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journal or publication title	Environmental Research Letters
volume	13
number	124027
page range	1-12
year	2018-12-17
URL	http://hdl.handle.net/10097/00125589

doi: 10.1088/1748-9326/aaec63

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Article *in* Environmental Research Letters · October 2018

DOI: 10.1088/1748-9326/aaec63

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IOP Publishing Environ. Res. Lett. 13 (2018) 124027 https://doi.org/10.1088/1748-9326/aaec63

Environmental Research Letters

RECEIVED
12 July 2018

REVISED
26 October 2018

ACCEPTED FOR PUBLICATION
29 October 2018

PUBLISHED
17 December 2018

LETTER

Reducing nitrogen footprints of consumer-level food loss and protein overconsumption in Japan, considering gender and age differences

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Keywords: food waste, net supply, consumption, optimum protein diet, body mass index

Supplementary material for this article is available online

Abstract

The agro-food system perturbs the nitrogen (N) cycle through its N loads to the environment. The present study focused on food-related consumer-level N loads in Japan from 1961–2015, with a particular focus on food loss and protein overconsumption. Gender and age differences were also analyzed. Consumer-level food loss was negligible until the 1970s, when it began to slowly increase, accounting for an average of 13.2% of the annual net supply during 2011–2015. Japanese people have consumed more protein than the World Health Organization's recommended intake since 1961. Protein overconsumption increased until the mid-1990s, when it began to decrease, but it still accounted for an average of 32.3% of total annual protein consumption during 2011–2015. The national mean of food N footprints (total release of reactive N into the environment related to individual food consumption) in the same period was 18.3 kg N capita^{-1} yr^{-1}, of which food loss accounted for 4% and protein overconsumption for 37%. The food N footprint of each sex/age class varied from 16.0–21.6 kg N capita^{-1} yr^{-1}, males had a larger footprint in each age class. Seven scenarios to reduce the N footprints were evaluated; a scenario that included halving protein overconsumption, livestock meat consumption, and food loss was estimated to reduce the food N footprint by 31%. Thus, there is room for reducing consumer-induced N loads to the environment. Campaigns aimed at boosting healthy and environmentally friendly diets should consider the diverse consumption patterns of different sex and age classes.

1. Introduction

Global anthropogenic creation of reactive nitrogen (Nr; all nitrogen [N] species except inert molecular N_2) increased from 15 Tg (10^{12} g) N yr^{-1} in 1860 to 156 Tg N yr^{-1} in 1995 to 187 Tg N yr^{-1} in 2005 (Galloway *et al* 2008). The Haber–Bosch process, the industrial process that fixes N_2 as ammonia, has largely contributed to Nr creation since its development in the early 20th century (Erisman *et al* 2018). Most fixed N is used for food production as fertilizer, because N is required for protein and nucleic acid formation. At present, world food production is dependent on the application of mineral fertilizers (Erisman *et al* 2008, Bouwman *et al* 2017), but the agro-food system has a low N use efficiency (NUE). The world cropping systems' NUE has remained at approximately 47% over the last three decades (Lassaletta *et al* 2014a), and N recovery in animal products ranged only from 5% to 20% in 2000 (Bouwman *et al* 2013, Leip *et al* 2014). Emissions of Nr to air, soil, and water from the agro-food system (Nr loss) to the environment can have harmful impacts on environmental quality, greenhouse gas balance, and ecosystems (Sutton *et al* 2011).

Therefore, improving NUE in the agro-food system by considering the full production chain is necessary for the sustainable use of N (Lassaletta *et al* 2016, Erisman *et al* 2018).

Consumers located at the end of the agro-food system are key players in human-induced N loads to the environment. Changes in food consumption alter food production and supply through effects on demand (Westhoek *et al* 2014, Lamb *et al* 2016). Economic growth generally results in a transition towards a diet higher in animal protein (Shindo *et al* 2006, Tilman and Clark 2014, Lassaletta *et al* 2014b, Bai *et al* 2018). A preference for livestock products increases Nr loss to the environment because of the low NUE of livestock production (Smil 2002).

Population growth also increases consumer-driven N flow. Consumer-level food loss through food that is supplied but uneaten contributes to N loads to the environment (Grizzetti *et al* 2013, Vanham *et al* 2015, Zhang *et al* 2018). Protein overconsumption also contributes to increased N loads through the production and supply of overconsumed protein (i.e. protein that is nutritionally unnecessary). Changes in population and age structure also affect food consumption qualitatively and quantitatively. Socio-economic development contributes to declines in birth rates and increases in longevity, which lead to a shrinking share of children and a growing share of older persons (population aging, UN 2017). Japanese experiences with changes in consumer-level N flow might provide insight to the future of other countries with aging populations because Japan is home to the world's oldest population (UN 2017). The traditional Japanese diet is characterized by high consumption of soybean, fish, seaweed, vegetables, fruits, and green tea; this diet contributes to reduced risk of cardiovascular disease and diabetes (Shimazu *et al* 2007) and thereby to longevity (Yamamoto *et al* 2016). However, Japanese consumers now eat more meat and less cereal (Oita *et al* 2018), especially those in their 20 s and younger (Shibata *et al* 2014). Japan depends on food and animal feed imports; in 2015, it was only 39% self-sufficient in food and 28% in animal feed (MAFF 2017). Imported food and feed lead to environmental Nr losses in the exporting countries (Shibata *et al* 2014, Oita *et al* 2016a). Japan also has spatially intensified Nr losses because of its dense population in some areas, thereby intensifying N loads per unit area in those areas (Liang *et al* 2018).

Although some studies have analyzed the evolution of human demand and the effect of dietary changes on the N cycle (e.g. Bodirsky *et al* 2014, Billen *et al* 2015, Davis and D'Odorico 2015, Lassaletta *et al* 2016), no study has analyzed the effect of consumer-level food loss and protein overconsumption in the long term. The aim of the present study was to analyze the net supply and consumption of N associated with consumers in Japan from 1961 to 2015 (figure 1). Consumer-level food loss is the difference between net supply and consumption, and overconsumption is the difference between consumption and recommended intake of the World Health Organization (WHO). The relationship between consumption and body composition was of interest because long-term overconsumption could have health effects and further affect food consumption via possible changes in diet. Differences in consumption patterns were also evaluated by gender and age. To quantify the N loads to the environment resulting from consumer-level food loss and protein overconsumption, corresponding food N footprints were calculated for the period from 2011–2015. Nitrogen footprints quantify the total Nr released into the environment in direct and indirect relation to individual consumption (Leach *et al* 2012). Finally, the potential for the reduction of food N footprints was evaluated under several reduction scenarios.

