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Key Points:
- Crop and animal production contributed the most to the food N footprint (FNF)
- Economic development and urbanization resulted in an increase of FNF
- The FNF and economic gradually become strongly decoupled

Supporting Information:
Supporting Information may be found in the online version of this article.

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Food Nitrogen Footprint Increased by 35% on the Third Pole During 1998–2018

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Abstract The N footprint is considered as an indicator of potential environmental damage from N. Quantitative analysis of N footprint distribution, sources and drivers can help mitigate its negative impacts and promote sustainable N management. In this study, we constructed a city-scale food N footprint (FNF) framework for the Qinghai-Tibet Plateau (QTP) using a N mass balance approach. We quantitatively analyzed the FNF during food production and consumption on the QTP from 1998 to 2018. We used the logarithmic mean Divisa index decomposition method to analyze the driving forces of the FNF, and the decoupling of the FNF. The results showed that the per capita FNF of the QTP increased from 24.92 kg N cap^{-1} in 1998 to 27.70 kg N cap^{-1} in 2018, and the total FNF increased by 35.11% from 1998 to 2018. The spatial distribution of the FNF was uneven, with N losses from crop production and animal production being the leading contributing source to the FNF (86%). Economic development and urbanization were the main driving forces behind the FNF increase, while N consumption intensity inhibited the growth of the FNF. With the rapid growth of GDP, the FNF in the eastern part of the QTP grew relatively slowly, indicating a gradual decoupling of the FNF from economic development. To reconcile the relationship between socioeconomic drivers and the FNF, it is necessary to focus on coupling relationships between subsystems within the food production and consumption system to promote N recycling.

Plain Language Summary We found that the FNF of the QTP increased from 540.97 to 745.84 Gg from 1998 to 2018, in which animal production and crop production were identified as the main sources. The per capita FNF on the QTP increased from 24.92 kg N cap^{-1} in 1998 to 27.70 kg N cap^{-1} in 2018. The spatial boundaries of hot spots (northwest and central) and cold spots (southeast and north-central) zones were obvious, and the spatial heterogeneity was significant. Changes in dietary patterns (more animal-derived food) due to economic development and urbanization were the main reasons for the increase of the FNF, while the factor of N consumption intensity had a negative impact. The economy and FNF in the eastern regions gradually became strongly decoupled from 1998 to 2018, indicating that the task of reducing the FNF was increasingly important in the process of economic development. Combining coordinated reduction of regional FNF with differential reduction in cities, reducing red meat consumption and increasing the reuse of N between the three subsystems can reduce FNF and benefit the environment. Insights are provided for policy-makers on the FNF of food production and consumption system at regional on the QTP.

1. Introduction

Nitrogen (N) pollution causes serious damage to the environment at regional, national and global scales (Rockstrom et al., 2009). The release of N from food production and consumption activities is a major source of N pollution (Galloway et al., 2008). Planetary boundaries are proposed to define a safe operating space for humans relative to the earth system, defining the processes and associated thresholds of the Earth system. Over the past century, anthropogenic N surpluses have increased above safe operating limits (i.e., for planetary boundaries set by the N cycle, a threshold value of 35 million tons of N per year is recommended to be accommodated) and placed a significant burden on the earth due to fossil fuel combustion (Elrys et al., 2019; Rockstrom et al., 2009), agriculture and livestock (Bouwman et al., 2009; Cui et al., 2013), and generally inefficient N use (Cui et al., 2013). To describe how human activities affect the natural world, the "footprint" framework has become an effective approach (Galli et al., 2012), and the N footprint is a major focus of research after the ecological footprint, water footprint, energy footprint and carbon footprint in the "footprint family" (Galli et al., 2012; Wackernagel et al., 1999, 2002). The N footprint framework and N-calculator were first developed as consumer-based tools to determine the contributions of individuals, institutions or countries to environmental losses from N resource use (Leach et al., 2012). It can also be applied to assess the extent of regional or global disruptions to the N cycle as well as the environmental effects of anthropogenic disturbances (Bakshi & Singh, 2011). One study assessed China's N footprint from a production perspective only, using the N mass balance approach (Gu et al., 2013), and another study used input-output theory to comprehensively account for the N footprint of different countries from a production and consumption perspective, taking the study of the N footprint a step further (Oita et al., 2016). Additionally, urbanization and international trade were integrated into a framework to determine and quantify the source of the contributions and dynamics of China's FNF (Cui et al., 2016). The amount of N released into the environment is increasing, and unevenly distributed over time and space (Cui et al., 2013; Galloway et al., 2008; Liu et al., 2010).

To control anthropogenic N emissions and achieve the sustainable development of ecology and human health, it is critical to reveal the drivers of food N emissions (Liu & Nie, 2021). Previous studies of the N footprint have been conducted at national, provincial and city scales in the agriculture-food-environment system (Cui et al., 2013, 2016). It was verified that the driving factors of the FNF include affluence, population growth, urbanization and N use efficiency and technology (Cui et al., 2013; Gu et al., 2013; Liao et al., 2021; Liu & Nie, 2021). Empirical research shows that the relationship between per capita income and environmental quality follows an inverted U-shape curve, which has attracted great attention (Can & Gozgor, 2017). Decoupling occurs when the growth rate of environmental pressure is less than its economically driven growth rate over a certain period of time, and its concept and indicators reflect the responsive relationship between resource consumption and economic growth (OECD, 2003). In the context of environmental pollution and limited resources, maximizing the decoupling of pollutant emissions from economic growth is a major problem faced by governments (Kang et al., 2012). The above studies have improved our understanding of N production from human activities, thus providing feasible strategies for N management. Due to natural factors, socioeconomic levels, and spatial differences in N sources, the FNF varies widely among regions, and few quantitative studies have been conducted on the Qinghai-Tibet Plateau (QTP) (Wang, Liu, et al., 2021). Moreover, the study of N flow on the QTP is limited to the temporal scale, and lack spatial consideration or comparison. As a major agricultural and pastoral area in China, the QTP has an important ecological role in global change research and is sensitive to changes in the external environment and increased atmospheric N deposition (Liu et al., 2013). Through nutrient cycling processes, N ecological stoichiometry directly affects ecosystem N cycling and accumulation (Giardina & Ryan, 2000). In turn, it affects the N sink ability of ecosystems and their response to climate change (Giardina & Ryan, 2000).

With economic development and population growth, food production and consumption have created more problems associated with population dietary needs and environmental N pollution (Chatzimpiros & Barles, 2013; Cui et al., 2013). In recent decades, from N fertilizer to crop products, feed, livestock and poultry products and household consumption, a series of N cascades have led to an increase in N losses (Gao et al., 2018; Li et al., 2018). The three systems of crop production, animal husbandry and household consumption have become the main body of the N flow research system (Gao et al., 2020; Wang, Cai, et al., 2021; Wang, Liu, et al., 2021). Studies have shown that the N losses caused by food-related production and consumption are the most important contributor to China's N footprint and have become a major environmental issue (Gu et al., 2013). Among existing studies in the literature, many regions, counties, and cities are neglected in N footprint research. Urban systems are also receiving increasing attention as an emerging and important natural N source. Extensive studies on urban-scale N flow are of great value for the sustainable development of the N cycles of megacity systems. While the QTP is an important ecological region in China, agriculture and animal husbandry serve as the basic industries supporting people's means of living and food needs. The N footprint in the production and consumption processes also contributes to and influences climate change. Thus, understanding the socioeconomic driving mechanisms of the FNF is particularly important to reconcile the relationship between anthropogenic drivers and N behavior. In this study, we aim to (a) construct a city-scale FNF framework with the N mass approach; (b) quantitatively analyze the spatiotemporal variation and the drivers of the FNF (1998–2018) on the QTP; and (c) further analyze the decoupling coefficient between the urban-scale FNF and economic growth, and explore the coordination relationship and change characteristics between them. This study provides important references and insights into the sustainable use and management of N resources in the food chains on the QTP.

