Nitrogen loss to the environment due to various nitrogen-use efficiencies during milk and beef production in Japan

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Abstract

Reactive nitrogen (Nr) is essential to livestock production, but its excess use can become a source of environment pollution, the extent of which can be evaluated by using a nitrogen (N) footprint model. Such a model provides a useful indicator linking consumers’ activity with Nr loss to the environment. To reduce Nr losses, it is crucial to reduce the use of ‘new-Nr,’ namely Nr chemically (synthetic-Nr) and biologically (BNF-Nr) fixed from the atmosphere, by recycling manure-Nr for crop production. When estimating the N footprint associated with the N use efficiency (NUE) of animal products and virtual N factor (VNF), namely the ratio of Nr released to the environment during the food production and consumption processes per unit Nr consumed, Nr flows from feed production in fields to milk and beef consumption by humans should be quantified. Here, we estimated the national-scale NUE of milk and beef production in Japan and quantified the VNF and N footprint, namely Nr losses to the environment per capita through milk and beef consumption by humans. Crop NUE (i.e. feed-Nr/(new-Nr + manure-Nr)) was greater in paddy fields and grassland than in upland fields. Milk NUE (i.e. consumed-Nr/new-Nr) and milk VNF were 15% and 5.6, respectively. Beef NUEs (i.e. consumed-Nr/new-Nr) and beef VNFs were 4.0% and 24.2 for dairy bullocks, 3.2% and 29.8 for crossbred cattle, and 2.4% and 41.5 for beef breeds, respectively. The length of the fattening period was an important determinant of beef NUE and beef VNF. When the components of slaughtered cattle (the three types previously mentioned + culled cattle) in Japan were considered, beef NUE and beef VNF were 3.7% and 26.3, respectively. We hope that providing consumers with this information will prompt them to choose more environmentally sustainable animal products and thus substantially reduce the worldwide N footprint.

1. Introduction

Reactive nitrogen (Nr; all nitrogen except N2) is essential to maintaining crop and livestock production. Once in environment, however, excess Nr has detrimental impacts on humans and the environment (Leach et al. 2012). In EU-27 countries, Nr loss from the agricultural sector to the environment has been estimated to account for about 80% of Nr losses from all sources (Westhoek et al. 2015). The portion of Nr that is not transferred to edible parts during the process of milk and beef productions changes to inorganic forms such as ammonia (NH3), nitrogen oxides (NOx), nitrate ion (NO3−), and nitrous oxide (N2O); in these forms, Nr increases air and water pollution in terrestrial and aquatic ecosystems and contributes to global warming (Sutton et al. 2011).
Livestock production in Japan substantially influences Nr flows in both Japan and other countries, because Japan imports more than 85% of its concentrated feeds on a total digestible nutrient (TDN) basis (1 kg of TDN is equivalent to 4.41 Mcal of digestible energy), and Japanese citizens obtain more than one-third of their protein from animal products (MAFF 2018). Besides, Japan imports more than 60% of dairy products (excluding drinking milk) and more than 65% of beef on a weight basis (MAFF 2018). Therefore, the import and export of animal products need to be included in the estimation of virtual N factor (VNF), which is the ratio of the Nr released to the environment during the food production and consumption processes per unit Nr consumed. VNF is important variable for determining the food N footprint during production processes.

In Japan, 599 thousand ha are used for forage production (MAFF 2019). Hilly and mountainous area is usually covered by forest (68.5% of Japan's land area), and besides, lowland area is usually used as paddy field. These geographic constrains restrict the feed production to meet the demand for animal products. More than 80% of the country's grassland and forage cropping area is located in Hokkaido prefecture (MAFF 2019). The cool climate (annual mean air temperature, 6.2 °C–9.1 °C) is suitable for temperate grass growth. The stocking rate of dairy and beef cattle per grassland and forage cropping area is located in Hokkaido prefecture (MAFF 2019). In Japan, 599 thousand ha are used for forage production (MAFF 2019). Hilly and mountainous area is usually covered by forest (68.5% of Japan's land area), and besides, lowland area is usually used as paddy field. These geographic constrains restrict the feed production to meet the demand for animal products. More than 80% of the country's grassland and forage cropping area is located in Hokkaido prefecture (MAFF 2019). The cool climate (annual mean air temperature, 6.2 °C–9.1 °C) is suitable for temperate grass growth. The stocking rate of dairy and beef cattle per grassland and forage cropping area is located in Hokkaido prefecture (MAFF 2019). In the case of beef cattle, however, feed composition (i.e. roughage vs. concentrates) differed only slightly between prefectures because of the high dependence on imported feed grain. Besides, production of animal, forage and other crops is interlinked in Japan. For example, animal feeds usually contain by-products such as oil meal from the production of plant oils. In recent years, rice grain and whole crop silage are also fed to cattle. Moreover, milk and beef are produced simultaneously, that is calves of dairy bullock and crossbred cattle and culled cattle are utilized for beef production. In Japan, three quarters of manure is derived from livestock management using imported feed, as most of cattle are fed inside (Hojito et al. 2003, MAFF 2018). Therefore, to reduce Nr losses to the environment, it is crucial to reduce the use of 'new-Nr,' that is, Nr chemically (synthetic-Nr) and biologically (BNF-Nr) fixed from the atmosphere, by recycling manure-Nr for forage and other crop productions. In Japan, more than 65% of dairy manure and more than 85% of beef manure are composted (GIO, 2020); more than 80% of composted manure derived from cattle, pig and poultry was estimated to be applied for the crops other than forage on a Nr basis (Mishima and Kohyama 2010).