2. Data and methods

2.1. Net supply and consumption

The national means of per-capita daily net supply of protein from 1961–2015 in Japan were obtained from agricultural statistics (MAFF 2017; supplementary I is available online at stacks.iop.org/ERL/13/124027/mmedia), where the net supply corresponds to the edible part of foods estimated from the gross supply (figure 1). Food categories in the original data were reclassified into livestock products, fish products, cereals, and other plant-based foods (others). The per-capita net supply of protein was converted to N by assuming a 16% mass fraction of N in protein (FAO 2003). The per-capita daily value of net supply as N was converted to an annual value, and the national total annual net supply as N was then calculated by multiplying the annual net N supply by the total population in each year (MIAC 2017).

The national means of per-capita daily consumption of protein from 1961–2015 in Japan were obtained from the national nutrition survey (MHW 1968, 1982, 1992, 2000, MHLW 2017; supplementary II). The original data include total protein consumption and animal or plant protein consumption. The per-capita annual consumption of protein as N and the national total of annual consumption as N were calculated as for net supply. Data on per-capita daily consumption of energy and fats were also collected. Energy conversion factors of 4 kcal g^{-1} for protein and 9 kcal g^{-1} for fats (FAO 2003) were used to separate protein and fat intake from total energy intake. For 1995 and beyond, data for sex and age class (every year for juveniles and every 5–10 years for adults) were obtained from Japan's annual national nutrition survey (MHW 1997–1999a, 2000, MHLW 2001–2004a, 2005–2009a, 2010–2012a, 2013, 2014a, 2015–2017). The per-capita annual protein consumption as N from 1995–2015 for each sex and age class

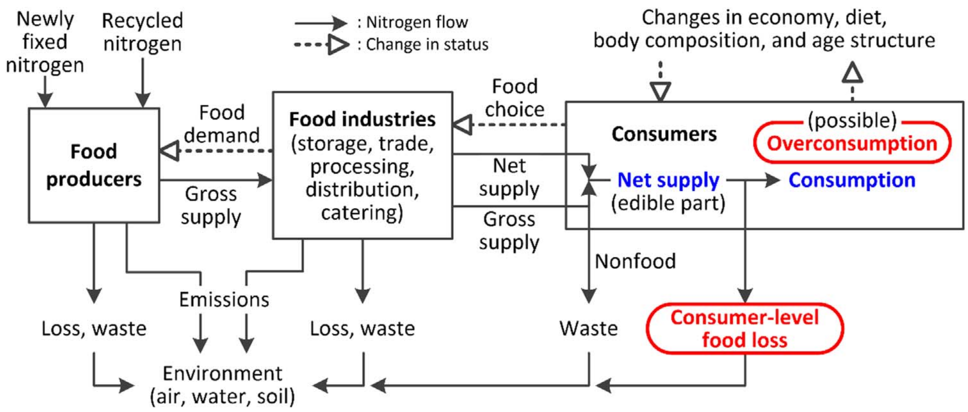

Figure 1. Nitrogen (N) flow in the agro-food system. Solid lines denote N flows and dashed lines factors affecting N flows. Blue words denote the target N flows and red words denote the reduction targets of consumer-induced N loads.

(juveniles, 0–17 years; adults, 18–64 years; elderly, ⩾65 years) was calculated, where the population of each sex and age class in 1 year intervals (MIAC 2017) was used as the weight for the calculations of the reclassified age classes.

Recommended values for daily protein intake per unit body weight were obtained from WHO (e.g. 0.83 g protein kg^{-1} body day^{-1} for adults ⩾18 years, WHO 2007). Japanese guidelines for protein and energy intake were collected for comparison (MHW 1999b, MHLW 2004b, 2009b, 2014b). The Japanese guidelines for recommended daily intake (e.g. 60 g protein $capita^{-1}$ day^{-1}) were revised in 1959 and 1969, and then at 5 year intervals. Using the calculated mean body weights (see section 2.3) and the population of each sex/age class, the national mean per-capita recommended daily intake of protein as N was calculated. The national total protein N intake corresponding to the WHO guideline was also calculated, as were the national values for each sex/age class (0–17, 18–64, ⩾65 years). National sex/age class values were also calculated for energy and fat intake.

2.2. Consumer-level food loss and protein overconsumption

Annual national total and per-capita values of consumer-level food N loss and protein N overconsumption were calculated. Consumer-level food N loss was estimated by subtracting consumption from net supply (figure 1), and the national mean food loss ratio was obtained by dividing the estimated food loss by the net supply. Protein overconsumption as N was estimated by subtracting the recommended intake from consumption. The composition ratio of animal and plant protein in overconsumption was assumed to be the same as that in consumption. The overconsumption ratio was obtained by dividing overconsumption by consumption. The overconsumption of each sex/age class was calculated from 1995–2015.

Uncertainty of food N loss expressed as the difference between net supply and consumption from different data sources was evaluated by two methods of determining food loss ratios. One was derived from the 2009 food loss survey (MAFF 2011). The household and eating-out food loss ratios for each food category were averaged by weighting the values by the ratio of eating out (FIRI 2018). The mean food loss ratio was then calculated from the net N supply of each food category (supplementary III). The other food loss ratio was derived from the nationwide food loss estimate as fresh weight from 2012 to 2015 (MAFF 2018). The estimated national food loss was converted to N using the water and N contents of household waste (Oita 2018). The mean food loss ratio was then calculated by dividing the N amount by the national total net food supply as N estimated in section 2.1 (supplementary III).

2.3. Body composition

Data on mean body height and weight of each sex/age class (⩾1 year; every year for age ⩽25 years and every 5–10 years for age >25 years) were obtained from the national nutrition survey (MHW 1968, 1982, 1992, 2000, MHLW 2017). Missing data in 1974 were obtained through linear interpolation of data from 1973 and 1975. Mean body height and weight of babies (<1 year) were available at 10 year intervals from 1960 to 2010 (MHLW 2012b); these data were linearly interpolated to obtain annual values. Data for 2010 were used for each year from 2011–2015. National means and the means of each sex/age class were calculated for body height, weight, and body mass index (BMI = weight [kg]/height $[m]^2$) using the population of each sex/age class in 1 year intervals (MIAC 2017).