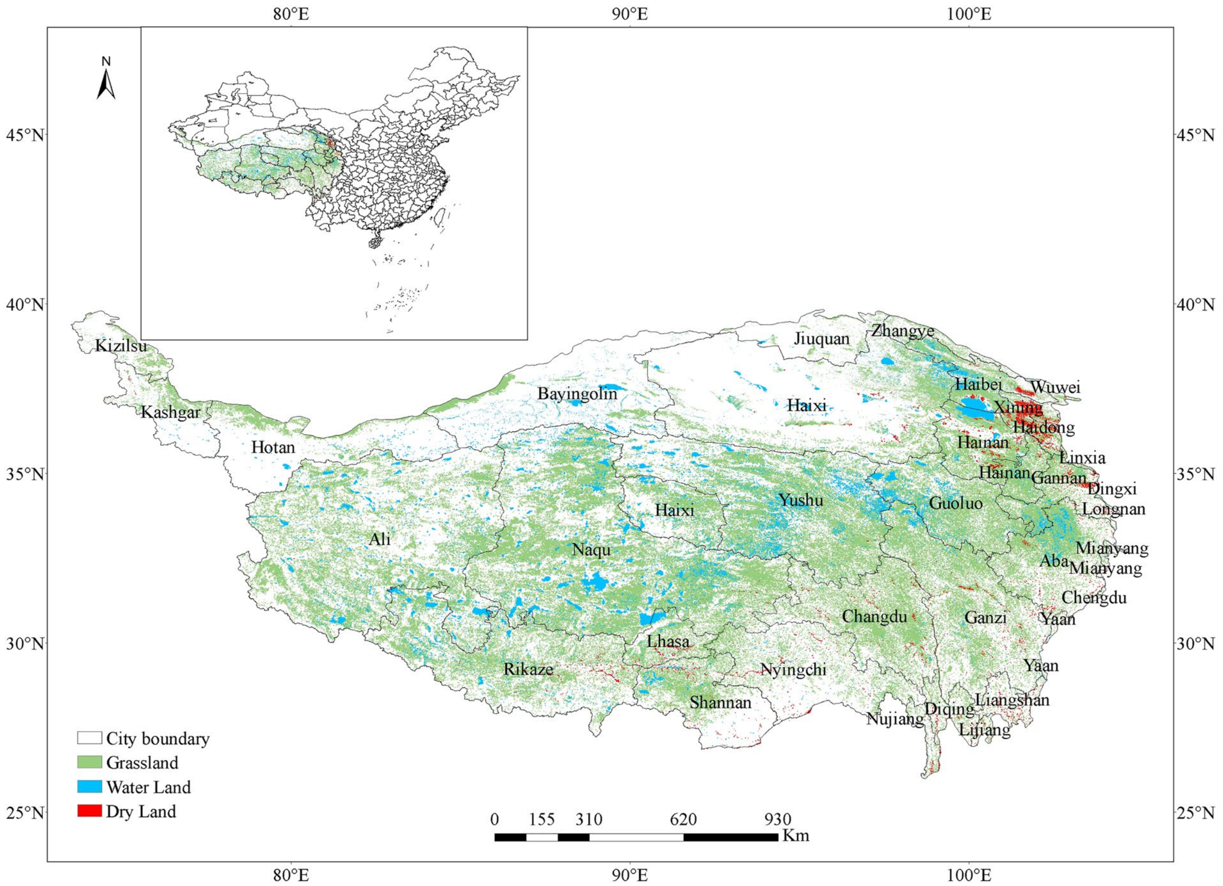

Figure 1. Location of study area. The map shows the names of the cities, and the main land use patterns. The names of the cities are marked on the map.

2. Materials and Methods

2.1. Study Area

The QTP (26°00′–39°47′N, 73°19′–104°47′E), known as the "roof of the world" and "third pole," is considered the largest and highest plateau in the world, with an average elevation of between 3,000 and 5,000 m (Chen et al., 2013). The total area is approximately 2.57×10^6 ha, accounting for a quarter of China's total area, including the Qinghai, Tibet, part of Xinjiang, Sichuan, Gansu and Yunnan provinces (Figure 1). Under the combined effects of various geographical factors, the northwestern part has a dry and cold climate, and the southeastern part has a warm and wet climate. Mean annual precipitation reaches 486 mm, and the average annual temperature is generally between −6° and 3°C. With a total area of 546.34 billion m^3 of water resources, the plateau is the birthplace of important rivers in China, known as the "Asian water tower" (Wang, Liu, et al., 2021). Its excellent location and climate support the valley agriculture and livestock industry. From statistical data, Qinghai and Tibet included 835,657 ha of arable land (year-end) in 2018. The number of large livestock (year-end) in Qinghai and Tibet was 37 million heads, of which cattle and sheep accounted for the majority with a percentage of 95.5%. Rice, highland barley, wheat, maize, soybeans, potatoes, oil crops, vegetables, cotton, melons and green feed are the main crops. The main livestock include cattle, sheep, pigs and poultry. The crop and livestock types selected for each city are shown in Table S1 in Supporting Information S1. In 2018, the per capita disposable income levels of urban residents in Qinghai and Tibet were 31,515 Yuan and 33,797 Yuan respectively, while the per capita grain consumption levels of urban residents were 90 and 207 kg, respectively, and those of meat consumption were 28.40 and 54 kg, respectively.

2.2. Food N Footprint Model and Data Sources

To quantify the FNF, the N-flow model was adopted, using the material flow analysis (MFA) method and mass balance approach (Cai et al., 2018). We conducted a FNF analysis of food production and consumption on the

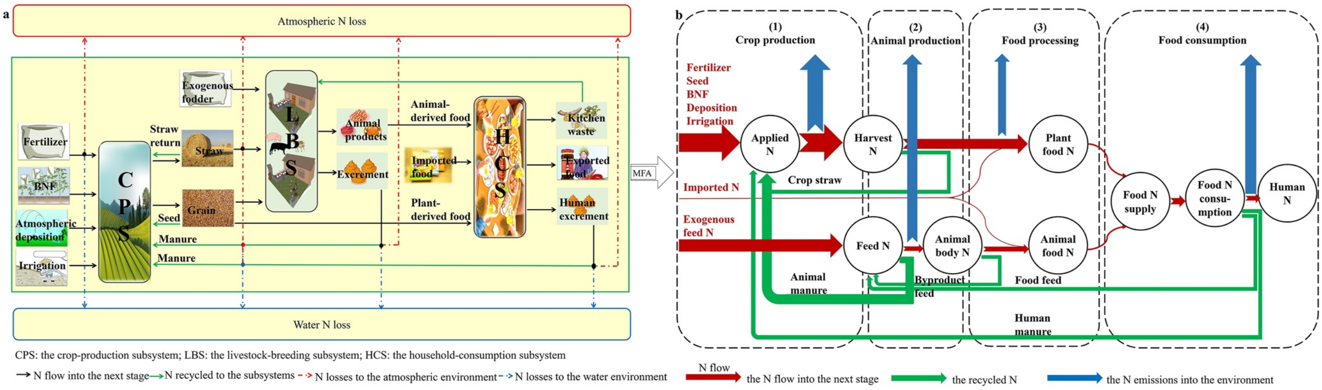

Figure 2. N flows in food production and consumption system to calculate the N footprint. (a) The urban-scale N flow model. (b) N flows through different stages (1) crop production, (2) animal production, (3) food processing, (4) food consumption.

