nr emission; (b) Air Nr emission; (c) Soil Nr emission; (d) Water Nr emission.

residents (an overall increase in Nr input), resulting in increased water Nr emission from human excreta. The rural residents' food consumption had a higher proportion of Nr emission reduction in water (67.0%) than that of soil (59.1%), whereas Nr emissions from crop planting and urban residents' food consumption were relatively lower under the recycling food system scenario (Figure 5d).

4. Discussion

4.1. Managing regional food system Nr metabolism in Fujian

The temporal trajectory of Nr utilization efficiency of the regional food system has significant implications for Nr metabolism management and environmental protection. From 2000 to 2019, the mean Nr use efficiency in Fujian of livestock, aquatic products, and crops was 12.28%, 17.69%, and 17.94%, respectively. These efficiencies are generally consistent with agricultural and livestock production in Shanghai and Changshu in China, and Uruguay, which amounted to 18.43%–27.6% (Liao, Xia, & Wu, 2021), 11.96%–31.59% (Wang, Cai, Lang, Yan, & Xu, 2021), and 23.1% (Castillo, Kirk, Rivero, Dobermann, & Haefele, 2021), respectively. However, there is a disparity with certain other countries, such as Italy, Egypt, and Canada, which show efficiencies of 40% (Erisman et al., 2018), 44% (Elrys et al., 2019), and 50.8% (Karimi et al., 2020), respectively. Furthermore, some scholars consider that an Nr utilization efficiency value of 70% or 90% its well-founded in arable systems, provided that many measures are adopted (Hutchings, Sorensen, Cordovil, Leip, & Amon, 2020). For example, the use of acid scrubbers in poultry barns can significantly increase Nr utilization efficiency by 13% in the egg supply chain (Ershadi, Heidari, Dutta, Dias, & Pelletier, 2021).

The Nr use efficiency in Fujian decreased in recent years, which increased Nr emissions. The present analysis of the conceptual causal chains showed that almost 53.28% of food system N outputs were environmental pollution. This is consistent with the food-sourced urban metabolism in a rapidly urbanized city (Xing et al., 2021), which is lower than the Nr loss in northern and southern European cities (94%) (Martinez, Alvarez, Martinez Marin, & del Mar Delgado, 2019). We also observed that gaseous Nr emissions in Fujian (75.45%) were higher than those from crop production in the Yangtze River Delta (72.55%) (Wang et al., 2021). More than half of the total N emissions in Fujian were as N_2 and NH_3, which was slightly lower than the proportion for the whole of China from 1961 to 2010 (N_2 and NH_3 each account for almost 40%) (Guo et al., 2017). The majority of gaseous Nr emissions were from crop planting (63.86%), which was almost identical to the proportion in the Yangtze River Delta (63.21%) (Wang et al., 2021). Soil Nr emission accounted for the second-highest proportion (10.78%) in Fujian, lower than more than one-third of Shanghai's surplus Nr (Liao et al., 2021). In addition, approximately 30% was from livestock excreta discharge in the present study, consistent with the previous finding that livestock supplies cause an equivalent of one-third of Nr emissions (Uwizeye et al., 2020). Water Nr emission, which is often replaced with graywater footprints in previous studies (Li et al., 2021; Wu, Cao, Guo, Xiao, & Ren, 2021), ranked third (9.66%) in Fujian from 2000 to 2019, with the Nr of crop planting runoff and leaching accounting for more than one-third (30.0%–37.21%). The ratio of cropland to China food production in the graywater footprint is almost 31.78% (Hu et al., 2018).

The present results showed that a fully coupled system that recycles both solid and liquid livestock excreta would be of great significance for sustainable livestock breeding in the future (Li et al., 2020). Emerging and current technologies have the potential to realize the projections in the present study, such as using a machine vision-based robot decreased the nitrogenous fertilizer consumption about 18% (Vakilian & Massah, 2017) or injected application, with ammonium nitrate or organic fertilizers, reduced NH_3 loss more than by 75% (Mencaroni et al., 2021), anaerobic digestion and fermentation of food wastes could ensure 55% contribution of its sector to China's national emission reduction goal in 2025 (Zhang et al., 2020), hydroponic technology for integrating domestic wastewater and crop planting had the advantage of reducing costs (Magwaza, Magwaza, Odindo, & Mditshwa, 2020; Sun, Gao, He, Huang, & Zhou, 2019), the effects of apple pomace (AP) addition during aerobic composting of agricultural wastes and livestock excreta was with a 19% increase of total N in the compost (Mao et al., 2017), the maximum ammonia removal was 79.1% with gamma irradiation of waste sewage sludge (Lim & Kim, 2018), as well as reuse of pangasius pond sediments had significantly higher levels of N than rice plot soil, as a highly effective fertilizer (Hague, Belton, Alam, Ahmed, & Alam, 2016). Moreover, the integration of livestock breeding, aquaculture, and crop planting in the same area may achieve a zero-emission system (Van Tung et al., 2021).