In addition, the per capita consumption of animal products is smaller in Japan than in the United States and Europe, but the food nitrogen (N) footprint (Leach et al. 2012), namely the Nr released to the environment per capita as a result of food production and consumption, is comparable among these populations (Shibata et al. 2014). This is partly due to the relatively low N use efficiency (NUE) of meat production in Japan (OECD 2008). NUEs can be estimated from plot/field-scale to regional/national-scale (Dalgard et al. 2012). In the Netherlands, dairy farmers are required to use the Annual farm Nutrient Cycle Assessment (ANCA, van Leeuwen et al, 2019) to improve NUE at their farm. The difference in NUE between the average and the most N-efficient farm is a key information to reduce Nr loss to the environment (Dalgard et al. 2012). Moreover, total Nr emissions are sensitive to social influences on food choices (Westhoek et al. 2015). In Japan, for example, consumptions of dairy products (e.g. cheese and cream) are increasing; marbled tender beef is popular. In addition, younger Japanese tend to consume more meat and less fish than older people leading to a larger N footprint (Shibata et al. 2014). For these reasons, it is crucial to refine the NUEs of animal products in Japan and better understand ways to reduce Nr losses.

The N footprint of milk and beef associated with their NUEs and VNFs might vary depending on the type of field used for feed production; rate of manure recycling; dosage and digestibility of feeds; animal’s age at slaughter; meat yield; loss of animal-based food products; hereditary components of crops and cattle; and the import and export of animal products, as well as social food choice. Therefore, to refine NUE, VNF, and N footprint to facilitate more sustainable food choices and develop strategies to reduce Nr losses, these various factors need to be incorporated into calculations of the N footprint, which can be accomplished simply by using the N-calculator (Leach et al. 2012). Our objectives here were (1) to evaluate the NUE and VNF of milk production for Hokkaido prefecture, for other prefectures, and for Japan overall focusing on the feed composition (i.e. roughage vs. concentrates); (2) to compare the NUE and VNF of beef production from beef breeds, dairy bullocks, crossbred cattle, and beef overall (namely, the three types just mentioned + culled cattle) for Japan overall focusing on the slaughter age; (3) to discuss how the N footprint of animal products can be reduced focusing on the import/export, food choice, and interregional and international difference in production system; and (4) to consider subjects for future study to improve estimates of NUE, VNF, and N footprint related to milk and beef consumed in Japan.
2. Materials and methods

2.1. Crop NUEs
The NUEs of crops (cropNUE_{i}) were calculated for grassland, upland fields, and paddy fields as follows. The index (i) for 'grass', 'upland', and 'paddy' corresponds to feed production in each of these respective types of fields:

\[ \text{cropNUE}_{i} = \text{feed} - \frac{\text{Nr}_{i}}{\text{applied}} - \text{Nr}_{j}, \]

where \( \text{feed} - \text{Nr}_{i} \) is the amount of Nr in feed (kg-N ha\(^{-1}\) yr\(^{-1}\); Mishima and Kohyama 2010) and \( \text{applied} - \text{Nr}_{j} \) is the sum of synthetic-Nr, manure-Nr, and BNF-Nr applied (kg-N ha\(^{-1}\) yr\(^{-1}\); Hojito et al 2003, Mishima and Kohyama 2010, Hatano 2017). The NUE of corn in the United States, namely edible-milk (kg-N feed \( \times \) milk, \( \text{MAFF} \)), was calculated by using the crop NUE mentioned above. Note that grassland includes forage cropping area; the area for grass is 10 and 5 times greater than that for corn in Hokkaido and other prefectures, respectively.