QTP. All flows related to the FNF calculation (i.e., N losses in the form of NH_3 volatilization, N_2O and NO_X emissions into the atmosphere and runoff, leaching and erosion into the water during food production and consumption) were then extracted from the N flow (Figure 2). The regional boundary of the N flow system forms the administrative boundary of the 6 provinces including 37 cities. The N-flow system consists of three subsystems: a crop-production subsystem (CPS), livestock-breeding subsystem (LBS) and household-consumption subsystem (HCS). The N input of the system includes new N (BNF, atmospheric N deposition, irrigation, chemical fertilizer, seeds, exogenous feed, and imported food) and recycled N (straw as feed, grain as feed, kitchen waste as feed, and livestock by-products as feed, etc., is also called local feed, livestock and poultry manure and human manure recycled to the field, and straw recycled to the field). The N output of the system includes the crop harvest (grain and straw), animal products (meat, milk and eggs), human body absorption, food export and N losses. The FNF includes four stages of N losses: (a) crop production, (b) animal production, (c) food processing, and (d) food consumption.

The data used in this study for the quantification of the FNF are of two categories. (a) Basic data on the urban and rural population, GDP, land use, crop production and livestock production were mainly collected from the Statistical Yearbooks of different provinces (1998, 2005, 2010, and 2018). To study the spatial and temporal characteristics of the FNF, we chose to compare changes in the FNF from the ninth Five-Year Plan to the 13th Five-Year Plan. (b) Parameters used in the calculation of N fluxes, which included the N content and N conversion coefficient of the main products, the fate of crop harvest, livestock and human excrement, and emission factors, were mainly derived from the China Food Composition, the FAO, the Second National Pollution Census, literature and a field investigation conducted in August 2020. The field investigation of N flow in human food production and consumption was carried out in Qinghai province, and approximately 150 questionnaires were completed over 21 days in the main townships of Ledu County, Guinan County and Maqin County. Additionally, detailed parameter data for the three subsystems of each city are described in Tables S2–S4 in Supporting Information S1.

2.3. Calculation of the Food N Footprint

The N balance of the whole system and three subsystems followed the principle whereby the N surplus was equal to the difference between the N inputs and N outputs. The N footprint is the total amount of N released directly or indirectly to the environment by a certain product or service during its production, transportation and consumption (Leach et al., 2012). The essential components included in the FNF are food production (crop production, animal production and food processing) and food consumption (Equation 1).

$$\mathrm{FNF} = \mathrm{NF}_P + \mathrm{NF}_C \tag{1}$$

where, FNF represents the total N losses associated with the food production and consumption system. NF_P denotes N losses to the atmosphere and water during production, including NH_3, NOx and N_2O, leaching, runoff and erosion (i.e., reactive N, N_2 is excluded). NF_P is the FNF in the crop production stage, animal production stage and food processing stage. Similarly, NF_C is the N losses to the atmosphere and water body during consumption. More specifically, the change in the FNF at each stage is governed by the following equations (Equations 2–5).

(1) Crop production: Fertilizer N (new N and recycled N) inputs to the CPS, and only a fraction of these inputs can be used by grain and straw to enter the next process, or denitrified into N_2; the remaining N is lost to the atmosphere and water when soil N is assumed to be constant (Cui et al., 2016). Due to the complexity of the soil N cycle and the indirect calculation of accumulated N (Cui et al., 2016; Wang, Liu, et al., 2021), the calculation of the FNF did not take N losses into the soil into account.

$$\mathrm{FNF}_{(1)} = N_{\text{fertilizer}} + N_{\text{BNF}} + N_{\text{deposition}} + N_{\text{seed}} + N_{\text{irrigation}} + N_{\text{manure recycled to the field}} + N_{\text{straw recycled to the field}} - N_{\text{denitrificaiton}} - N_{\text{crop harvest}} - N_{\text{accumulation}} \quad (2)$$

(2) Animal production: Feed N (local feed and exogenous feed) inputs to the LBS, in addition to N converted into animal protein in live animal bodies and animal manure N recycled into the field, and the remaining N is lost to the surrounding environment during animal production.

$$\mathrm{FNF}_{(2)} = N_{\text{grain as feed}} + N_{\text{kitchen waste as feed}} + N_{\text{byproducts as feed}} + N_{\text{straw as feed}} + N_{\text{exogenous feed}} - N_{\text{animal body}} - N_{\text{animal manure recycled to the field}} \quad (3)$$

(3) Food processing: Crop harvest and animal body can vary across different utilization patterns, being used for feed, seed, fertilizer, fuel, etc. A portion eventually becomes plant-derived food and animal-derived food available for human consumption; the rest is either recycled to agroecosystems or lost to the surrounding environment.

$$\mathrm{FNF}_{(3)} = N_{\text{crop harvest}} + N_{\text{animal body}} - N_{\text{straw as feed}} - N_{\text{plant-derived feed}} - N_{\text{animal-derived food as feed}} - N_{\text{straw}} - N_{\text{food supply}} \quad (4)$$

(4) Food consumption: Food N (plant-derived food and animal-derived food) inputs to the HCS, approximately 2% of the edible N is absorbed by the human body (Wang et al., 2020), most of the N consumed by human is excreted and released to the environment, and some kitchen waste and human manure is recycled to the CPS and LBS.

$$\mathrm{FNF}_{(4)} = N_{\text{food consumption}} - N_{\text{human body absorption}} - N_{\text{human manure recycled to the field}} - \mathrm{N}_{\text{kitchen waste as feed}} \quad (5)$$

A detailed calculation of the input and output items of the three subsystems is given in Tables S5–S7 in Supporting Information S1.

2.4. Logarithmic Mean Divisia Indmean Divisia Index (LMDI) Model

The index decomposition analysis approach is widely used to analyze the driving forces of energy, resource consumption and pollution emission changes. The method can clearly reveal how such driving factors affect quantitative changes (Su & Ang, 2015). The logarithmic mean Divisa index (LMDI) model, a commonly used tool of index decomposition analysis, has the unique advantages of being path independent, residual free, able to handle zero values, and aggregation consistent (Ang, 2005). Therefore, the LMDI model is widely employed in the analysis of spatiotemporal drivers (Hang et al., 2019; Ma et al., 2019). According to the Kaya identical extension model (Ang, 2005), the FNF can be decomposed into environmental technology, agricultural productivity, the animal food self-sufficiency rate, diet structure, N consumption intensity and economic structure, as shown in Equations 6–9.

$$\mathrm{FNF}^t = \sum_m^n \mathrm{FNF}_m^t = \sum_m^n \left(\frac{\mathrm{FNF}_m^t}{\mathrm{NC}_m^t} \times \frac{\mathrm{NC}_m^t}{\mathrm{FP}_m^t} \times \frac{\mathrm{FP}_m^t}{\mathrm{AC}_m^t} \times \frac{\mathrm{AC}_m^t}{\mathrm{FC}_m^t} \times \frac{\mathrm{FC}_m^t}{G_m^t} \times G_m^t = \sum_m^n \left(\mathrm{FNF}_{m,\mathrm{tec}} \times \mathrm{FNF}_{m,\mathrm{pro}} \times \mathrm{FNF}_{m,\mathrm{sel}} \times \mathrm{FNF}_{m,\mathrm{die}} \times \mathrm{FNF}_{m,\mathrm{con}} \times \mathrm{FNF}_{m,\mathrm{eco}} \right) \right) \quad (6)$$

$$\mathrm{FNF}_{m,\mathrm{tec}} = \frac{\mathrm{FNF}_m^t}{\mathrm{NC}_m^t}, \mathrm{FNF}_{m,\mathrm{pro}} = \frac{\mathrm{NC}_m^t}{\mathrm{FP}_m^t}, \mathrm{FNF}_{m,\mathrm{sel}} = \frac{\mathrm{FP}_m^t}{\mathrm{AC}_m^t}, \mathrm{FNF}_{m,\mathrm{die}} = \frac{\mathrm{AC}_m^t}{\mathrm{FC}_m^t}, \mathrm{FNF}_{m,\mathrm{con}} = \frac{\mathrm{FC}_m^t}{G_m^t}, \mathrm{FNF}_{m,\mathrm{eco}} = G_m^t \quad (7)$$