2.4. Nitrogen footprints and reduction scenarios

The years from 2011–2015 were selected to calculate N footprints for the national mean and each sex/age class. This period was chosen so as to base the future reduction potential of the food N footprint on current conditions. There are three ways to calculate N footprints: a bottom-up approach with the N-calculator method (Leach *et al* 2012, Shibata *et al* 2014, Oita *et al* 2018), a top-down approach with N input data (Shindo and Yanagawa 2017), and a top-down approach with multi-region input–output analysis (Oita *et al* 2016a). The N-calculator method was used in the present study, which expresses the N footprint as (Oita *et al* 2018):

$$NF = NF_{\rm prod} + NF_{\rm cons}, \tag{1a}$$

$$NF_{\rm prod} = \sum_{i=1}^{n} VNF_i \times Intake\ N_i, \tag{1b}$$

$$NF_{\rm cons} = \left(1 - \frac{R_{denit}}{100}\right)\sum_{i=1}^{n} Intake\ N_i, \tag{1c}$$

where NF is the food N footprint (kg N capita^{-1} yr^{-1}), $NF_{\rm prod}$ is the food-production N footprint (kg N capita^{-1} yr^{-1}), $NF_{\rm cons}$ is the food-consumption N footprint (kg N capita^{-1} yr^{-1}), and VNF_i is the virtual N factor (VNF) of food category i (kg N kg^{-1} N). VNF denotes the amount of N released to the environment per unit N intake of each food category from production to just before consumption (Leach *et al* 2012, Supplementary IV). $Intake\ N_i$ is the N consumed in food category i (kg N capita^{-1} yr^{-1}), and $R_{\rm denit}$ is the average ratio of complete denitrification to N_2 during sewage treatment (%). N emissions as N_2 were excluded from N loads because of the inert nature of N_2. $R_{\rm denit}$ in Japan was set to 32% (Oda and Matsumoto 2006).

The original VNF involves food loss. A modified VNF for net supply (VNFns) was derived from the original VNF to evaluate N footprints of food loss:

$$NF_{\rm prod} = \sum_{i=1}^{n} VNFns_i \times Net\ supply\ N_i + Food\ loss\ N_i, \tag{2a}$$

$$Net\ supply\ N_i = Food\ loss\ N_i + Intake\ N_i, \tag{2b}$$

where $VNFns_i$ is the VNFns of food category i (kg N kg^{-1} N), $Net\ supply\ N_i$ is the net N supplied in food category i (kg N capita^{-1} yr^{-1}), and $Food\ loss\ N_i$ is the food N loss in food category i (kg N capita^{-1} yr^{-1}). $VNFns_i$ is obtained from equations (1*b*) and (2*a*) as:

$$VNFns_i = \left(1 - \frac{R_{foodloss\_i}}{100}\right) VNF_i - \frac{R_{foodloss\_i}}{100}, \tag{3}$$

where $R_{foodloss\_i}$ is the food loss ratio of food category i (%), which is theoretically equal to $Food\ loss\ N_i/Net\ supply\ N_i$. The VNF of each food category and the corresponding food loss ratio to obtain the VNF in Japan were derived from Shibata *et al* (2014) and Oita *et al* (2016b). VNFns of each food category was then calculated (supplementary IV).

N footprints of total, food loss, and protein overconsumption are expressed as:

$$NF = \sum_{i=1}^{n} VNFns_i \times Net\ supply\ N_i + Food\ loss\ N_i + \left(1 - \frac{R_{denit}}{100}\right) Intake\ N_i, \tag{4a}$$

$$NF_{\rm foodloss} = \sum_{i=1}^{n} VNFns_i \times Food\ loss\ N_i + Food\ loss\ N_i, \tag{4b}$$

$$NF_{\rm overcons} = \sum_{i=1}^{n} VNFns_i \times Overcons\ N_i + \left(1 - \frac{R_{denit}}{100}\right) Overcons\ N_i, \tag{4c}$$

$$NF_{\rm propercons} = NF - {\rm NF_{foodloss}} - {\rm NF_{overcons}}, \tag{4d}$$

$$Overcons\ N_i = Intake\ N_i - Propercons\ N_i, \tag{4e}$$

where $NF_{\rm foodloss}$ is the N footprint of food loss (kg N capita^{-1} yr^{-1}), $NF_{\rm overcons}$ is the N footprint of protein overconsumption (kg N capita^{-1} yr^{-1}), $NF_{\rm propercons}$ is the N footprint of recommended protein intake (kg N capita^{-1} yr^{-1}), $Overcons\ N_i$ is the N overconsumed in food category i (kg N capita^{-1} yr^{-1}), and $Propercons\ N_i$ is the N in properly consumed food (or recommended N intake) of food category i (kg N capita^{-1} yr^{-1}).

To calculate the national mean N footprint, the *Net supply N* and food loss ratio (*Food loss N*/*Net supply N*) of each food category were derived from national statistics (MAFF 2017) and calculated (MAFF 2018) as explained in section 2.2. *Intake N* was calculated from *Net supply N* and *Food loss N*. *Propercons N* was obtained as the WHO guideline of recommended protein intake (section 2.1) × mean body weight (section 2.3). *Overcons N* was derived as *Intake N* – *Propercons N*. The N footprint of each sex/age class was also calculated. *Intake N* of each sex/age class was obtained as the national mean *Intake N* × weighted ratio of consumption of each food category for each sex/age class to the national mean. The food loss ratio of each food category was assumed to be the same as the national mean because of the lack of relevant data (see supplementary IV for details). A sensitivity analysis was performed to evaluate the effect of change (+10%) in several input parameters on the total N footprint.

Three scenarios were modeled to evaluate the potential for reduction of consumer-level N footprints: A, 50% reduction in livestock meat consumption (due to its lower NUE than other protein sources; e.g. Billen *et al* 2018); B, 50% reduction in food loss; and C, 50% reduction in protein overconsumption. The following combinations were also modeled; D, A + B; E, A + C; F, B + C; and G, A + B + C. A 50% reduction in livestock meat corresponds to halving the consumption of livestock meat as N; however, the reduced N consumption as livestock meat is compensated for by an increase in the consumption of other foods, with their original composition ratios used as a weighting factor in the calculations.