2.2. Milking cow NUEs
The NUEs of milking cows (milkingcowNUE_{j}) were calculated for Hokkaido prefecture, for other prefectures, and for Japan overall as follows. The indexes (i and j) were the same as those used in the crop NUE (2.1.) and milking cow NUE (2.2.) sections, respectively:

\[ \text{milkingcowNUE}_{j} = \text{milk} - \frac{\text{Nr}_{j}}{\text{feed}} - \text{Nr}_{k}, \]

where \( \text{milk} - \text{Nr}_{j} \) is the Nr in milk (kg-N head\(^{-1}\) yr\(^{-1}\)), which was calculated by multiplying the amount of milk produced (kg-milk head\(^{-1}\) yr\(^{-1}\), MAFF 2012b) by the Nr content of the milk (kg-N kg-milk\(^{-1}\), MEXT 2015), and \( \text{feed} - \text{Nr}_{j} \) is the Nr in feed (kg-N head\(^{-1}\) yr\(^{-1}\)), which was calculated by multiplying the feed dosage (kg-feed head\(^{-1}\) yr\(^{-1}\), MAFF 2012b) by the Nr content of the feed (kg-N kg-feed\(^{-1}\), JLIA 2009). Both \( \text{milk} - \text{Nr}_{j} \) and \( \text{feed} - \text{Nr}_{j} \) were based on annualized statistics that took into account the cycle of lactation and dry periods of milking cows and heifers being raised for milking; \( \text{feed} - \text{Nr}_{j} \) includes the Nr in feed for milking cows during both lactation and dry periods and the Nr in feed for heifers soon to be milked.

2.3. Milk NUEs and milk VNFs
The NUEs of milk production (milkNUE_{j}) were calculated for Hokkaido prefecture, for other prefectures, and for Japan overall as follows. The indexes (i and j) were the same as those used in the crop NUE (2.1.) and milking cow NUE (2.2.) sections, respectively:

\[ \text{milkNUE}_{j} = \frac{\text{consumed} - \text{Nr}_{j}}{\sum_{i} \text{new} - \text{Nr}_{ji}}, \]

where \( \text{consumed} - \text{Nr}_{j} \) is the Nr in milk consumption (kg-N head\(^{-1}\) yr\(^{-1}\)), which was calculated by multiplying the Nr content of milk (kg-N head\(^{-1}\) yr\(^{-1}\), MEXT 2015) by the ratio of milk and dairy products consumed (Eguchi and Hirano 2019). \( \text{new} - \text{Nr}_{ji} \) is the sum of synthetic-Nr and BNF-Nr applied to produce feeds (kg-N head\(^{-1}\) yr\(^{-1}\)); however, manure-Nr is excluded because it was recycled.

The VNFs of milk without trade (milkVNF\_without\_trade) and with trade (milkVNF\_with\_trade) were calculated as follows:

\[ \text{milkVNF}_{\text{without\_trade}} = \frac{1 - \text{milkNUE}_{\text{natl}}}{\text{milkNUE}_{\text{natl}}} \text{ and} \]
\[ \text{milkVNF}_{\text{with\_trade}} = \text{SSR} \times \text{milkVNF}_{\text{without\_trade}} + (1 - \text{SSR}) \times \text{milkVNF}_{\text{import}}, \]

where SSR is the self-sufficiency rate for milk and dairy products supplied in Japan (MAFF 2018). MilkVNF\_import is the VNF of milk production in exporting countries. We used the VNF of the European Union (3.9) for milkVNF\_import, because we assumed that the European Union comprises representative countries with industrialized production systems (Stevens et al 2014).

2.4. Beef cattle NUEs
The NUEs of beef cattle (beefcattleNUE_{k}) were calculated for beef breeds (e.g. Japanese Black), dairy bullocks (e.g. Holstein bullocks), and crossbred cattle (e.g. Japanese Black \( \times \) Holstein), as follows. The index (k) for 'beef breed', 'dairy bullock', and 'crossbred' corresponds to each respective type of cattle:

\[ \text{beefcattleNUE}_{k} = \text{cattle} - \text{Nr}_{k}/\text{feed} - \text{Nr}_{k}, \]

where \( \text{cattle} - \text{Nr}_{k} \) is the Nr in the entire bodies of fattening cattle just before slaughter (kg-N head\(^{-1}\), Matsumoto 2000) and \( \text{feed} - \text{Nr}_{k} \) is the Nr in feed (kg-N head\(^{-1}\)), which is calculated by multiplying the feed dosage throughout an animal's entire life (kg-feed head\(^{-1}\); MAFF 2012b) by the Nr content of the feed (kg-N kg-feed\(^{-1}\), JLIA 2009). Note that \( \text{feed} - \text{Nr}_{\text{beef\_breed}} \) includes the Nr of the feed required for breeding beef cattle to each produce one beef calf; however, \( \text{feed} - \text{Nr}_{\text{dairy\_bullock}} \) and \( \text{feed} - \text{Nr}_{\text{cross\_breed}} \) do...
not include this factor, because the calves of dairy bullocks and crossbred cattle were considered to be by-products (figure 1). In addition to the three cattle types just described, culled cattle are slaughtered (figure 1). The beef cattle NUE of culled cattle was not calculated, because they were by-products. However, as described later, beef derived from culled cattle was considered in the calculation of beef VNF of overall beef produced in Japan.