$$\mathrm{FNF}^t = \sum_m^n \mathrm{FNF}_m^t = \sum_m^n \left(\mathrm{FNF}_{m,\mathrm{tec}} \times \mathrm{FNF}_{m,\mathrm{pro}} \times \mathrm{FNF}_{m,\mathrm{sel}} \times \mathrm{FNF}_{m,\mathrm{die}} \times \mathrm{FNF}_{m,\mathrm{con}} \times \mathrm{FNF}_{m,\mathrm{eco}} \right) \quad (8)$$

$$\triangle\mathrm{FNF} = \mathrm{FNF}^t - \mathrm{FNF}^0 = \triangle\mathrm{FNF}_{m,\mathrm{tec}} + \triangle\mathrm{FNF}_{m,\mathrm{pro}} + \triangle\mathrm{FNF}_{m,\mathrm{sel}} + \triangle\mathrm{FNF}_{m,\mathrm{die}} + \triangle\mathrm{FNF}_{m,\mathrm{con}} + \triangle\mathrm{FNF}_{m,\mathrm{eco}} \quad (9)$$

where FNF^0 and FNF^t represent the value of the FNF in the base year and t year, respectively; m represents each city on the QTP ($m = 37$); NC_m^t is the amount of new N of region m in t year (new N denotes N inputs from outside the food production and consumption system such as chemical fertilizer, BNF, atmospheric deposition, irrigation and exogenous feed); FP_m^t represents food production, including plant-derived food and animal-derived food of region m in t year; AC_m^t is the animal food consumption of region m in t year; FC_m^t is the food consumption of region m in t year, including plant-derived food and animal-derived food consumption of region m in t year; and G_m^t is the GDP of region m in t year.

Specifically, $FNF_{m,\mathrm{tec}}$ reflects environmental technology; $FNF_{m,\mathrm{pro}}$ is agricultural productivity, where the lower the ratio is, the higher the N use efficiency; $FNF_{m,\mathrm{sel}}$ denotes the animal food self-sufficiency rate, where the lower the ratio is, the higher the animal food self-sufficiency rate is and the lower N losses and the FNF are (Guo et al., 2017); $FNF_{m,\mathrm{die}}$ represents the diet structure, and studies have shown that the residents' food consumption patterns have a great impact on N losses and the FNF (Martinez et al., 2019; Wang et al., 2020); $FNF_{m,\mathrm{con}}$ represents N consumption intensity, and $FNF_{m,\mathrm{eco}}$ is the economic structure expressed in terms of GDP, which reflects the combined effect of economic development on the FNF. The effects of various driving factors are calculated by Equations 10–15:

$$\triangle FNF_{\mathrm{tec}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t - \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{tec}}^t}{FNF_{m,\mathrm{tec}}^0}\right) \tag{10}$$

$$\triangle FNF_{\mathrm{pro}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{pro}}^t}{FNF_{m,\mathrm{pro}}^0}\right) \tag{11}$$

$$\triangle FNF_{\mathrm{sel}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t - \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{sel}}^t}{FNF_{m,\mathrm{sel}}^0}\right) \tag{12}$$

$$\triangle FNF_{\mathrm{die}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t - \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{die}}^t}{FNF_{m,\mathrm{die}}^0}\right) \tag{13}$$

$$\triangle FNF_{\mathrm{con}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t - \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{com}}^t}{FNF_{m,\mathrm{com}}^0}\right) \tag{14}$$

$$\triangle FNF_{\mathrm{eco}}^{t-0} = \sum_m \frac{FNF^t - FNF^0}{\ln FNF^t - \ln FNF^0} \ln\left(\frac{FNF_{m,\mathrm{eco}}^t}{FNF_{m,\mathrm{eco}}^0}\right) \tag{15}$$

The increase in the FNF under different economic growth rates in different cities and the decoupling coefficient of the FNF and economic growth are as follows (Equations 16 and 17):

$$FNFR^m = \triangle FNF^m - \triangle FNF_{\mathrm{eco}}^m = \triangle FNF_{\mathrm{tec}}^m + \triangle FNF_{\mathrm{pro}}^m + \triangle FNF_{\mathrm{sel}}^m + \triangle FNF_{\mathrm{die}}^m + \triangle FNF_{\mathrm{con}}^m \tag{16}$$

$$\begin{aligned} D_m = 1 - \frac{\triangle FNF^m}{\triangle FNF_{\mathrm{eco}}^m} = -\frac{\triangle FNFR^m}{\triangle FNF_{\mathrm{eco}}^m} = \frac{-\triangle FNF_{\mathrm{tec}}^m}{\triangle FNF_{\mathrm{eco}}^m} + \frac{-\triangle FNF_{\mathrm{pro}}^m}{\triangle FNF_{\mathrm{eco}}^m} + \frac{-\triangle FNF_{\mathrm{sel}}^m}{\triangle FNF_{\mathrm{eco}}^m} \\ + \frac{-\triangle FNF_{\mathrm{die}}^m}{\triangle FNF_{\mathrm{eco}}^m} + \frac{-FNF_{\mathrm{con}}^m}{\triangle FNF_{\mathrm{eco}}^m} = D_m^{\mathrm{tec}} + D_m^{\mathrm{pro}} + D_m^{\mathrm{sel}} + D_m^{\mathrm{die}} + D_m^{\mathrm{con}} \end{aligned} \tag{17}$$

where, $FNFR^m$ is the increase in the FNF and D_m represents the decoupling coefficient of the FNF and economic growth. According to the formula, when the growth of economic driving factors exceeds the increase in environmental pressure, the $\frac{\triangle FNF^m}{\triangle FNF_{\mathrm{eco}}^m}$ value is less than 1, and $D_m > 0$, indicating that the two systems are decoupled, and the higher the economic growth is, the more significant the decoupling of the FNF is.

3. Results and Discussion

3.1. Comparison of the Food N Footprint on the QTP With Other Regions

3.1.1. Temporal Variations in the Food N Footprint on the QTP

The per capita FNF of the QTP increased from 24.92 kg N cap^{-1} in 1998 to 27.70 kg N cap^{-1} in 2018 (Figure 3), and the total FNF increased from 540.97 Gigagram (Gg) in 1998 to 745.84 Gg in 2018, representing an increase