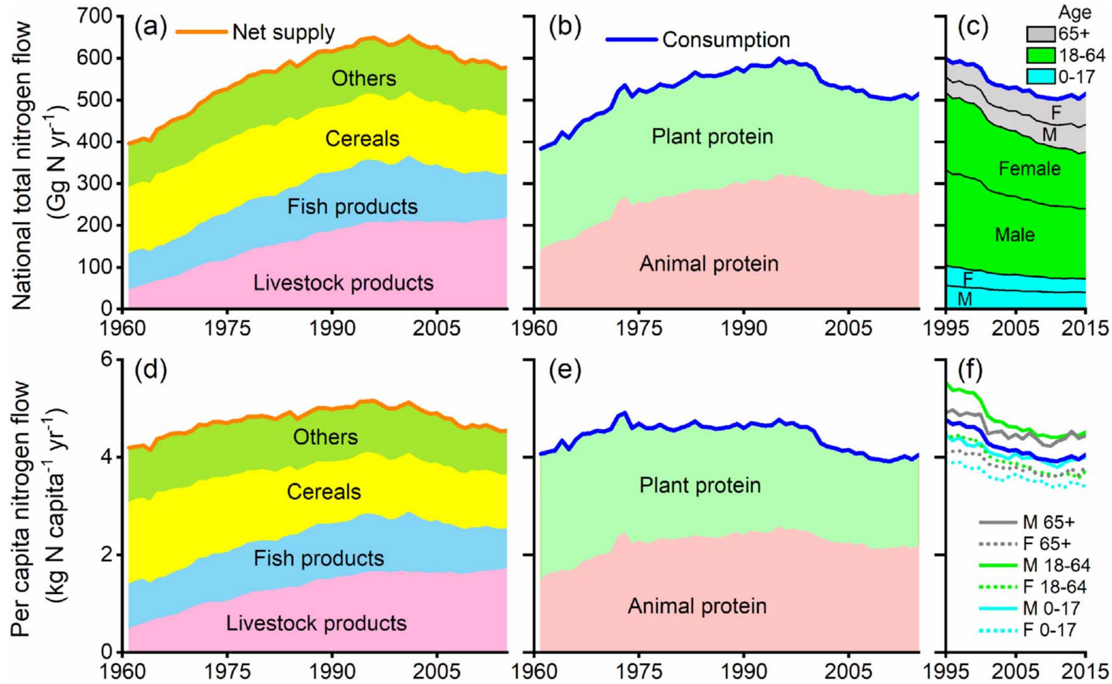

Figure 2. Net supply and consumption of protein as nitrogen in Japan from 1961–2015: (a) national annual total net supply, (b) national annual total consumption, (c) composition of national annual total consumption by sex and age classes, (d) per-capita annual net supply, (e) per-capita annual consumption, (f) per-capita annual consumption for each sex/age class.

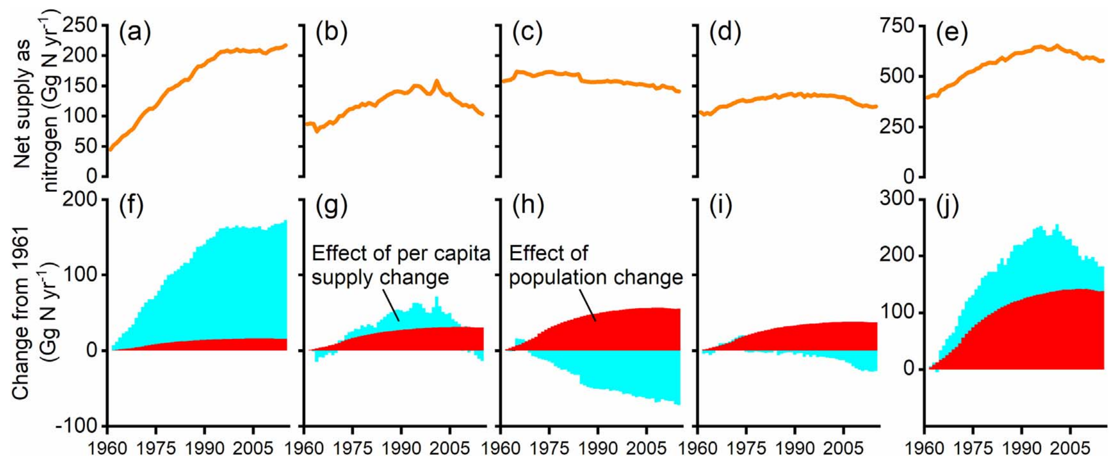

Figure 3. (a)–(e) Net nitrogen supply of (a) livestock products, (b) fish products, (c) cereals, (d) others, and (e) all food commodities. (f)–(j) Contributions of per-capita changes (blue) and population changes (red) to the net N supply of (a)–(e), respectively, with 1961 as the base year.

3. Results and discussion

3.1. Net supply and consumption

The national total net protein supply as N was 396 Gg N yr^{-1} in 1961, peaked at 649 Gg N yr^{-1} in 1996, and then decreased to 578 Gg N yr^{-1} in 2015 (figures 2(a) and (d)). The Japanese population increased from 94 million in 1961 to 128 million in the late 2000s and then started slowly decreasing, whereas the elderly population (⩾65 years) increased from 5.8% in 1961 to 26.6% in 2015 (figure S2). The population increase accounted for 59% of the cumulative increase in the net N supply (from 1961–2015), and the rest was a result of the increase in per-capita net N supply (figure 3). The per-capita net N supply started to decrease in the 2000s, and by 2015 was only slightly larger than it was in 1961 (figure 2(d)). The changes in per-capita net N supply were the result of a large increase in the net N supply of livestock products (from 11% in 1961 to 38% in 2015), partly counter-balanced by a decrease in that of cereals (from 40% to 24%). The net N supply of fish products did not change greatly in its contribution to the total (18% to 24%), because people consistently preferred fish products throughout the period. The estimated national total net N supply was lower than estimates in

Shindo *et al* (2009) and Lassaletta *et al* (2016), but it followed a similar trend (figure S3).

The national total protein consumption as N was 384 Gg N yr^{-1} in 1961, peaked at 599 Gg N yr^{-1} in 1995, and then decreased to around 510 Gg N yr^{-1} in the latest decade (figures 2(b) and (e)). The population increase accounted for 70% of the cumulative increase in protein consumption (from 1961 to 2015), and the rest was a result of changes in per-capita protein consumption. National total protein consumption increased through the 1970s owing to increases in both per-capita protein consumption and population. The increase continued until about 2000 as a result of population increase, but then the trend reversed because of decreased per-capita protein consumption. After an initial increase, per-capita protein consumption was mostly flat from 1970–2000 and then decreased to about the 1961 level. The national total protein consumption of each sex/age class has increased among the elderly but decreased among others since 1995. The protein consumption by the elderly increased by 69 Gg N yr^{-1} between 1995–2015 (figure 2(c)); the increase was attributed to an increase in the elderly population because their per-capita protein consumption slightly decreased during the same period (figure 2(f)). A decrease in per-capita protein consumption since 1995 was a common feature across all sex and age classes (figure 2(f)).

