LETTER

Nutrient-extended input−output (NutrIO) method for the food nitrogen footprint

Azusa Oita1,2,*, Kiwamu Katagiri1, Tetsuya Eguchi1, Ryoko Morioka1, Junko Shindo3,4, Kentaro Hayashi1,6, and Kazuyo Matsubae1

1 Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, 3-1-3, Kannondai, Tsukuba 305-8604, Japan
2 Research Center for Agricultural Information Technology, National Agriculture and Food Research Organization, 2-14-1-B Nishishinbashī, Minato-ku, Tokyo 105-0003, Japan
3 Graduate School of Engineering, Tohoku University, 6-6 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan
4 Tohoku Agricultural Research Center, National Agriculture and Food Research Organization, 50 Harajukuminami, Arai, Fukushima, Fukushima 960-2156, Japan
5 Emeritus, University of Yamanashi, Takeda 4-4-37, Kofu, Yamanashi 400-8510, Japan
6 Research Institute for Humanity and Nature, 457-4, Motoyama, Kamigamo, Kita-ku, Kyoto 603-8047, Japan
7 Graduate School of Environmental Studies, Tohoku University, 468-1 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-0845, Japan
8 Present address: Environmental Restoration and Conservation Agency, Omiyacho 1310, Saiwai-ku, Kawasaki, Kanagawa 212-8554, Japan
* Author to whom any correspondence should be addressed.
E-mail: a.oita@affrc.go.jp

Keywords: nutrient use efficiency, supply chains, agro-food systems, material flow analysis, input−output analysis

Abstract

Agro-food systems require nutrient input from several sources to provide food products and food-related services. Many of the nutrients are lost to the environment during supply chains, potentially threatening human and ecosystem health. Countries therefore need to reduce their nutrient/nitrogen footprints. These footprints are importantly affected by links between sectors. However, existing assessments omit the links between sectors, especially between the agriculture, manufacturing, and energy sectors. We propose a novel approach called the nutrient-extended input−output (NutrIO) method to determine the nutrient footprint as a sum of direct and indirect inputs throughout the supply chains from different sources of nutrients. The NutrIO method is based on a nutrient-based material flow analysis linked to economic transactions. Applying this method, we estimated the nitrogen footprint of Japan in 2011 at 21.8 kg-N capita−1 yr−1: 9.7 kg-N capita−1 yr−1 sourced from new nitrogen for agriculture and fisheries, 7.0 kg-N capita−1 yr−1 from recycled nitrogen as organic fertilizers, and 5.1 kg-N capita−1 yr−1 from industrial nitrogen for chemical industries other than fertilizers. A further annexed 55.4 kg-N capita−1 yr−1 of unintended nitrogen input was sourced from fossil fuels for energy production. The nitrogen intensity of the wheat and barley cultivation sector, at 1.50 kg-N per thousand Japanese yen (JPY) production, was much higher than that of the 0.12 kg-N per thousand JPY production for the rice cultivation sector. Industrial nitrogen accounted for 2%–7% of the nitrogen footprint of each major food-related sector. The NutrIO nitrogen footprint sourced from new nitrogen for agriculture and fisheries, at 8.6 kg-N capita−1 yr−1 for domestic final products, is comparable to the food nitrogen footprint calculated by other methods, at 8.5–10.5 kg-N capita−1 yr−1. The NutrIO method provides quantitative insights for all stakeholders of food consumption and production to improve the nutrient use efficiencies of agro-food supply chains.

© 2021 The Author(s). Published by IOP Publishing Ltd
1. Introduction

Agro-food systems today are highly dependent on the input of nutrients, including nitrogen, phosphorus, and potassium. However, a large portion of these nutrients is lost to the environment. Excess nutrients in the environment can harm human and environmental health [1].

The nutrient use efficiencies of agro-food systems have been explored at different scales (e.g. [2–8]). Material flow analyses (MFA) have been employed with clear system boundaries to determine the flows of nutrients (e.g. [9–13]). The nutrient use efficiency of the whole agro-food supply chain (full-chain nutrient use efficiency) tends to decrease as the nutrient input increases to meet the demand for animal-based foods [14, 15]. Both consumption- and production-oriented measures are vital for improving the full-chain nutrient use efficiency [15, 16].

Pollution due to reactive nitrogen (all forms of nitrogen except for dinitrogen) has received considerable attention in recent policy dialogues [17]. Although the proposed planetary boundary of nitrogen, the industrial and intentional biological fixation of nitrogen, ranges between 62 and 82 Tg-N yr⁻¹, nitrogen fixation is currently estimated to be approximately 150 Tg-N yr⁻¹ (ca. 21 kg-N capita⁻¹ yr⁻¹) [18, 19]. Chemical fertilizers and biological nitrogen fixation (BNF) for agriculture account for 89% of the global intentional nitrogen fixation [20].

The recently introduced nitrogen footprint concept shows the effect of consumer food choices on nitrogen pollution [21, 22]. Two methods have been employed for detailed food nitrogen footprint analyses for Japan and China: the N-Calculator [23–30] and N-Input [31, 32]. The N-Calculator method quantifies ‘nitrogen lost to the environment’, and provides virtual nitrogen factors (VNFs) to indicate the indirect nitrogen loss per unit of nitrogen in food for each food category, assuming that the supply chain is limited to one country. The N-Input method examines the ‘input of newly fixed nitrogen’ for each food category: the nitrogen use efficiency during production in the target country and in the main trade partners of that country are taken into consideration in this method. The focus of the VNF and the N-Input approaches is on nitrogen for food and feed and not on nitrogen for non-fertilizer industrial products (hereafter referred to as ‘industrial nitrogen’). The N-Calculator method separately analyzes the nitrogen emissions of nitrogen oxides (NOₓ) due to energy production for housing, transportation, goods, and services. A simple supply chain is assumed for each food category, even though the chain tends to be long and complicated.

Environmentally-extended input–output (IO) analyses have been developed to investigate the environmental aspects of the entire supply chain across economic sectors by linking an IO table, a database for economic transactions, and data on environmental emissions or resource requirements [33]. These approaches have been applied to trace reactive nitrogen emissions (e.g. [34–36]) and phosphorus resource requirements (e.g. [15, 37]). The IO-based study by Oita et al [36] reported the nitrogen footprints of nations based on a world multi-region IO (MRIO) table and country-level emissions data rather than detailed MFA data. A detailed MFA linked to an IO table, an IO-MFA, is useful for tracing resource use through long and complicated supply chains of detailed economic sectors and has been applied to plastics and carbon [38, 39]. An early attempt toward such an IO-MFA for nitrogen explored the supply chains of three crops at a state level in the United States [40]. An IO-MFA based on anthropogenic nutrient flows in all economic sectors would provide the basis for a comprehensive tool to boost practices, adaption of technologies, and consumer choices for improving the full-chain nutrient use efficiency.