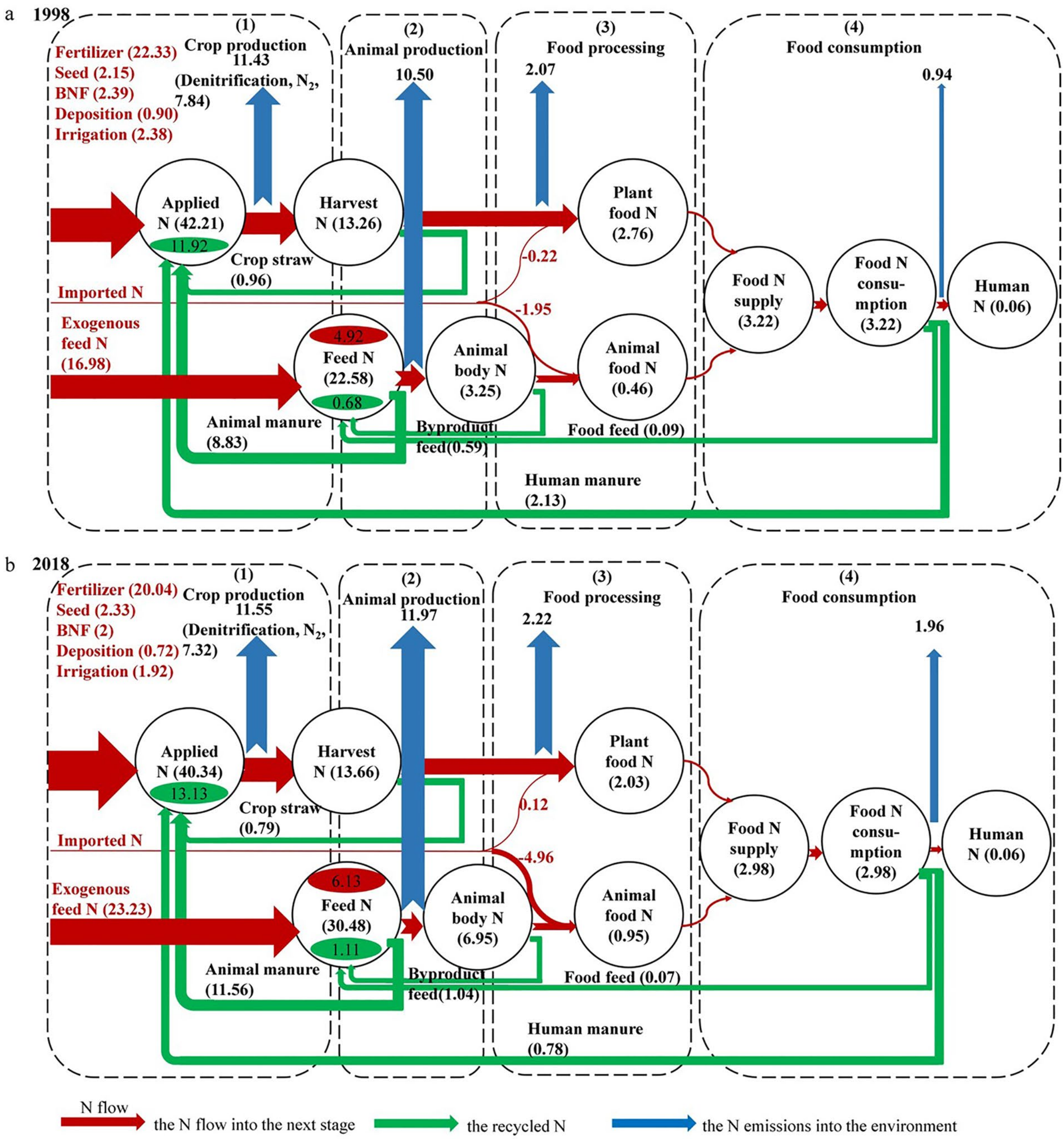

Figure 3. N flows in food production and consumption system to calculate the N footprint in 1998 and 2018 on the Qinghai-Tibet Plateau. Red represents the "new" N input from the external systems into the food production and consumption system. The negative value of food N means exported food, and the positive value means imported food. The widths of the arrows roughly correspond to the relative amounts of N flows (Unit: kg N cap^{-1}).

of 35.11% (Figure S1 in Supporting Information S1).The rapid increase was mainly a result of the low N utilization efficiency of chemical fertilizer and rapid urban expansion, which aggravated agricultural N pollution. The new N input to the whole system increased from 44.72 kg N cap^{-1} in 1998 to 45.40 kg N cap^{-1} in 2018. A total of 11.92 kg N cap^{-1} of organic fertilizer in 1998 and 13.13 kg N cap^{-1} in 2018 was recycled to the field in the CPS, including crop straw, human manure and animal manure, while 0.68 kg N cap^{-1} and 1.11 kg N cap^{-1} of byproduct and food feed, respectively were recycled to the LBS (Figure 3). The N cost (kg kg^{-1}) of food consumption (i.e., total N input into the food production and consumption system per unit food N consumed) reflects the resource and environmental costs of food consumption (Ma et al., 2010). The N cost on the QTP increased from 20.05 kg kg^{-1} in 1998 to 25.51 kg kg^{-1} in 2010 and then decreased to 23.70 kg kg^{-1} in 2018. Our analysis shows

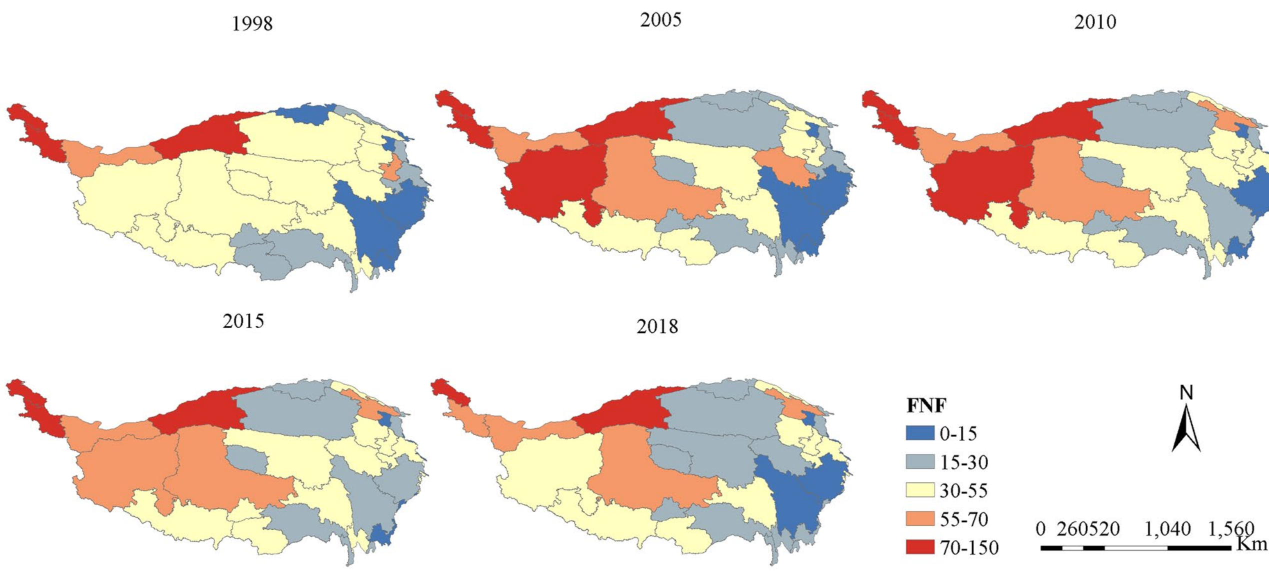

Figure 4. Spatial variability of city scale per capita food N footprint on the Qinghai-Tibet Plateau in 1998, 2005, 2010, 2015, and 2018 (Unit: kg N cap^{-1}).

that a low recycling rate and high N cost inevitably lead to significant N losses into the environment. We found that animal production contributed the most to the FNF, with an annual average proportion of approximately 44% (Figure S1 in Supporting Information S1). The FNF in 2015 reached its maximum and then declined in 2018. Crop production was also an important source of the FNF on the QTP and increased from 11.43 kg kg^{-1} in 1998 to 12.56 kg kg^{-1} in 2015 and then decreased to 11.55 kg kg^{-1} in 2018.

We compared the FNF results calculated by the N-flow method on the QTP with the N footprint in other countries using the N-Calculator method. The average annual per capita FNF across the QTP was 28.26 kg N cap^{-1} (the average annual FNF was 687.16 Gg) from 1998 to 2018, far exceeding the mean level in China (22 kg N cap^{-1}) and the Netherlands (22 kg N cap^{-1}), and being slightly lower than that in the USA (30 kg N cap^{-1}) (Gu et al., 2013; Leach et al., 2012). Studies have shown that the level of the FNF depends on the amount and type of N consumed by residents (Hertwich & Peters, 2009). In the USA, the main source of animal-derived consumption was meat, while in the Netherlands, the main source of animal-derived consumption included dairy products, eggs and fish. The QTP was dominated by animal husbandry, and residents needed to consume more meat to adapt to the cold local climate. In China, cattle and goats have a much higher feed conversion rate than any other animal (Bouwman et al., 2005). However, most cattle and goats on the QTP are raised in grazing systems, leading to a large input of grass N from external systems and becoming the main reason for the increase in the FNF. Second, the low education level of local residents and a lack of knowledge of different N fertilizer application levels that should be applied to different crops have led to an excessive use of fertilizer and an increase in the FNF. Third, economic development and urbanization have led to a shift in dietary patterns toward meat diets (Li et al., 2013). Animal-derived food consumption increased by 128.57% from 1998 to 2018 (Figure S2 in Supporting Information S1), inevitably leading to food loss and an increase in the FNF, which remains consistent with previous findings (Cui et al., 2016; Gu et al., 2013).