In terms of uncertainty, the net supply data are provided as national derived statistics; they are relatively reliable information based on a top-down approach to determine the food supply (supplementary I). The consumption data are obtained from the national nutrition survey, which was based on random sampling, e.g. about 15 000 people in 2015 (MHLW 2017; supplementary II). However, this survey is conducted once a year in November and might include some biases, such as seasonality in diet (Yuize and Miura 2004, supplementary III). Yuize and Miura (2004) reported that the consumption data of the Ministry of Health, Labour and Welfare (MHLW), Japan were 5.8% ± 2.7% ($n = 11$) larger than their estimates calculated using the net supply data.

3.2. Consumer-level food loss and overconsumption

The national total consumer-level food N loss was negligible until 1975; it peaked at >100 Gg N yr^{-1} in 2001, and averaged 77 Gg N yr^{-1} from 2011–2015 (figure 4(c)). The average per-capita food N loss (2011–2015) was 0.61 kg N $capita^{-1}$ yr^{-1} (figure 4(d)). The food N loss ratio also peaked in 2001 (16.4%) and averaged 13.2% from 2011 to 2015 (figure 4(e)). The consumer-level food N loss values might be underestimated because the net N supply estimated here was lower than those of two other similar studies (section 3.1; figure S3).

Since 1961, protein has been overconsumed relative to the WHO-recommended intake (figures 4(a) and (b)). National total N overconsumption increased from 181 Gg N yr^{-1} in 1961 to about 260 Gg N yr^{-1} in the 1970s to 1990s, and averaged 164 Gg N yr^{-1} in 2011–2015 (figure 4(c)). The per-capita N overconsumption peaked in 1973, decreased steadily through the 2000s, and became stable in recent years at 1.3 kg N $capita^{-1}$ yr^{-1} (2011–2015) (figure 4(d)). The overconsumption ratio peaked at >50% of food intake in the 1970s (i.e. double the recommended intake) and then steadily decreased to 32.3% (2011–2015) (figure 4(e)). Throughout the study period, the Japanese guideline of protein intake was higher than the WHO guideline (figures 4(a) and (b)), and this disparity might have contributed to overconsumption. The Japanese guideline began to be gradually reduced after 1975 and was notably reduced to approach the WHO guideline in 2005, but it is still 15% higher (figure 4(b)). The decrease in per-capita protein consumption since 1995 (figure 4(b)) might have been affected by the reduction in the Japanese guideline, but consumption since 2005 has not changed in response to the 2005 reduction in the Japanese guideline. Future studies are needed to elucidate why per-capita consumption decreased but then remained flat despite the changing guidelines. As shown in figure 4(e), the food loss ratio mainly increased during the study period, whereas the protein overconsumption ratio decreased. No information was available about food loss by sex and age. Changes in food loss and overconsumption in each sex/age class, particularly in light of Japan's aging population, should be a subject of future study.

The food loss ratios determined from the difference between net supply and consumption from different data sources could have large uncertainties. The average food loss ratio from 2011–2015 was 13.2%, whereas the ratio in 2009 obtained by a bottom-up approach was 4.3% (section 2.2) and the average value derived from the national estimation of food loss from 2012–2015 was 8.5% (section 2.2). Conversely, the food loss ratio corresponding to the difference between net supply and consumption increased from 13.2% to 18.0% considering the possible overestimation of the national consumption data pointed out by Yuize and Miura (2004). Further research is therefore needed to refine estimates of consumer-level food loss in Japan. Even so, the supply of unnecessary N expressed as the difference between net supply and WHO-recommended intake (figure 4(b); 1.9 kg N $capita^{-1}$ yr^{-1} from 2011 to 2015, 41.3% of net N supply), which is equal to the sum of food loss and overconsumption, is a good reduction target. The net supply is obtained through national derived statistics, and the WHO-recommended intake is expressed as the recommended protein intake (per unit body weight) of the WHO guideline × mean body weight, and both of these elements are based on relatively reliable information.

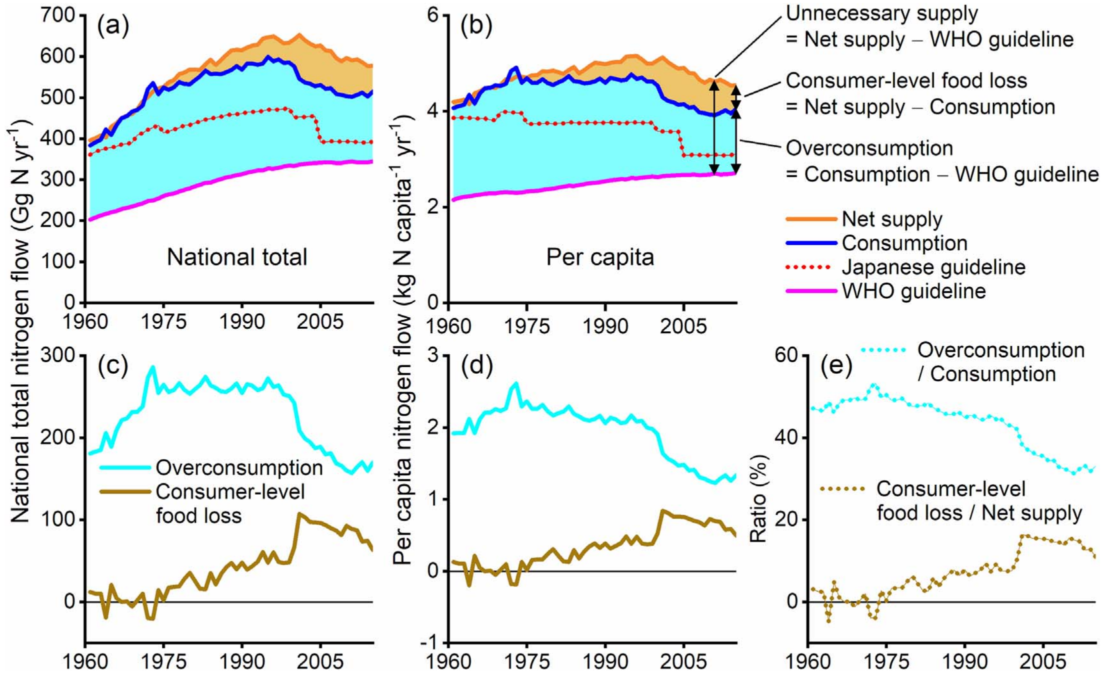

Figure 4. Consumer-level food loss and protein overconsumption as nitrogen (N) in Japan from 1961–2015: (a) national total net supply, consumption, WHO-recommended intake, consumer-level food loss, and overconsumption; (b) per-capita net supply, consumption, WHO-recommended intake, consumer-level food loss, and overconsumption; (c) national total consumer-level food loss and overconsumption; (d) per-capita consumer-level food loss and overconsumption; (e) ratios of consumer-level food loss/net N supply and overconsumption/consumption.