In this paper, we propose the nutrient-extended IO (NutrIO) approach, an IO-MFA based on anthropogenic nutrient input data that is the first to include all economic sectors, as a method to assess nutrient footprints. The applicability of the NutrIO approach was assessed by exploring the nitrogen footprint of Japan. A nitrogen extension of a Japanese IO table, a NutrIO table for nitrogen in Japan, was constructed as a database. Based on the developed NutrIO table, the nitrogen footprint of Japan was assessed with a focus on food. Here, the NutrIO nitrogen footprint is defined as the total intentional input of nitrogen for human consumption throughout the supply chains of all the economic sectors from five non-energy sources: chemical fertilizers, organic fertilizers, BNF, wild-caught fish and seafood, and industrial nitrogen. The unintentional input of nitrogen sourced from fossil fuels (hereafter referred as ‘fossil fuel nitrogen’) for energy production was annexed since most of it is denitrified by the addition of ammonia and energy. The features of the NutrIO method were examined from the perspective of the factors that affect the analysis of the nitrogen flows along the supply chains. The aspects of the method to complement the existing methods and to contribute to the development of a comprehensive view of nutrient flows were then discussed.

2. Data and methods

The NutrIO approach employs anthropogenic nutrient input data and an IO table of a target area from the municipality level to the global level. The nutrient input data are provided as physical quantities based on nutrient-based material flows. The input data are then allocated to the economic sectors of the IO table in proportion to the relevant physical output of the sectors. The following subsections explain the
2.1. The material flow analysis
A nitrogen-based material flow was determined with a focus on the domestic nitrogen input to industrial activities (see figure S1 and table S1 in the supplementary material, available online at stacks.iop.org/ERL/16/115010/mmedia). Nitrogen input here only refers to the reactive nitrogen input and excludes dinitrogen. The main nitrogen input data were the national total nitrogen applied for crop cultivation as chemical and organic fertilizers, according to the 2011 National Greenhouse Gas Inventory Report [41]. The input of newly fixed nitrogen is ultimately equivalent to the nitrogen loss to the environment, following the N-Input method for the nitrogen footprint [31, 32]. Here, we consider the input of nitrogen, including recycled nitrogen from organic fertilizers, as the nitrogen footprint, to be consistent with the national inventory report [41].

The nitrogen input for agricultural production (B2–B5 in figure S1) was determined for 114 crop categories (table S2). The 2011 data for crop production and harvested area at a prefectural level [42] and the recommended rate of fertilizer application for the most typical cultivation method for each crop category in each prefecture [43] were used to provide the weight for allocating the national total chemical fertilizer nitrogen input [41] for each crop. The weight of the chemical fertilizer nitrogen input to each crop category in each of the 47 prefectures of Japan was first calculated by multiplying the recommended chemical nitrogen fertilizer application per unit area by the harvested area. Similarly, the weights of the nitrogen inputs from organic fertilizer and BNF were calculated by multiplying the applied nitrogen and BNF per unit area [31, 41], respectively, by the harvested area for each crop [42]. The sum of each type of nitrogen input in each prefecture yielded the weight for allocating the national total for each type of nitrogen input [41, 44] for each crop category. The nitrogen input from wild-caught seafood and seaweed (B1) was calculated by multiplying the nitrogen content of the domestic seafood/seaweed protein supply by the ratios of wild-caught seafood/seaweed to the total seafood/seaweed production [45, 46]. Here, seafood includes finfish, mollusks, crustaceans, and other aquatic animals, both inland and marine. For the industrial nitrogen input for chemical industry production (B6), seven first ammonia derivatives and the ammonia used directly in the chemical industry were considered, following Katagiri et al [47]. For the fossil fuel nitrogen input for energy production (B7), petroleum, coal, and natural gas were considered (data listed in tables S1 and S3). All fossil fuel nitrogen was assumed to be treated as exhaust gas under the waste management section (L1, L5). The annual generation of recovered materials, which become nitrogen sources for the following years, was estimated using the physical quantities of materials [48] and the ratios of the nitrogen contents [49].

2.2. Construction of the NutrIO table
For a detailed analysis of agro-food products, a 126-sectored IO table for Japan in 2011 was developed based on the 108-sectored IO table and the basic sector classified data for 2011 (both with transactions valued at producers’ prices) by the Ministry of Internal Affairs and Communications (MIC) of Japan [50]. For the 126-sectored IO table, crop cultivation, livestock, and ‘feeds and organic fertilizer, not elsewhere classified’ were divided into 13, 6, and 2 detailed sectors, respectively. In the table developed, the harvested crops, live animals, and caught seafood are produced by the primary sectors of the economy: rice, ‘wheat, barley and the like’, ‘potatoes and sweet potatoes’, pulses, vegetables, fruits, sugar crops, crops for beverages, miscellaneous edible crops, ‘feed and forage crops’, ‘seeds and seedlings’, ‘flowers and plants’, miscellaneous inedible crops, dairy cattle farming, beef cattle, hogs, hen eggs, chickens, miscellaneous livestock, and fishery. Most raw food materials are sold as ingredients of processed products to the secondary sectors of the economy, including sectors of foods, beverage, feeds, and tobacco. Most of the processed products are then sold to the service sectors. The final consumers buy raw food materials from the primary industries and processed food products from the secondary industries or consume food provided by the service industries.

The NutrIO table for nitrogen was developed by allocating the detailed nitrogen input data to the corresponding IO sectors. In cases with more than two corresponding IO sectors, the ratios of the physical output of the sectors were used whenever possible. Using the ratios of seed to domestic production in the 2011 food balance sheet [45], some portions of other crop cultivation sectors were allocated to the ‘seed and seedlings’ sector. In the case of industrial nitrogen, each first ammonia derivative was allocated to corresponding sectors using the physical quantity per unit of output and the ratios of output of the derivative to each sector (see [51] for details). The fossil fuel nitrogen was allocated to all sectors based on the physical quantities used in each sector [34].