3.1.2. Spatial Variations in the Food N Footprint on the QTP

Figure 4 provides the FNF of 37 cities on the QTP for 1998–2018 to further explore the spatial variation relationship of the FNF of each city and clarify the spatial evolution pattern of the FNF at the city scale. The FNF was divided into five classes (low level: 0–15 kg N cap^{-1}, medium-low level: 15–30 kg N cap^{-1}, medium level: 30–55 kg N cap^{-1}, medium-high level: 55–70 kg N cap^{-1}, and high level: 70–150 kg N cap^{-1}) according to natural breakpoints from high to low. Overall, the FNF of most cities of the QTP increased from 1998 to 2015, and the number of cities with a medium and medium-high level FNF also increased, increasing from 10 to 2 in 1998 to 13 and 4 in 2015, respectively. After 2015, the FNF level of more than 70% of cities started to decrease, but the decrease in the FNF level was not obvious. From the perspective of distribution characteristics, "hot" spots (high concentration areas) of the FNF are mainly distributed in the central and western parts of Bayinguolin, Kizilsu, Naqu, Changdo, Kashgar and Hotan. "Cold" spots (low concentration areas) are mainly distributed southeast of Aba and Ganzi, Nyingchi. The two distribution areas have a relatively obvious boundary with great spatial heterogeneity. From the perspective of dynamic changes, the original high level areas of the FNF continued to expand, showing a trend of expansion from the west to the eastern cities of the QTP.

As the "12th Five-Year Plan" took into account the fairness and balance of economic development in the northwestern region, a policy of care for these regions was adopted and no emission reduction task was given. Moreover, the increase in the FNF of Naqu was obvious, the livestock industry in Naqu was relatively developed, livestock raised accounted for 30% of the livestock in Tibet, and the rate of returning manure to the field was only 27% in 2015. During the "13th Five-Year Plan" period, the western region followed the "lucid waters and lush mountains are invaluable assets," and the importance of ecological prioritization and green development have not only reached consensus but also been implemented in various ways. Under the requirements and efforts of the plan, in 2018, more than 70% of the cities reduced their FNF. With rapid socioeconomic development, animal-derived food consumption on the QTP will at least double by 2050. This will put tremendous pressure on the food production system and continue to increase the FNF of the QTP. Therefore, reducing N losses during food production and enhancing the recycling rate among the three subsystems, that is, increasing the recycling rate of waste N, can reduce the amount of N fertilizer and feed N that needs to be produced, which can reduce the FNF and benefit the environment.

3.2. Decomposition of the Food N Footprint

FNF_{eco} is a decisive factor in promoting the increase in the FNF on the QTP. The FNF_{eco} in different periods from 1998 to 2015 contributed positively to the increase in the FNF, playing a continuous role in promoting the increase in the FNF. Not only has the FNF increased due to the expansion of the economic scale of the QTP, but it has also shown obvious regional differences. The greatest contributions of FNF_{eco} in the first three periods occurred in Bayinguolin and Kizilsu, reaching 90.64 and 94.31 (1998–2005), 154.71 and 70.66 (2005–2010), 133.16 and 130.14 (2010–2015), respectively (Figure 5). The rapid development of the economy is an important factor driving the growth of the FNF. The QTP has adopted the principles of ecological prioritization and green development and taken various actions and the region has begun to urgently seek a sustainable development approach to maintain moderate economic growth while reducing its FNF. This has transformed the region's extensive economic development model into an intensive economic development mode.

FNF_{con} had a significant negative effect on the increase in the FNF, as shown by Bayinguolin (−79.98) and Kizilsu (−85.60) from 1998 to 2005, Bayinguolin (−147.48) and Kizilsu (−57.85) from 2005 to 2010, and Bayinguolin (−107.97) and Kizilsu (−109.49) from 2010 to 2015. Environmental protection measures can effectively improve N use efficiency, and the improvement of N use efficiency is an important means to reduce the FNF. Since the "13th Five-Year Plan" period, national environmental policy documents have set cleartargets for the reduction of total emissions of major pollutants and have taken into account the economic development of the Northwest Territories. Despite high N cost (22.81 kg kg^{-1} on average) of the QTP, from 2015 to 2018, the N use efficiency of the system increased from 13.14% to 15.54%, and the FNF decreased from 31.28 kg N cap^{-1} to 27.69 kg N cap^{-1}. The FNF_{con} of Haibei, Yushu and Zhangye shifted from inhibiting to promoting the FNF, and it was thus necessary to pay attention to the food production and diet structure of the three cities to facilitate a reduction of the FNF.

FNF_{die}, FNF_{sel}, FNF_{pro}, and FNF_{tec} had less of an effect on the FNF than FNF_{eco} and FNF_{con} and showed positive and negative fluctuations in all four periods. The dietary structure of residents of the QTP was dominated by plant-derived food, and from 1998 to 2018, plant-derived food changed from being exported to imported, with demand exceeding supply. Exported plant-derived food in 1998 reached 0.22 kg N cap^{-1}, and the imported volume in 2018 was 0.12 kg N cap^{-1}. Animal-derived food was always oversupplied; the animal-derived food self-sufficiency rate decreased from 12.12% in 1998% to 8.23% (Figure S3 in Supporting Information S1), and exported animal-derived food increased from 2.20 kg N cap^{-1} to 4.96 kg N cap^{-1} from 1998 to 2018. Although N emission reduction exhibited a good trend, the impacts of these four influencing factors on the FNF cannot be easily ignored.

3.3. Decoupling Effect and Driving Factors of the Food N Footprint

According to the decoupling coefficient of the FNF of each stage, the "natural break" method was used to show spatial variations (Chong et al., 2017). Therefore, 37 cities of the QTP were divided into 5 levels, representing