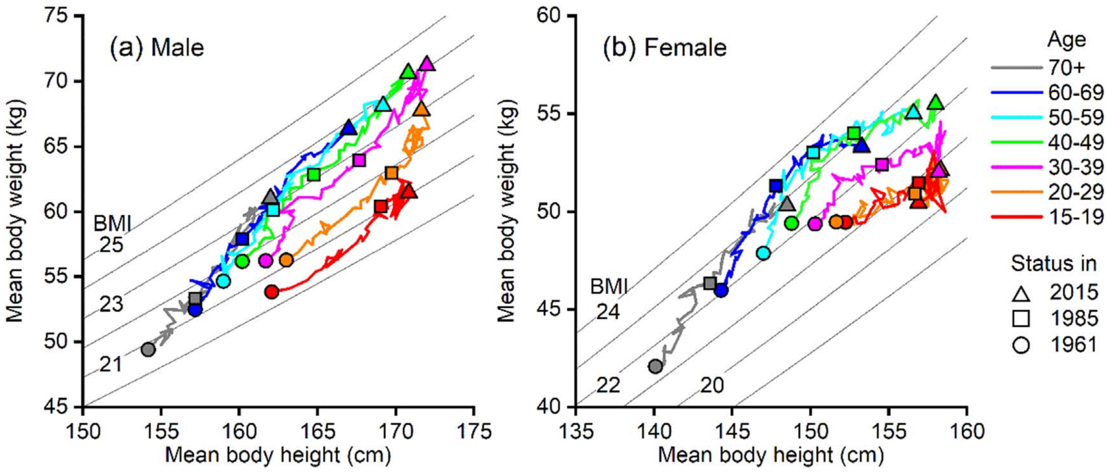

Figure 5. Body composition for each age class in 1961, 1985, and 2015 for (a) Japanese males and (b) Japanese females. BMI: body mass index.

3.3. Body composition and nutritional intake

Japanese males and females have both grown taller since the late 20th century, whereas BMI has increased in adult males (⩾20 years) but decreased in adult females since 1985 (figure 5). The difference in male BMI is particularly large between the 15–19 year and 20–29 year age groups (almost 2 points as of 2015; figure 5(a)). BMI is an index of the energy balance of the human body (MHLW 2014b), and the increasing BMI of Japanese males indicates a continuous excess energy intake compared to energy expenditure, whereas the reverse is true for Japanese females after 1985. The recommended target BMI ranges for Japanese of both sexes are 18.5–24.9 for 18–49 years, 20.0–24.9 for 50–69 years, and 21.5–24.9 for ⩾70 years (MHLW 2014b). Although the mean BMIs of adult males and females were entirely within the target ranges, their long-term food preferences might be the root cause of the changes in mean BMI.

Protein is difficult to store in the body, but it promotes body growth especially in youth (MHLW 2014b). The observed protein overconsumption was particularly remarkable in juveniles

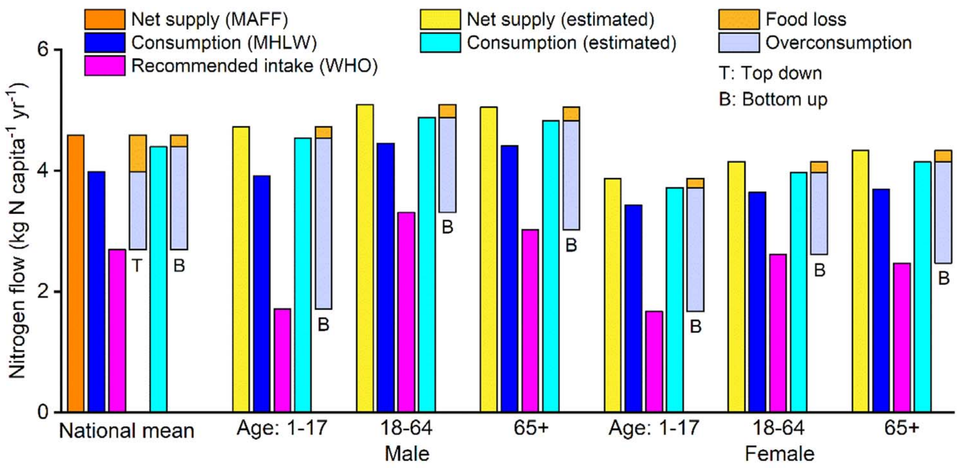

Figure 6. Per-capita nitrogen flows at the consumer level nationally and for the sex/age classes in Japan from 2011–2015. Net supply was provided by the food balance sheet (MAFF 2017), consumption was provided by the national nutrition survey (MHLW 2013–2017), and recommended intake was calculated by using the mean body weight and the WHO guideline for recommended protein intake. Net supply (estimated) and consumption (estimated) were derived using the national means of net supply and the food loss ratio of each food category.

(0–17 years, figure S4) and might have contributed to the steady increases in body height (figure 5).

In contrast to the protein overconsumption trends, Japan has experienced an overall decrease in its food-derived energy intake since the 1970s. The national mean daily energy intake fell below the recommended intake at normal intensity of daily activity in the 1990s, and the disparity has continued to increase (figure S5). At the same time, the fat composition in the energy intake increased from 11% in 1961 to 25% in 1988, and has since remained stable at about 26% (figure S5), which is within the FAO (2010) guidelines for fat intake by adults. The national mean BMI has increased since 1961, showing a positive relationship with per-capita daily fat intake (figure S6).

An increase in body weight at constant body height, that is, an increase in BMI, increases the recommended protein intake per person according to intake guidelines per unit body weight. In this case, an unnecessary body weight gain can appear to decrease the protein overconsumption ratio even with the same protein intake. Of course, unnecessary weight gain is not a reliable way to reduce protein overconsumption. Possible solutions for protein overconsumption should avoid increased health risk. Therefore, all possible solutions should be evaluated in combination with health indices such as BMI, nutrition intake guidelines, and actual consumption (intake).