2.3. Calculating the nitrogen footprint of Japan
The developed NutrIO table for nitrogen provides three different types of information for the economic sectors: nitrogen demand factors, nitrogen intensities, and nitrogen footprints. The nitrogen demand factor of a sector is the ‘direct’ nitrogen input per ‘unit of economic production’, including only the input by the sector itself. The nitrogen intensity of a sector is the sum of the ‘direct and indirect’ nitrogen input per
‘unit of economic production’, including the input through the production of the raw materials, intermediate products, and the energy used by the direct and indirect suppliers of the sector as well as the sector’s own input. Therefore, the nitrogen intensity indicates how much nitrogen the sector uses throughout its supply chain per unit of economic production. The nitrogen footprint of a sector refers to the ‘direct and indirect’ nitrogen input for ‘total economic production’ in the sector, considering the expenditure of final consumers in each sector. The nitrogen footprint reveals the overall effect of the sector in terms of nitrogen input throughout the supply chains. When the expenditure by final consumers is the same, the nitrogen footprint of a sector with higher nitrogen intensity is higher than that of a sector with lower nitrogen intensity.

The NutriIO nitrogen footprint $F_j$ of industrial sector $j$ for nitrogen source $k = \{\text{chemical fertilizers, organic fertilizers, \(BFN\), wild-caught seafood, industrial nitrogen, and fossil fuel}\}$ is calculated as [52]

$$F_j^k = \sum_{i=1}^p q_i^k L_{ij} y_j,$$

where $q$ is the nitrogen demand factor (Gg-N direct nitrogen input per million Japanese yen (JPY) production), $L$ is the Leontief inverse, which computes the effects of all the direct and indirect links between industries (see Methods and SI 3.1 of [36] for more information on the IO analysis for the nitrogen footprint), $y$ is the consumption expenditure for final products (million JPY), sector $i$ is the sector of primary production, sector $j$ is the sector of final production, and $p = 126$ is the number of sectors. $L = (I - A)^{-1}$, where $I$ is an identity matrix and $A$ is an input coefficient matrix.

The nitrogen intensity of sector $j$ for nitrogen source $k$ is expressed as $\sum_{i=1}^p q_i^k L_{ij} y_j$ and can be decomposed as follows:

$$\sum_{i=1}^p q_i^k L_{ij} = \sum_{i=1}^p \left\{ q_i^k I_{ij} + q_i^k A_{ij} + q_i^k (A^2)_{ij} + \ldots + q_i^k (A^\infty)_{ij} \right\}.$$

The first term on the right-hand side of equation (2) shows the nitrogen input directly required for sector $j$ for production. The second term gives the nitrogen input required for the sectors of the direct (or tier 1) suppliers $i$ of sector $j$ for their production. The third term indicates the nitrogen input required for the sectors of the first indirect (or tier 2) suppliers $i$ of sector $j$ for their production. The nitrogen input required for the sectors of tier 3 to tier infinity suppliers $i$ of sector $j$ for their production are similarly expressed in the following terms. The economic intensity $\left( \sum_{i=1}^p L_{ij} \right)$ can be similarly decomposed.

The nitrogen footprint for the nitrogen source $k$ for the final domestic products was calculated as follows:

$$F_{\text{dom}}^k = \sum_{j=1}^p \sum_{i=1}^p q_i^k L_{ij} (I - \hat{m}_j) y_j,$$

where $m_i = tm_i/d_i$ is the imported ratio, $tm$ is the total imports, $d$ is the total domestic demand, and the symbol (·) diagonalizes a vector to a matrix. The imported part was calculated as

$$F_{\text{im}}^k = \sum_{j=1}^p F_j^k - F_{\text{dom}}^k.$$
of food transferred to the final product (not wasted) during food processing, $T_2$ is the ratio of food consumed (not wasted) at the consumer level, $r$ is the food item category, $s = \{\text{domestic}, \text{imported}\}$ is the target of the VNFs, and $u$ is the number of food item categories.

Because the N-Input method captures detailed trade relations, the food nitrogen footprint for Japan according to the N-Calculator with dVNFs, VNFs derived by the N-Input method calculation, was also calculated (table S5, [32]). The N-Calculator food nitrogen footprint with the dVNFs (for domestic food $F_{d, dom}$ and imported food $F_{d, im}$) was calculated as follows:

$$F_d = F_{d, dom} + F_{d, im} = \sum_{r=1}^{u} \sum_{s=1}^{u} \alpha_r \{ \delta_r V_d a + \delta_r (1 - D) \}$$

$$+ \sum_{r=1}^{u} \sum_{s=2}^{u} (1 - \alpha_r) \{ \delta_r V_d a + \delta_r (1 - D) \},$$

where $V_d$ is the dVNFs.

3. Results

3.1. Material flow analysis of nitrogen

The estimated nitrogen flows for Japan in 2011 illustrated that the total input to agricultural sectors was 523 Gg-N yr$^{-1}$ (55%) from newly fixed nitrogen sources (chemical fertilizers and BNF) and 430 Gg-N yr$^{-1}$ (45%) from recovered materials (figure 1). The nitrogen input to the fishery sector was 102 Gg-N yr$^{-1}$ (100 Gg-N yr$^{-1}$ from seafood and 2 Gg-N yr$^{-1}$ from seaweed), accounting for one-ninth of the agricultural sectors. The 754 Gg-N yr$^{-1}$ input of industrial nitrogen was notable, as it was four-fifths of the agricultural sectors. The input of fossil fuel nitrogen was on the order of 104 Gg-N yr$^{-1}$, which is approximately 13–100 times higher than the intentional input from other nitrogen sources. The agricultural and industrial nitrogen inputs interact with each other during industrial activities. Since this analysis was focused on nitrogen inputs to industrial activities, all intended inputs were considered as nitrogen directly or indirectly used for human consumption, equivalent to the nitrogen footprint (2774 Gg-N yr$^{-1}$ or 21.8 kg-N capita$^{-1}$ yr$^{-1}$).