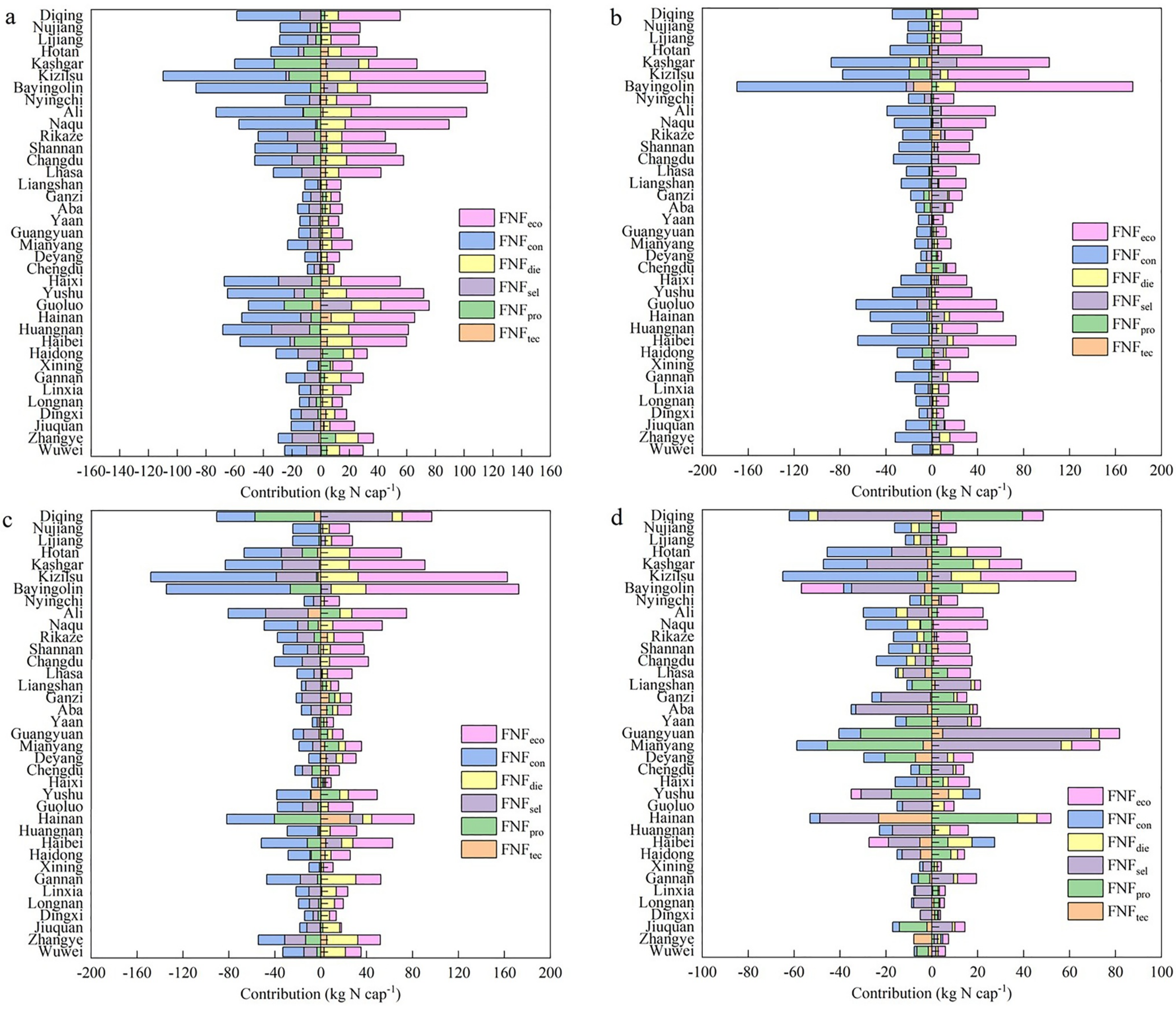

Figure 5. Decomposition results of food N footprint influencing factors of 37 cities on the Qinghai-Tibet Plateau. (a) for the year of 1998–2005; (b) for the year of 2005–2010, (c) for the year of 2010–2015; (d) for the year of 2015–2018.

"weak decoupling ($D_m < 0$)," "weak decoupling ($0 \le D_m < 0.5$)," "medium decoupling ($0.5 \le D_m < 1$)," "strong decoupling ($1 \le D_m < 2$)" and "absolute decoupling ($D_m \ge 2$)" (Figure 6). It was found that in the first three periods from 1998 to 2018, the FNF between cities showed mainly medium and strong decoupling levels, with 17 and 14, 20 and 14, and 15 and 18 cities respectively at these levels. From 2015 to 2018, strong and absolute decoupling were the main types, and the number of cities reached 17 and 9, respectively. From the perspective of time and space, Ganze, Aba, Diqing and Guoluo in the eastern regions gradually became strongly decoupled (Figure 4). This indicates that the task of reducing the FNF is gradually being taken into account in the process of economic development. These cities have achieved significant FNF emission reductions by improving N use efficiency and FNF_{sel} (the decoupling of the FNF and the contribution data of each factor are shown in Tables S8–S11 in Supporting Information S1). It is worth mentioning that the FNF of Bayinguolin showed a moderate decoupling, but the FNF was always above a medium level. There was an unreasonable dietary structure, and it was necessary to improve the dietary structure to reduce N loss (Figure 5). From 1998 to 2018, the waste N utilization rate of Bayinguolin (waste generated by human food production and consumption activities such as those related to crop straw, human excrement, animal manure, and kitchen waste, the N contained in waste is called "waste N") in the HCS (i.e., human excrement and kitchen waste recycled to the CPS and LBS) decreased from

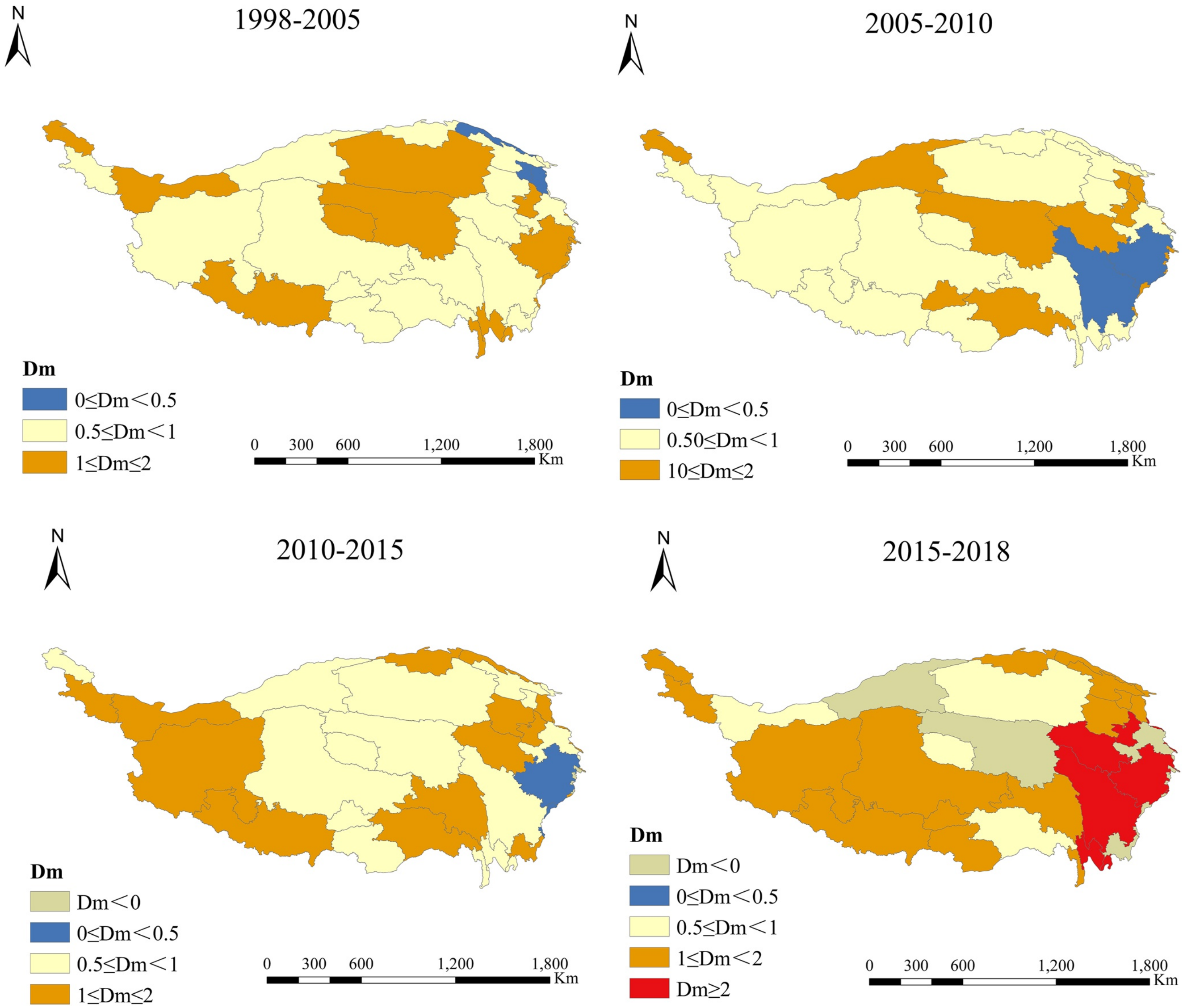

Figure 6. Spatial variability of food N footprint (FNF) decoupling index of 37 cities on the Qinghai-Tibet Plateau. $D_m > 0$, indicating that the two systems are decoupled, and the larger the economic growth, the more significant the decoupling of FNF.

68% to 34%. This shows that the loss of N entering the environment increases, and the coupling degree between subsystems is lower, resulting in imbalance between the three subsystems of the CPS, LBS, and HCS.