4.2. Towards a sustainable regional-food-system Nr metabolism

Recycling food systems is the decisive driver for sustainable Nr metabolism in a montane regional food system. It is estimated that only 9% of Nr became resources through recycling during the food supply–consumption–waste treatment–recycling chain in the Pearl River Delta region (Chen, Wen, & Wang, 2020). In the present study, 8.66% of food-sourced Nr was recycled as food production Nr inputs in Fujian, which was much higher than that reported in the urban system of Toronto, Canada (4.7%) (Forkes, 2007). The Nr in rural human and livestock excreta, most of which are not currently returned to the field (15.81% and 26.03%, respectively), was consistent with the global Nr in human excreta (less than 15%) (Bouwman, Beusen, & Billen, 2009; Trimmer & Guest, 2018). Therefore, it is imperative to promote Nr recycling, as well as advocate for a sustainable Nr cycle. In the present study we established a scenario to explore the sustainable Nr cycle system. Compared with the baseline emissions in 2019, analysis under the recycling food system scenario proved that livestock breeding "by field", aquaculture "by water", and consumer waste treatment would decrease the system's total Nr emissions to the environment by 39.5%, which was more than the 10.2% reduction of environmental Nr emissions under a higher excreta and straw recycling ratio scenario (Luo et al., 2018). Moreover, recycling Nr not only replaces the use of New Nr, such as mineral fertilizers to replace manure but also has a smaller emission factor (Gu, Ju, Chang, Ge, & Vitousek, 2015).

The dietary habits of urban and rural residents are an additional crucial factor affecting the inputs and outputs of regional-food-system Nr metabolism (Huang et al., 2021; Zhang, Xu, & Lahr, 2022). These dietary habits have two aspects. The first is the maintenance of a healthy diet and the second is a reduction of FLW (Lin et al., 2016). However, the residents' diet, as based on the the "Chinese Residents Dietary Guidelines (2021)", did not significantly contribute to the reduction in Nr emissions under the balanced diet for residents scenario (emissions increased by 15.5%). Similar results have been reported for greenhouse gas emissions in Chinese cities (Xiong et al., 2022). Reduction in FLW partially neutralized the impact of a balanced diet for residents on the environment under the minimized FLW scenario, and would ultimately preclude about 17.9% of Nr emissions, which is similar to the 20% reduction expected in China by 2030 (Hu, Su, et al., 2020), a much higher than a 5% decline when only reducing FLW of raw agricultural products is considered in Chinese urban agglomerations (Hu, Cui, et al., 2020). In addition, fruits and vegetables are the categories with the largest potential for FLW mitigation (Garcia-Herrero et al., 2019). Hence, a reduction in FLW in combination with a balanced diet is a more effective action to reduce Nr emissions than a balanced diet alone for residents in Fujian in the next few years, and a minor change in food conservation behavior can have a significant influence. For example, a 50% reduction in FLW at the consumption stage would directly lessen the Nr footprint by 0.8%–2.4% (Xue et al., 2021). This percentage is similar to the 3.07% reduction in Nr emissions from urban and rural residents' food consumption under the minimized FLW scenario observed in the present analysis. In terms of the reduction of FLW to values near 50%, we suggest that prevention and management strategies distinguish three stages: pre-meal, mid-meal, and post-meal. Before meals, moderation purchase (accept strange-looking food), green transportation (box instead of the bag), good storage (sealed and refrigerated), and reasonable donation (edible food). During meals, cook (use leftovers for safe periods), eat on demand, as well as reduce fruit and vegetable discards. After meals, food sorting, recycling, and composting, for instance, energy recovery or anaerobic digestion are implemented in FLW treatment.

Conclusions

As anthropogenic Nr emission becomes a primary global environmental problem, regional-food-system Nr metabolism is increasingly important. The present research helps to understand the food-sourced Nr emissions inventory by calculation of the province-level inputs and outputs in Fujian from 2000 to 2019. There was an initially increasing and then decreasing trend in new and recycled Nr inputs from 2000 to 2019, with the peak in 2016. Recycled Nr accounted for less than 10% of the total inputs, which is lower than that reported in the Pearl River Delta region. This finding indicated that recycled Nr inputs in the coastal and montane regions of Fujian were relatively low and that threats to the environment remain significant. Compared with aquaculture and livestock breeding, crop planting accounted for the majority of Nr inputs and the component was relatively diverse. In general, the majority of N outputs were environmental emissions and the main form was as gaseous Nr (NO_x and NH_3). Less than 1% were stored in urban and rural human bodies. The Nr utilization efficiency of all three types of food production (crops, livestock, and aquatic products) was less than 20%, which is generally consistent with that observed in most areas in China. Accordingly, N outputs from crop planting and aquaculture have become the major components of environmental Nr emission; therefore, implementation of Nr management measures for crop production and aquaculture is a matter of urgency. Based on the emission sources and contribution of Nr flow in the regional food system, we evaluated three mitigation strategies: a balanced diet for residents, minimized FLW, and a recycling food system.

We observed that a recycling food system scenario would significantly decrease (by 39.5%) environmental Nr emissions, followed by minimized FLW (reduction by 17.9%). Hence, integration of residents' food consumption, livestock breeding, aquaculture, and crop planting in the same area can achieve a lower Nr emission system. The novel framework coupling MFA and SD in the present study enhances the understanding of regional sustainable food systems in Fujian and many other regions undergoing urban expansion and contraction in arable land area. The results provide a foundation for further exploration of the impacts of food-sourced Nr metabolism and of management measures for environmental Nr emissions.

CRediT authorship contribution statement

Li Xing: Conceptualization; Data curation; Methodology; Resources; Visualization; Writing—original draft. **Tao Lin:** Conceptualization; Formal analysis; Funding acquisition; Methodology; Resources; Supervision; Writing—review and editing. **Yuanchao Hu:** Conceptualization; Formal analysis; Methodology; Supervision; Writing—review, and editing. **Meixia Lin:** Data curation; Investigation; Resources; Validation. **Yuqin Liu:** Investigation; Software; Validation. **Guoqin Zhang:** Investigation; Software; Validation. **Hong Ye:** Investigation; Resources; Validation. **Xiongzhi Xue:** Project administration; Resources; Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106726.

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