3.2. NutriIO approach to the nitrogen footprint

3.2.1. Nitrogen input per unit of production

The nitrogen demand factors based on the NutriIO table for Japan in 2011 revealed that sectors related to crop cultivation, fisheries, synthetic fibers, synthetic resin, electricity, and coal and steel products required high direct nitrogen input per unit of economic production (figure S2). The calculated nitrogen intensities demonstrated that, including nitrogen input through feed and forage, the livestock sectors required high indirect nitrogen input per unit of economic production throughout the supply chains, in addition to the above-listed sectors with high nitrogen demand factors (figure 2 and table S6, available online at stacks.iop.org/ERL/16/115010/mmedia). The agricultural sectors tended to have a higher agricultural nitrogen input and lower industrial and fossil fuel nitrogen inputs throughout their supply chains (figure 2 and table S6). The sectors of wheat and barley, feed and forage, pulses (mainly soybean), crops for beverages (mainly tea), and sugar crops were the highest for both the nitrogen demand factors and nitrogen intensities (figures S2 and 2). A comparison of the nitrogen intensities (in kg-N per thousand JPY production) revealed that the wheat and barley sector required much more nitrogen input per production (1.50 from non-energy sources and 0.07 from energy sources) than the rice sector (0.12, 0.01) throughout the supply chains (figure 2). Similarly, the sectors of dairy cattle farming (non-energy 0.28, energy 0.02) and beef cattle (0.23, 0.02) required even more nitrogen input per production than the sectors of chicken (0.08, 0.02), hen egg (0.08, 0.02), and hog (0.07, 0.03) (figure 2(a) and table S6).

In terms of the nitrogen intensities of secondary industries and service industries (in kg-N per thousand JPY production), the sectors of foods (0.06 from non-energy sources and 0.02 from energy sources), beverages (0.03, 0.02), and eating and drinking services (0.02, 0.02) required more non-energy nitrogen input than energy nitrogen input for production throughout their supply chains (table S6). In the case of the eating and drinking services sector, while no direct non-energy nitrogen input was needed for production (the rightmost half-circles showing nitrogen inputs in figure 3), a considerable amount of non-energy nitrogen, in g-N per million JPY production, was required along the supply chains: 2900 through the direct (tier 1) suppliers, 6731 through the first indirect (tier 2) suppliers, and another 6617 through third or higher tier suppliers (other half-circles in figure 3). These nitrogen inputs to the supply chains did not correlate with the economic inputs to the supply chains, which tended to decrease for higher-tier suppliers (figure 3). The NutriIO approach links all of these otherwise invisible or unquantifiable nitrogen inputs to the supply chains.

3.2.2. NutriIO nitrogen footprint

The estimated NutriIO nitrogen footprints reflect consumption expenditures on sectors, in addition to their nitrogen input per unit of economic production (figure 4). Among the food-related sectors, foods (food manufacturing, 1185 Gg-N yr$^{-1}$ or 9.3 kg-N capita$^{-1}$ yr$^{-1}$) and eating and drinking services (401 Gg-N yr$^{-1}$) had the highest nitrogen footprints because more food materials were purchased as processed food products or served dishes than raw materials at the current time. In addition to agricultural
nitrogen, industrial nitrogen accounted for a small but not insignificant part of the nitrogen footprints of food-related sectors, such as foods (3.1%), eating and drinking services (5.5%), vegetables (2.1%), beverages (7.2%), fruits (3.4%), and fisheries (2.2%) (figure 4(a)). Furthermore, agricultural and fishery nitrogen also contributed to the nitrogen footprints of sectors with no apparent link to agro-food systems, for example, 11.5% for the footprint of the passenger motor car sector and 2.8% for final chemical products (figure 4(a)).

The per-capita NutriIO nitrogen footprint was estimated at 21.8 kg-N capita\(^{-1}\) yr\(^{-1}\) (6.7 kg-N capita\(^{-1}\) yr\(^{-1}\) from chemical fertilizers, organic fertilizers 7.0, BNF 2.0, wild-caught seafood 1.0, and industrial nitrogen 5.1), with the consumption of domestic final products accounting for 19.2 kg-N capita\(^{-1}\) yr\(^{-1}\) (6.0 kg-N capita\(^{-1}\) yr\(^{-1}\) from chemical fertilizers, organic fertilizers 6.3, BNF 1.7, wild-caught seafood 0.9, and industrial nitrogen 4.3). As an annexed part, the fossil fuel nitrogen input was estimated at 55.4 kg-N capita\(^{-1}\) yr\(^{-1}\) (52.4 kg-N capita\(^{-1}\) yr\(^{-1}\) for domestic products).

4. Discussion

4.1. Considering nitrogen flows along supply chains

The NutriIO approach traces nitrogen input throughout supply chains by linking nitrogen input to economic transactions (equations (1) and (2) and figure 3). The links are developed through the nitrogen intensities of the sectors, based on the ratios of nitrogen input to domestic production for each sector (in gross economic input, which equals the gross economic output). These nitrogen intensities indicate the effects of unit consumption expenditure on the direct and indirect nitrogen inputs. The nitrogen intensities are affected by product prices. The products with lower market prices, such as domestically-grown edible crops for feed and imported feed and forages, require more crops as ingredients per economic production, which equates to a higher nitrogen input for crop cultivation and higher nitrogen intensities (see section 4.2 for discussion on imported final products). Because edible crop sectors are not separated for food and feed, the indirect nitro-
Figure 2. Nitrogen intensities of the economic sectors. The 20 sectors with the highest nitrogen intensities sourced from non-energy (a) and all (b) nitrogen sources. The nitrogen intensities: the direct and indirect nitrogen input (kg-N) per thousand Japanese yen (JPY) production. Non-energy nitrogen sources refer to all nitrogen sources other than fossil fuel nitrogen. Abbreviations: 'chem. prds. (exc. PBP)' refers to ‘chemical products (except petrochemical basic products)’.

To further examine the estimated nitrogen intensities (figure 2 and table S6), the nitrogen intensities based on economic production were converted to ‘nitrogen physical intensities’ based on production in physical quantities. Considering only agricultural and fishery nitrogen, sectors with high nitrogen intensities...
Figure 3. Nitrogen input along the supply chains of eating and drinking services. The eating and drinking services sector required the nitrogen input shown in the numbers in half-circles (g-N) throughout the supply chains for production of one million Japanese yen (JPY).

Figure 4. Non-energy N input and economic input by eating and drinking services.