3.4. Nitrogen flows and nitrogen footprints from 2011–2015

The national mean per-capita N flows and those of each sex/age class averaged from 2011–2015 are shown in figure 6. Key characteristics of the national mean are discussed in section 3.2; the smaller food loss ratio derived from the bottom-up approach resulted in an estimated consumption that was larger than that obtained by the MHLW national nutrition survey (figure 6). However, the smaller ratio was used to calculate N footprints, because the dataset provided the food loss ratio of each food category necessary for N footprint calculation. The sum of food loss and protein overconsumption (unnecessary supply) was largest in young males (1–17 years), at 3.0 kg N capita^{-1} yr^{-1}, followed by young females (1–17 years), at 2.2 kg N capita^{-1} yr^{-1} (figure 6), reflecting their large protein overconsumption (figure S4). The unnecessary supply for elderly males and females (⩾65 years), at 2.0 and 1.9 kg N capita^{-1} yr^{-1}, respectively, was larger than that for adult males and females (18–64 years), at 1.8 and 1.5 kg N capita^{-1} yr^{-1}, respectively (figure 6). The net supply in each sex/age class, however, was estimated using the previously noted smaller food loss ratios and without considering the differences among sex/age classes (section 2.4). Therefore, similar to the national mean, the estimated consumption of each class was larger than the consumption obtained by the MHLW national nutritional survey (figure 6). More details are shown in supplementary VIII.

The average national mean food N footprint in Japan from 2011–2015 was 18.3 kg N capita^{-1} yr^{-1}, of which 0.8 (4%) and 6.8 (37%) kg N capita^{-1} yr^{-1} were attributed respectively to food loss and protein overconsumption (figure 7). Livestock meat had the largest contribution (39%) to the national mean N footprint, followed by eggs and milk products (22%); therefore, livestock products accounted for 61% of the total N footprint. The contribution of livestock products to net N supply in the same period was 36% (figure 2(d)). Thus, it is expected that measures to reduce livestock product consumption would effectively reduce N footprint.

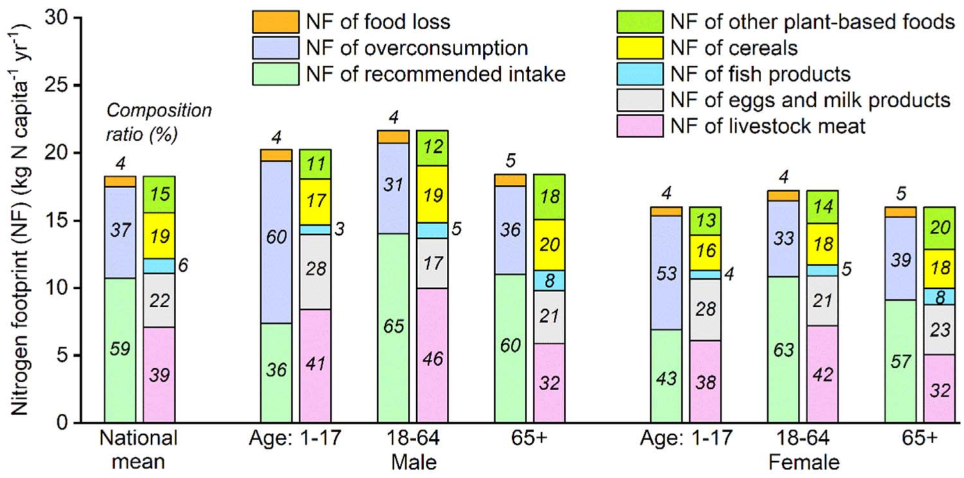

Figure 7. Average food nitrogen footprints (NF) for the national mean and sex/age classes in Japan from 2011–2015. The left column in each category shows recommended intake of protein, protein overconsumption, and food loss, and the right shows the food categories.

The food N footprint of each sex/age class varied from 16.0 kg N capita^{-1} yr^{-1} (female, 1–17 and ⩾65 years) to 21.6 kg N capita^{-1} yr^{-1} (male, 18–64 years), and the larger food consumption of males (figure 6) explained the larger N footprint of males than females in each age class (figure 7). The N footprints of food loss were similar regardless of sex/age class (0.7–0.9 kg N capita^{-1} yr^{-1}) because of the fixed food loss ratio used. The N footprints of overconsumption were particularly large in juveniles, accounting for 60% (male) and 53% (female) of the total (figure 7). The composition ratios of livestock products to the N footprints were similar between juveniles and adults in same sex, but the composition ratio of livestock meat was higher in adults than in juveniles of both males and females (figure 7). More detailed data are shown in supplementary IX.

Previous studies estimated the food N footprint in Japan as 26 (Shibata *et al* 2014) and 15.2 kg N capita^{-1} yr^{-1} (Oita *et al* 2018). The present estimation of 18.3 kg N capita^{-1} yr^{-1} is closer the latter. The reported food N footprints of other countries include 28 (USA), 23 (UK), 21 (The Netherlands), 19 (Germany), and 17 (Austria) kg N capita^{-1} yr^{-1} (Leach *et al* 2012, Pierer *et al* 2014, Stevens *et al* 2014).

As noted previously, the smaller food loss ratio (section 3.2) used in the N footprint calculations might underestimate the flows and footprints of N as food loss and therefore overestimate those of protein overconsumption. In addition, using a fixed food loss ratio regardless of sex/age class also introduces uncertainty.

The sensitivity of the N footprint calculations is also of interest. Terms directly affecting the total N footprint are VNFns, net N supply, food loss ratio, and complete denitrification ratio (equation (4*a*)), where food N loss and intake N are derived from the net N supply and the food loss ratio. The total N footprint responded to a 10% increase in each term as follows: VNFns, +8.3%; net N supply, +10.0%; food loss ratio, +0.03%; and complete denitrification ratio, –0.8%. Thus, improving the reliability of the estimates of net N supply and VNFns should be a priority. Although the effects of the food loss ratio and the complete denitrification ratio on the total N footprint are small, these variables affect the calculations of N footprints divided into food loss and protein overconsumption. According to equation (4*a*), once supplied, foods should be consumed rather than lost to reduce their N footprints because of the complete denitrification during sewage treatment.