In general, the spatial distribution of FNF decoupling on the QTP ranged from medium and strong decoupling to strong and absolute decoupling. Absolute decoupled cities made a relatively large contribution to emission reduction in economic development because they entered a bottleneck period, and the potential for subsequent emission reductions was small. Emission reduction tasks should mostly occur in medium or weakly decoupled cities, which also have certain emission reduction potentials. It was necessary to formulate reasonable emission reduction targets according to local conditions by region and city and to coordinate emission reduction plans for neighboring cities. Reducing N losses in the food production process and increasing the recycling of N between the CPS, LBS and HCS can reduce the FNF and contribute to environmental protection.

At present, consumers and policy-makers of the QTP have an incomplete understanding of N issues. Relevant studies have shown that the amount of N applied to cash crops is greater than that applied to grain crops, and other natural sources of N (atmospheric deposition, BNF, livestock manure, etc.) have not been considered when defining the N application level (Miao et al., 2011). According to our field survey, the Bureau of Agriculture and

Animal Husbandry purchased chemical fertilizers and distributed them to farmers with subsidies. Local residents believed that more N input is preferred, which in turn led to low N use efficiency, and the increase in the FNF had a significant environmental impact (Ahrens et al., 2010; Ma et al., 2010). Currently, China is undergoing a rapid transformation of its human diet structure (FAO, 2013). The proportion of animal-derived food of total food consumption on the QTP increased from 14% in 1998% to 32% in 2018. Because of the higher N cost of animal-derived food, this will place great pressure on food production and will continue to increase the FNF (Gu et al., 2013; Martinez et al., 2019).

3.4. Limitations and Suggestions for Improving N Management

Many factors lead to uncertainty in our research, mainly including methods and parameters. In terms of methodological uncertainty, the FNF was not verified using previous integrated methods (namely, MFA and input-output analysis (IOA)) or by calculating the FNF from the subsystem and the system levels based on the N balance method (Cui et al., 2016; de Vries and de Boer, 2010; Gu et al., 2013; Roy et al., 2009). In this study, the FNF was obtained through the mass balance and N flow calculation method, which only includes three subsystems: the CPS, LBS and HCS. Furthermore, since the operation of the Qinghai-Tibet Railway in 2006, the number of tourists has rapidly increased (Hu et al., 2021). From national statistical data, in 2018, the number of tourists reached 42.04 million and 33.69 persons-time in Qinghai Province and Tibet, respectively. Therefore, some animal-derived food, such as beef, is sold to tourists. Although we estimate that the average amount of exported animal-derived food is 3.43 kg N cap^{-1}, mobile tourists may lead to a larger FNF for the QTP.

In addition, there were some uncertainties in our calculations of N input, N output and the FNF due to the limited and lack of raw parameters. The parameter data used to calculate the N flux and FNF were mainly drawn from the literature and field investigations. The above coefficients may vary slightly between different years or regions. To ensure the reliability of the FNF results, Monte Carlo simulations were used to check the uncertainty of the parameters on the output results. The results (see Table S12 in Supporting Information S1) showed that the accuracy of the straw/grain ratio had the greatest impact on the reliability of the simulation results. These parameters were mainly derived from existing research results, and were related to their own characteristics despite of the spatial and temporal variability, and we believed they were reasonably well constrained. For other important parameters required to calculate the FNF, such as emission factors for NH_3 volatilization, leaching and runoff rates, we referred to relevant studies on the differences in loss factors between northern and southern China and between dryland and paddy fields to determine the parameters (Gu et al., 2013; Ma et al., 2014). We adjusted and filtered the data according to the actual situation so that the results could be considered reliable on the QTP (detailed parameters are shown in Tables S2–S4 in Supporting Information S1). To accurately quantify N inputs and outputs to regional food production and consumption system, region-specific parameters need to be determined, which is important for the implementation of regional or national sustainable N management.

In response to the losses in the N-flow system, we propose three ways to reduce the environmental FNF and reduce adverse ecological effects. First, the significant spatial spillover effect of the FNF on the QTP indicates that policy-makers, especially local governments, should not only focus on local N emissions but also consider the impacts of N emissions on surrounding cities. Local governments were encouraged to actively participate in programs that promote N reduction in both food production and consumption. According to the field survey, farmers have little professional training due to the low development levels and remoteness of the regions. Although a fertilizer subsidy policy is in place, crop planting, fertilization amounts and fertilization methods are based on farmers' own experiences. Fertilizers in different regions have different sensitivities to climates, crop types, planting structures and soil properties. Standardized technologies and policies are needed to provide guidance and annual nutrient management plans should be formulated for soil, crop nutrient demand and fertilizer crop nutrient supply assessment (Chadwick et al., 2020; Xu et al., 2019). This will require scientific researchers, decision-makers, and local governments to publicize the policies and explain methods to farmers and give them with personal guidance. Second, regarding coupling between the CPS, LBS and HCS, despite the rapid transition of livestock production to landless industrial systems from 1980 to 2010 (Bai et al., 2018), grazing and mixed traditional systems remained main part of livestock farming in China, and the coupling of the CPS and LBS has always been the focus of N pollution reduction (Jin et al., 2021; Zhang et al., 2019). The Ministry of Agriculture and Rural Affairs (MOARA) in China has initiated 200 demonstration projects to promote manure recycling (Chadwick et al., 2020; MOARA, 2017) to achieve high N use efficiency in crop-livestock systems and promote sustainable recycling of waste N. It is helpful to reconnecting livestock production and crop production geospatially and return manure to the field can be more efficient in recovering manure nutrients as most herder dry cattle and sheep manure and burn it as fuel. Spatial planning can also be considered in terms of environmental protection and socioeconomic development, for example, pig and poultry farms can be relocated to reduce the threat of high livestock density to the environment and humans (Bai et al., 2019; Yu et al., 2019). Third, reducing red meat consumption has been shown to be the most promising option for reducing N losses (Alexander et al., 2017; Willett et al., 2019), and studies have revealed that 12% of food per capita is wasted in restaurants or school cafeterias (XHNA, 2020; Xue et al., 2017). Currently, the government is emphasizing the importance of reducing food waste by implementing the "clean your plate" initiative, while the decision to change the diet structure to include more plant-derived food has not been widely discussed. Future research could focus on integrated assessment approaches using a new "environmental footprint series" and an integrated "FNF-environment-economy" evaluation system, addressing the trade-offs of changing food consumption patterns and the inherent complexities of environmental policy decision-making.

4. Conclusions

We studied the spatiotemporal dynamics of the FNF and its driving forces in different periods of the food production and consumption system at the city scale on the QTP for 1998–2018. We found that the FNF of the QTP increased from 540.97 to 745.84 Gg from 1998 to 2018, and animal production and crop production were identified as the main sources. The per capita FNF of the QTP increased from 24.94 kg N cap^{-1} in 1998 to 27.69 kg N cap^{-1} in 2018. The spatial boundaries of hot spots (northwest and central) and cold spots (southeast and north-central) zones were obvious, and spatial heterogeneity was significant. Changes in dietary patterns (more animal-derived food) due to economic development and urbanization were the main reasons for the increase in the FNF, while N consumption intensity had a negative impact. Economic development and FNF between the northwestern and central regions gradually became strongly decoupled from 1998 to 2018, indicating that the task of reducing the FNF became increasingly important in the process of economic development. Combining coordinated reduction of regional FNF values with differential reduction in cities, reducing red meat consumption and increasing the reuse of N between the three subsystems can reduce the FNF and benefit the environment. Insights are provided for policy-makers on the FNF of food production and consumption system and driving forces at the regional and city scales on the QTP.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the basic data for quantifying the FNF are available at the websites (http://www.epschinadata.com/auth/platform.html?sid=549E624432945773891F667C9CCBB941_ipv422908441 and https://data.stats.gov.cn/english/easyquery.htm?cn=E0103). Supplementary data associated with this article will be archived in a general repository.

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