The sectors with both the highest nitrogen intensities, in kg-N per thousand JPY production, and physical nitrogen intensities, in kg-N kg-food$^{-1}$, were sectors of wheat and barley (1.49 for nitrogen intensity, 0.04 for nitrogen physical intensity), feed and forage crops (1.20, 0.25), pulses (0.55, 0.35), crops for beverages (mainly tea, 0.48, 1.10), dairy cattle farming (0.28, 0.24), and beef cattle (0.23, 0.61), followed by fisheries (0.08, 0.20), and other livestock (0.06–0.07, 0.10–0.17) (figure 5). Sectors with both the highest nitrogen intensities and the highest ratios of subsidies to the gross economic inputs were wheat and barley (387.6%), pulses (131.7%), feed and forage crops (20.7%), sugar crops (37.3%), and miscellaneous edible crops (96.6%). Supposing that subsidies in the wheat and barley sector were 0%, the nitrogen intensity of the sector sourced from agriculture and fisheries would be reduced to 0.31 kg-N per thousand JPY production. The VNFs of the N-Calculator approach are also high for beef and relatively high for other livestock products, whereas the VNFs for milk and seafood were relatively low [23, 26, 27]. The high nitrogen physical intensities and the low VNFs for milk [23, 27] and seafood [24] suggest that because milk and seafood are rich in protein, a high nitrogen input is required, but the nitrogen loss on the way to the table is relatively low. Both sectors with high nitrogen intensities and sectors with high nitrogen physical intensities are important targets for improving nitrogen use efficiency. In sectors with high nitrogen intensities, providing support for better technological options, such as enhanced-efficiency fertilizers and feeds, as well as best management practices, would be effective in improving the nitrogen use efficiencies [58, 59]. For sectors with high nitrogen physical intensities, branding or labelling with reliable certifications of product qualities would also be effective [60, 61].

4.2. Comparison of food nitrogen footprint methods

The estimated NutrIO nitrogen footprint for Japan in 2011, at 21.8 kg-N capita$^{-1}$ yr$^{-1}$, is 39%–48% larger than the food nitrogen footprints estimated by the N-Calculator method with the VNFs [26] (15.6 kg-N capita$^{-1}$ yr$^{-1}$) and the N-Calculator method with the dVNFs [32] derived from the N-Input method (14.7 kg-N capita$^{-1}$ yr$^{-1}$) (figure 6). The relatively large differences between the NutrIO method and the other methods are partly because...
Figure 4. The NutrIO nitrogen footprints of the economic sectors. The 20 sectors with the highest nitrogen footprints sourced from non-energy (a) and all (b) nitrogen sources. Units are in Gigagram (Gg) nitrogen (N). Non-energy nitrogen sources refer to all nitrogen sources other than fossil fuel nitrogen. Abbreviations: ‘ready-made garments’ refers to ‘wearing apparel and miscellaneous ready-made textile products’, ‘chem. prods. (exc. pharma)’ refers to ‘chemical products (except medicaments)’, ‘s.’ refers to ‘services’, ‘w.’ refers to ‘welfare’ and ‘equip.’ refers to ‘equipment’.

The industrial nitrogen (5.1 kg-N capita$^{-1}$ yr$^{-1}$) is only considered in the NutrIO method. Recycled nitrogen (7.0 kg-N capita$^{-1}$ yr$^{-1}$ from organic fertilizers estimated by the NutrIO method) is not included in the N-Input method. In the N-Calculator method, all agricultural nitrogen recycled at each of the six/eight stages of production processes are subtracted from the nitrogen footprint, cancelling the recycled nitrogen input. In turn, the application of the NutrIO method in this study covers a
Figure 5. Comparison of nitrogen intensities, nitrogen physical intensities, and ratios of subsidies to domestic production for the 20 economic sectors with the highest nitrogen intensities. Only agricultural and fishery nitrogen (N) sources were considered.

Figure 6. Comparison of per-capita food nitrogen (N) footprint for Japan in 2011 estimated by different methods (kg capita\(^{-1}\) yr\(^{-1}\)). The estimate of the NutrIO method includes agricultural, fishery, and industrial nitrogen. The estimate of the N-Calculator method with virtual N factors (VNFs) is based on the factors from Oita et al [26] and consumed N calculation from Shindo et al [32]. The estimate of the N-Calculator method using the N-Input method-derived VNFs (dVNFs) from Shindo et al [32] is similar to the estimate calculated by the N-Input method.

one-year time frame and does not subtract nitrogen recovered by waste management from nitrogen input in the previous years. Regarding this point, the current application of the NutrIO method overestimates the recycled nitrogen footprint, and further extension of the NutrIO table is needed to consider the detailed flows of recycled materials. The differences between using the VNFs and dVNFs are mainly due to how food and feed trade is considered. The VNF approach assumes that supply chains are limited to one country, whereas the dVNFs are derived from an in-depth analysis of bilateral food and feed trade.

Without considering industrial nitrogen or recycled nitrogen, the NutrIO nitrogen footprint was 9.7 kg-N capita\(^{-1}\) yr\(^{-1}\) (8.63 kg-N capita\(^{-1}\) yr\(^{-1}\).
for domestic final products). For the domestic final products, this estimate of the nitrogen footprint sourced from new nitrogen for agriculture and fisheries is comparable to the domestic part of the food nitrogen footprint calculated by the N-Calculator method with the dVNFs (8.5 kg-N capita\(^{-1}\) yr\(^{-1}\)) and slightly less than that using the N-Calculator method with the VNFs (10.5 kg-N capita\(^{-1}\) yr\(^{-1}\)). The N-Calculator method assumes a simple production process for each food item in a bottom-up approach to provide sensitivity to the detailed choices of consumers, whereas the NutrIO method and the N-Input method take a top-down approach to capture the big picture of nitrogen flows. As is the nature of a bottom-up approach, the double-counting or miscounting of the nitrogen flows in the agro-food supply chains is expected in the calculation of the VNFs of products, for example, the by-product meat from dairy cattle and vegetable oil [27, 62].