3.5. Effects of reduction scenarios on nitrogen footprints

Reducing protein overconsumption by 50% would reduce the national mean N footprint by 19% (figure 8). Reducing livestock meat by 50% would reduce the footprint by 12% that reduces the footprints of both overconsumption and recommended intake. A 50% reduction in food loss results in only a 2% reduction. Scenario E, which combines the two most effective options, achieves a 29% reduction, and scenario G, which combines the three options, achieves the largest reduction (31%). However, the reduction effects of the two most effective options might be overestimated if the food loss ratio (4.3% on average) was underestimated. As discussed in section 3.2, the food loss ratio expressed by the difference between net supply and consumption (13.2%) and that estimated from the national food loss survey (8.5%) are larger than the food loss ratio used to calculate the N footprints. Huge food losses have been recorded in Japan, which had an average loss of 6360 Gg yr^{-1} as fresh weight from 2012–2015 (MAFF 2018). For comparison, this amount is larger than the world food aid by the World Food Programme in 2015 (5400 Gg yr^{-1}, WFP 2016). Therefore, reducing food

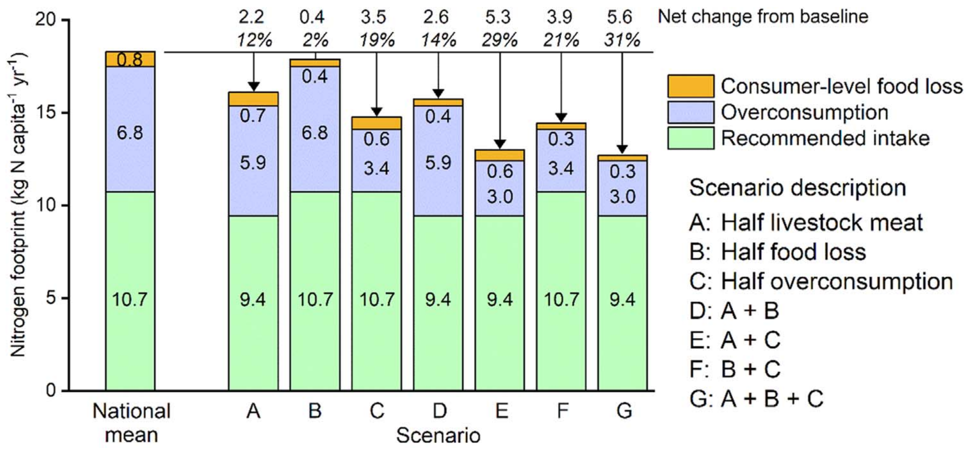

Figure 8. Potential for reduction of nitrogen footprints from 2011–2015 average national mean in Japan. 'Half livestock meat' denotes a diet where the relative consumption of livestock meat is reduced by 50% while maintaining the same protein intake by increasing consumption of other food items. 'Half food loss' and 'Half overconsumption' indicate a 50% reduction in food loss and protein overconsumption, respectively.

loss in Japan should be a priority, but future reanalysis of N footprints with a refined dataset is needed to help decision on concrete countermeasures and set priorities. More detailed data are shown in supplementary X.

The feasibility of the options in the scenarios should also be discussed. Consumers might resist reducing protein overconsumption by half, because there was no observed response to the 2005 reduction in the Japanese guideline of protein intake (figure 4(b)). Reducing livestock meat consumption might face similar resistance. To achieve reductions in protein overconsumption and livestock meat consumption, dietary changes that benefit both human and environmental health must be promoted (e.g. the traditional Japanese diet with less meat consumption; Oita *et al* 2018). Consumer actions should also be encouraged, for example, through campaigns for wise shopping, food sharing, and using food already on hand to reduce loss. Changes in consumer actions are expected to be reflected in the food-supply chain. Adequate supply adjustments corresponding to reductions in consumers' N loads are vital to achieving the scenario outcomes. Parallel approaches to improving the NUE of food production (e.g. Lassaletta *et al* 2016) are recommended to further reduce the entire food N footprint. Although it will take time to change the import dependency of the current Japanese food system, reducing the net imports of food and animal feed would have global benefits for environmental health, as well as enhance Japanese food security. In addition, fish products are an important protein source in Japan (19% of net N supply from 2011–2015, figure 2(d)), and they have a lower relative contribution to the N footprint (6% in the same period, figure 7). This difference is attributed to the low VNFns of fish products (table S4; Oita *et al* 2016b). Care must be taken in any option that substitute consumption of livestock meat partly with fish in order to maintain the sustainability of aquatic resources.

4. Conclusions

Consumer-level food N loss in Japan has been relevant since the 2000s, and the food loss ratio relative to net supply averaged 13.2% from 2011–2015. Japanese people overconsumed protein N relative to the WHO-recommended intake since the beginning of the study period (1961), and overconsumption relative to consumption averaged 32.3% from 2011–2015. The food loss ratio obtained by a bottom-up approach used to calculate the food N footprint was 4.3% in 2009, lower than the top-down estimation of 13.2%. Even though uncertainty was introduced in the calculation of the food loss ratio, the unnecessary N supply (net food N supply-recommended food N intake), equal to the sum of food N loss and overconsumed N, is a relatively robust index of N reduction targets. The unnecessary N supply averaged 41.3% from 2011– 2015 relative to net supply, showing much room for reduction. The N-calculator method used to determine the food N footprint was modified to handle changes in food N loss explicitly. The national mean food N footprints from 2011–2015 averaged 18.3 kg N capita^{-1} yr^{-1}, of which food loss accounted for 4% and protein overconsumption for 37%. The food N footprint of each sex/age class varied from 16.0–21.6 kg N capita^{-1} yr^{-1}, and was larger for males in each age class. The food N footprints of protein overconsumption were particularly large in juveniles, accounting for 53%–60% of the total. Seven scenarios to reduce the N footprints were modeled, and a scenario of halving protein overconsumption, livestock meat consumption, and food loss was estimated to reduce the food N footprint by 31%. To achieve the scenario results, the NUE in the food production and supply chain will need to increase, and changes in consumer behavior will need to be encouraged. Future challenges include improving the reliability of the food loss ratio and other variables used to calculate N footprints, and striking a balance between reducing Nr loss to the environment and maintaining or enhancing Japan's food security under increasing globalization of food/feed markets. In addition, analyses of dietary preferences to estimate health and environmental implications should also consider differences in gender, generation, and physique.

Acknowledgments

This study was partly supported by the Science and Technology Research Promotion for Agriculture, Forestry, Fisheries and Food Industry (28005 A) provided by Japan's Ministry of Agriculture, Forestry and Fisheries, and by Grants-in-Aid for Scientific Research (No. 17H00794) provided by the Japan Society for the Promotion of Science. LL acknowledges support from MINECO, Spain, co-founded by European Commission ERDF (Ramon y Cajal fellowship, RYC-2016-20269) and from Programa Propio from Universidad Politécnica de Madrid.

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