In the case of imported final products, the estimated NutrIO nitrogen footprint sourced from new nitrogen for agriculture and fisheries (1.04 kg-N capita\(^{-1}\) yr\(^{-1}\)) appeared to be much lower than the nitrogen footprints for imported food calculated by the N-Calculator method (5.1 kg-N capita\(^{-1}\) yr\(^{-1}\) with VNFs and 6.1 kg-N capita\(^{-1}\) yr\(^{-1}\) with dVNFs). In the current application of the NutrIO method, a single-country IO table is used owing to data availability (see section 4.3 for further discussion). Thus, the importing partner sectors are assumed to have the same nitrogen input per unit of economic production as the corresponding domestic sectors. In the case of Japan, on a nitrogen content basis, the self-sufficiencies of vegetal and animal (excluding seafood) products in 2011 were 36% and 73%, respectively [45]. On an economic basis, however, the average self-sufficiencies of the sectors of crop cultivation and foods (processed food products, including meat) in 2011 were 74% and 86%, respectively [50]. Since the prices of imported products tend to be cheaper for competition purposes than domestic products, and cheaper products imply higher nitrogen intensities (section 4.1), the imported food part of the NutrIO nitrogen footprint may be underestimated in this regard. In addition, the NutrIO nitrogen footprint for domestic final products includes nitrogen inputs through supply chains of production, including the usage of imported commodities as intermediate inputs. From the nitrogen use efficiency point of view, the direct nitrogen input per unit of nitrogen in main imported crop (wheat, maize, and soybean) and meat (bovine, pig, and poultry) products in major importing partners is between 0.3–1.0 times and 0.6–1.2 times that of those in Japan, respectively (supplementary table A1 of [31]), leading to an over-estimation in the NutrIO nitrogen footprint calculation in this study. The nitrogen footprint of imported food would be better estimated with detailed nitrogen input data on crop production in different regions of the countries and a world MRIO table with good resolution in agriculture.

The high NutrIO nitrogen footprint of the sector of foods (9.3 kg-N capita\(^{-1}\) yr\(^{-1}\)) indicates the need for detailed analysis of processed food products. In future work, the single sector of foods will be divided into the sectors of various products: meat, dairy, seafood, and crop-based products. An IO-MFA based analysis with detailed food sectors will reveal the effects of the use of nitrogen along the agro-food supply chains of different categories of foods in further detail. The quantitative insights for all stakeholders of food consumption and production will strengthen strategies for improving the full-chain nitrogen use efficiency. As the minimum nitrogen requirement for food, Wim de Vries et al [18] assumed an intake of 3 kg-N capita\(^{-1}\) yr\(^{-1}\) as protein (ca. 51 g-protein capita\(^{-1}\) d\(^{-1}\)), the current full-chain nitrogen use efficiency of 16.7%, and the ratio of agricultural fixation to the total agricultural nitrogen input of 48.5%. These assumptions estimate that a nitrogen fixation of 8.7 kg-N capita\(^{-1}\) yr\(^{-1}\), or 80 Tg-N yr\(^{-1}\), is required to feed the global population of 9 billion people. They argue that it can be reduced to 5.8 kg-N capita\(^{-1}\) yr\(^{-1}\) by improving the full-chain nitrogen use efficiency to 25%.

### 4.3. Toward integrated nutrient management

The NutrIO approach is the first footprint method to provide an integrated perspective of agricultural, industrial, and fossil fuel nitrogen (figures 2 and 4). When compared with the planetary boundaries (62–82 Tg-N yr\(^{-1}\), ca. 8.8–11.6 kg-N capita\(^{-1}\) yr\(^{-1}\) for the global population of 7.04 billion people in 2011), the newly fixed nitrogen part of the estimated NutrIO nitrogen footprint for Japan (14.8 kg-N capita\(^{-1}\) yr\(^{-1}\)) is 127%–168% of the Earth’s limit. This demonstrates the need to reduce the Japanese nitrogen footprint. To improve the full-chain nitrogen use efficiency, actions to reduce the loss of food and chemical materials, and choose more efficiently-produced products by the midstream and downstream suppliers and consumers are important in addition to actions through crop and livestock production-oriented measures [25, 26, 63–65]. From an industrial perspective, the recycling of fibers and the enhanced use of renewable energy sources would also be effective. By considering different nitrogen sources in the same framework, the NutrIO approach enables us to understand the big picture of nitrogen flows at the country level (or the level of the IO table used) and the interactions and contributions of different sectors and consumers for the nitrogen inputs of different sources. This framework can be extended to an integrated analysis of agriculture and manufacturing to deal with issues related to biofuels, plastics, and other resource management. Linking the evaluated nitrogen inputs to the flows of nitrogen loss in the next step will strengthen the NutrIO method.
Identifying the amounts and forms of nitrogen loss along the supply chains will provide the whole picture of economy-wide nitrogen flows and the type and magnitude of the contribution of each sector. The incorporation of different nitrogen sources in the IO-MFA based framework is relevant when using an IO table for detailed agricultural and manufacturing sectors. Thus, the national IO table with 19 sectors for crop cultivation and livestock was used in this study to focus on agro-food systems and nitrogen flows within Japan. If a world MRIO table with good resolution in agricultural and manufacturing sectors for all countries and corresponding nitrogen flow data become available, future work can extend the NutrIO approach to a global analysis and better incorporate the trade-related nitrogen footprints.

The nitrogen flows in Japan which remain poorly understood include those related to the combustion of fossil fuels at the national level. To date, there are no data for the Japanese national total quantities on the removal of NO\(_x\) by equipment and the addition of thermally produced NO\(_x\) formed from dinitrogen in the combustion air [49]. Hayashi et al has recently estimated the overall NO\(_x\) emissions from the combustion of fossil fuels in Japan at 755.9 Gg-N yr\(^{-1}\) or 5.9 kg-N capita\(^{-1}\) yr\(^{-1}\) in 2011 [49]. This represents 10.6% of the fossil fuel nitrogen input estimated in this study. Further analysis based on quantitative data on nitrogen input from fossil fuels is required.

The findings of this application of the NutrIO approach to the nitrogen footprint of Japan can serve as a basis for policies to improve the full-chain nitrogen use efficiency [66]. Moreover, a joint approach to nitrogen and phosphorus for the United Nations Sustainable Development Goals and climate change have stressed the benefits of an integrated management approach to science, policies, and practice [67]. The application of the NutrIO approach to other nutrients, such as phosphorus, based on the integrated MFA, would promote the development of a comprehensive framework for integrated nutrient management for sustainable development.

### 5. Conclusions

In this study, we proposed the NutrIO method for nutrient footprints based on a nutrient-based MFA linked to an IO table. A Japanese IO table was extended to develop the NutrIO table to represent all economic sectors for nitrogen flows using the 2011 data on agricultural, industrial, and fossil fuel nitrogen. The detailed IO-MFA for food-related sectors revealed interactions between the agriculture, fisheries, manufacturing, and services industries along complex agro-food systems. An in-depth assessment of nitrogen intensities related to agro-food supply chains in Japan uncovered the sensitivities of sectors to support for improving the nitrogen use efficiencies. A comparison with the other food nitrogen footprint methods confirmed that the accuracy of the NutrIO method is similar to that of other methods, but the NutrIO method is capable of investigating a wider scope of nitrogen sources and supply chain networks. The NutrIO approach, an extension of the nitrogen footprint, is well-suited as a tool for policymakers to develop a big picture of the economy-wide nitrogen flows and for secondary and higher tier producers, retailers, and shop owners to realize their potential roles to better manage all types of nitrogen. By connecting detailed data on the flows of various nutrients in the supply chains, the NutrIO approach opens up great opportunities for the development of an integrated nutrient management platform.

### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

### Acknowledgments

The authors thank Aurup Ratan Dhar and Farah Wirasenjaya for data collection on fossil fuels. This work was supported in part by JSPS KAKENHI Grant Numbers JP17H00794 and JP19K20496 and the Research Institute for Humanity and Nature Project Numbers 14200135 and 14200156.

### ORCID iDs

Azusa Oita [https://orcid.org/0000-0002-1876-2033](https://orcid.org/0000-0002-1876-2033)
Kiwamu Katagiri [https://orcid.org/0000-0002-2960-070X](https://orcid.org/0000-0002-2960-070X)
Tetsuya Eguchi [https://orcid.org/0000-0001-9016-5906](https://orcid.org/0000-0001-9016-5906)
Junko Shindo [https://orcid.org/0000-0002-6320-1980](https://orcid.org/0000-0002-6320-1980)
Kentarō Hayashi [https://orcid.org/0000-0002-2936-9544](https://orcid.org/0000-0002-2936-9544)
Kazuyo Matsubae [https://orcid.org/0000-0002-3816-3898](https://orcid.org/0000-0002-3816-3898)

### References

[1] Sutton M A et al 2013 Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution. Global Overview of Nutrient Management (Edinburgh: Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative) ([http://nora.nerc.ac.uk/id/eprint/3007001/1/N508700BK.pdf](http://nora.nerc.ac.uk/id/eprint/3007001/1/N508700BK.pdf))

[2] Gerber P, Uwizeye A, Schulte R, Opio C. and De Boer I 2014 Nutrient use efficiency: a valuable approach to benchmark the sustainability of nutrient use in global livestock production? Cur. Opin. Environ. Sustain. 9–10 122–30
[3] Uwizeye A et al 2020 Nitrogen emissions along global livestock supply chains Nat. Food 1 437–46
[4] Bai Z, Ma L, Jin S, Ma W, Velthof G L, Oenema O, Liu L, Chadwick D and Zhang F 2016 Nitrogen, phosphorus, and potassium flows through the manure management chain in China Environ. Sci. Technol. 50 13409–18
[5] Coppins J, Meers E, Boon N, Buysse J and Vlaeminck S E 2016 Follow the N and P road: high-resolution nutrient flow analysis of the Flanders region as precursor for sustainable resource management Resour. Conserv. Recycl. 115 9–21
[6] Wang H J, Huang B, Shi X Z, Darilek J L, Yu D S, Sun W X, Zhao Y C, Chang Q and Oborn I 2008 Major nutrient balances in small-scale vegetable farming systems in peri-urban areas in China Nutr. Cycling Agroecosyst. 81 203–18
[7] Quemada M et al 2020 Exploring nitrogen indicators of farm performance among farm types across several European case studies Agric. Syst. 177 102689
[8] Grönnman K, Ypyä J, Virtanen Y, Kurppa S, Soukka R, Seuri P, Finér A and Linnanen L 2016 Nitrient footprint as a tool to evaluate the nutrient balance of a food chain J. Cleaner Prod. 112 2429–40
[9] Ma L, Wang F, Zhang W, Ma W, Velthof G, Qin W, Oenema O and Zhang F 2013 Environmental assessment of management options for nutrient flows in the food chain in China Environ. Sci. Technol. 47 7260–8
[10] Bellarby J, Surridge B W J, Haygarth P M, Liu K, Siciliano G, Smith L, Rahn C and Meng F 2018 The stocks and flows of nitrogen, phosphorus and potassium across a 30-year time series for agriculture in Huantai county, China Sci. Total Environ. 619–620 606–20
[11] Shindo J, Okamoto K and Kawashima H 2003 A model-based estimation of nitrogen flow in the food production–supply system and its environmental effects in East Asia Ecol. Modell. 169 197–212
[12] Van Dijk K C, Lesschen J P and Oenema O 2016 Phosphorus flows and balances of the European Union Member States Sci. Total Environ. 542 1078–93
[13] Lassalleta L, Billen G, Grizzetti B, Garnier J, Leach A M and Galloway J N 2014 Food and feed trade as a driver in the global nitrogen cycle: 50-year trends Biogeochemistry 118 225–41
[14] Erisman J W, Leach A, Bleeker A, Atwell B, Cattaneo L and Galloway J N 2018 An integrated approach to a nitrogen use efficiency (NUE) indicator for the food production–supply system and its environmental effects in Asia’s giants: China, India, and Japan Resour. Conserv. Recycl. 157 104752
[15] Mori A, Eguchi S, Higuchi M and Shibata H 2020 Nitrogen loss to the environment due to various nitrogen-use efficiencies during milk and beef production in Japan Environ. Res. Lett. 15 125007
[16] Hirono Y, Sano T and Eguchi S 2021 Changes in the nitrogen footprint of green tea consumption in Japan from 1965 to 2016 Environ. Sci. Pollut. Res. 28 49356–48
[17] Guo M, Chen X, Bai Z, Jiang R, Galloway J N, Leach A M, Cattaneo L R, Oenema O, Ma L and Zhang F 2017 How China’s nitrogen footprint of food has changed from 1961 to 2010 Environ. Res. Lett. 12 104006
[18] Zhang Y, Liu Y, Shibata H, Gu B and Wang Y 2018 Virtual nitrogen factors and nitrogen footprints associated with nitrogen loss and food wastage of China’s main food crops Environ. Res. Lett. 13 014017
[19] Shindo J and Yanagawa A 2017 Top-down approach to estimating the nitrogen footprint of food in Japan Ecol. Indic. 78 502–11
[20] Shindo J, Oita A, Hayashi K and Shibata H 2021 Comparison of food supply system in China and Japan based on food nitrogen footprints estimated by a top-down method Environ. Res. Lett. 16 045003
[21] Miller R E and Blair P D 2009 Input-Output Analysis: Foundations and Extensions Second Edition (Cambridge: Cambridge University Press)
[22] Nansai K, Kondo Y, Kagawa S, Suh S, Nakaïma K, Inaba R and Töhnö S 2012 Estimates of embodied global energy and air-emission intensities of Japanese products for building a Japanese input–output life cycle assessment database with a global system boundary Environ. Sci. Technol. 46 9146–54
[23] Kanemoto K, Moran D, Lenzen M and Geschke A 2014 International trade undermines national emission reduction targets: new evidence from air pollution Glob. Environ. Change 24 52–59
[24] Oita A, Malak A, Kanemoto K, Geschke A, Nishijima S and Lenzen M 2016 Substantial nitrogen pollution embedded in international trade Nat. Geosci. 9 111–5
[25] Yang H, Liu Y, Liu J, Meng J, Hu X and Töhnö S 2019 Improving the Irrebalanced Global Supply Chain of Phosphorus Fertilizers Earth’s Future 7 638–51
[26] Nakamura S, Nakajima K, Yosihizawa Y, Matsubae-Yokoyama K and Nagasaka T 2009 Analyzing polyvinyl chloride in Japan with the waste input–output material flow analysis model J. Ind. Ecol. 13 706–17
[27] Ohno H, Sato H and Fukushima Y 2018 Configuration of material contained in our society: a WIO-MFA-based approach for Japan J. Ind. Ecol. 22 327–38
[28] Singh S, Compton J E, Hawkins T R, Sobota D J and Cooter E J 2017 A nitrogen physical input–output table (PIOT) model for Illinois Ecol. Modell. 360 194–203
[29] Greenhouse Gas Inventory Office of Japan (GIO) and Ministry of the Environment, Japan (MOE) (eds) 2020 National greenhouse gas inventory report of JAPAN 2020 (Japan: Center for Global Environmental Research, National...
[42] Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) 2012 Statistical survey on crops (in Japanese) (available at: www.maff.go.jp/j/tokei/kouhyou/sakumotu/) (Accessed 7 February 2020)

[43] National Agriculture and Food Research Organization (NARO) 2012 Database of fertilizer recommendations (in Japanese) (www.naro.affrc.go.jp/collab/program/laboratory/carc/039854.html) (Accessed 25 October 2020)

[44] Organisation for Economic Cooperation and Development (OECD) OECD stat (available at: http://stats.oecd.org/) (Accessed 17 March)

[45] FAO 2017 Food balance sheet in FAOSTAT database on agriculture (available at: www.fao.org/faostat/en/#data/FBS1) (Accessed 18 May 2020)

[46] FAO 2019. Fishery and aquaculture statistics. global production by production source 1950–2017 (FishstatJ) v4.00.9 (Rome: FAO Fisheries and Aquaculture Department) Updated 2019 (available at: www.fao.org/fishery/statistics/software/fishstatj/en) (Accessed 29 March 2020)

[47] Katagiri K, Mizoguchi M, Matsubae K and Nagasaka T 2018 Material flow analysis of nitrogen around industries in Japan from 2005 to 2015 J. Life Cycle Assess. Japan 14 319–31 (in Japanese with English summary)

[48] Ministry of the Environment of Japan (MOE) 2014 Environment and the challenge to further reduce nitrogen waste Environ. Pollut. 286 117559

[49] Hayashi K, Shibata H, Oita A, Nishina K, Ito A, Katagiri K, Shindo J and Winiwarter W 2021 Nitrogen budgets in Japan from 2000 to 2015: decreasing trend of nitrogen loss to the environment and the challenge to further reduce nitrogen waste Environ. Res. Lett. under review

[52] Peters G P 2008 From production-based to consumption-based national emission inventories Ecol. Econ. 65 13–23

[53] UN Comtrade 2012 United Nations commodity trade statistics database (available at: http://comtrade.un.org/db/) (Accessed 8 December 2020)

[54] International Monetary Fund (IMF) 2012 IMF exchange rate report wizard (available at: www.imf.org/external/np/exr/er/nr/March2020/Pages/Exhibit.aspx) (Accessed 9 December 2020)

[55] Suh S et al 2004 System boundary selection in life-cycle inventories using hybrid approaches Environ. Sci. Technol. 38 657–64

[56] Yamashita K 2018 Japan’s agricultural policy: escaping the ancien régime Econmic Challenges Facing Japan’s Regional Areas ed T Hatta (Singapore: Palgrave Pivot) pp 19–27

[57] MAFF 2020 Farmers support projects Monthly report for rice January issue 43–50 (in Japanese) (available at: www.maff.go.jp/j/seisan/keikaku/soukatu/mr.html) (Accessed 16 December 2020)

[58] Veltman K et al 2018 A quantitative assessment of Beneficial Management Practices to reduce carbon and reactive nitrogen footprints and phosphorus losses on dairy farms in the US Great Lakes region Agric. Syst. 166 10–25

[59] Kanter D R and Searchinger T D 2018 A technology-forcing approach to reduce nitrogen pollution Nat. Sustain. 1 544–52

[60] Kanter D R, Chodos O, Nordland O, Rutigliano M and Winiwarter W 2020 Gaps and opportunities in nitrogen pollution policies around the world Nat. Sustain. 3 956–63

[61] Vittersø G and Tangeland T 2015 The role of consumers in transitions towards sustainable food consumption. The case of organic food in Norway J. Cleaner Prod. 92 91–99

[62] Hayashi K, Oita A and Nishina K 2020 Concealed nitrogen footprint in protein-free foods; an empirical example using oil palm products Environ. Res. Lett. 15 035006

[63] Uwizeye A, Gerber P J, Schulte R P O and De Boer I J M 2016 A comprehensive framework to assess the sustainability of nutrient use in global livestock supply chains J. Cleaner Prod. 129 647–58

[64] Gu B, Chang J, Min Y, Ge Y, Zhu Q, Galloway J N and Peng C 2013 The role of industrial nitrogen in the global nitrogen biogeochemical cycle Sci. Rep. 3 2579

[65] Oita A, Nagano I and Matsuda H 2018 Food nitrogen footprint reductions related to a balanced Japanese diet Ambio 47 318–26

[66] Kanter D R, Bartolini F, Kugelberg S, Leip A, Oenema O and Uwizeye A 2020 Nitrogen pollution policy beyond the farm Nat. Food 1 27–32

[67] Kanter D R and Brownlie W J 2019 Joint nitrogen and phosphorus management for sustainable development and climate goals Environ. Sci. Policy 92 1–8