2.5. Beef NUEs and beef VNFs

The NUEs of beef production (beef NUE<sub>k</sub>) were calculated for beef breeds, dairy bullocks, and crossbred cattle as follow. The indexes (i and k) were the same as those used in the crop NUE (2.1.) and beef cattle NUE (2.4.) sections, respectively:

\[
\text{beef NUE}_k = \frac{\text{consumed} - \text{Nr}_k}{\sum_i \text{new} - \text{Nr}_i},
\]

where \(\text{consumed} - \text{Nr}_k\) is the Nr for beef consumption (kg-N head<sup>-1</sup>), which was calculated from the yield and composition of the carcass (kg head<sup>-1</sup>, Higuchi et al. 2017), the Nr content in red meat and fat (kg-N kg-beef<sup>-1</sup>, MEXT 2015), and the ratio of meat consumed (Eguchi and Hirano 2019). \(\text{new} - \text{Nr}_{i\text{beef breed}}\) includes the Nr applied to produce feed for breeding cattle to each produce one calf. However, \(\text{new} - \text{Nr}_{i\text{dairy bullock}}\) and \(\text{new} - \text{Nr}_{i\text{crossbred}}\) did not include this factor, because calves of dairy bullocks and crossbred cattle were considered to be by-products (figure 1).

The NUE of overall beef production (beef NUE<sub>overall</sub>) was calculated as follows:

\[
\text{beef NUE}_\text{overall} = \frac{\text{consumed} - \text{Nr}_{\text{beef overall}}}{\sum_i \sum_k \text{new} - \text{Nr}_k \text{and}}
\]

where \(\text{consumed} - \text{Nr}_{\text{beef overall}}\) is the sum of synthetic-Nr and BNF-Nr applied to produce feeds (kg-Nr head<sup>-1</sup>); however, manure-Nr is excluded because it was recycled. In particular, \(\text{new} - \text{Nr}_{\text{dairy bullock}}\) and \(\text{new} - \text{Nr}_{\text{crossbred}}\) did not include this factor, because calves of dairy bullocks and crossbred cattle were considered to be by-products (figure 1).

\[
\text{consumed} - \text{Nr}_{\text{beef overall}} = \sum_k \text{consumed} - \text{Nr}_k + \text{consumed} - \text{Nr}_{\text{culled cattle}},
\]

where \(\text{consumed} - \text{Nr}_{\text{culled cattle}}\) is the Nr for beef consumption (kg-N head<sup>-1</sup>), which was calculated from the yield and composition of the carcass (kg head<sup>-1</sup>, Higuchi et al. 2017), the Nr content in red meat and fat (kg-N kg-beef<sup>-1</sup>; MEXT 2015), and the ratio of meat consumed (Eguchi and Hirano 2019). In addition, culled cattle were by-products. Therefore, new-Nr does not need to be applied for beef production derived from culled cattle.

The VNFS of beef without trade (beef VN F<sub>without trade</sub>) and with trade (beef VN F<sub>with trade</sub>) were calculated as follows:

\[
\text{beef VN F}_{\text{without trade}} = \left(1 - \frac{\text{beef NUE}_\text{overall}}{\text{beef NUE}_{\text{overall}} + \text{beef NUE}_\text{import}}\right)
\]

\[
\text{beef VN F}_{\text{with trade}} = \text{SSR} \times \text{beef VN F}_{\text{without trade}} + \left(1 - \text{SSR}\right) \times \text{beef VN F}_{\text{import}}.
\]

where \(\text{beef VN F}_{\text{overall}}\) is the VNF when the percentage components of all slaughtered cattle in Japan—namely beef breeds, dairy bullocks, crossbred cattle, and culled cattle—were considered (MAFF 2012a). SSR is the self-sufficiency rate for beef supplied in Japan (MAFF 2018). \(\text{beef VN F}_{\text{import}}\) is the VNF of beef production in exporting countries; we used the VNF of Australia (13.4) for \(\text{beef VN F}_{\text{import}}\), because we assumed that Australia is a representative country with an industrialized production system (Liang et al. 2016).

3. Results and discussion

3.1. Crop NUEs

Crop NUE decreased in the order of crop NUE<sub>paddy</sub> (0.74) > crop NUE<sub>gravel</sub> (0.68) > crop NUE<sub>upland</sub> (0.64) (figure 2). We surmise that crop NUE<sub>paddy</sub> was greater than crop NUE<sub>upland</sub> becauseNr leaching was lower in paddy fields than in upland fields; the oxidation of ammonium (NH<sub>4</sub><sup>+</sup>) to nitrate (NO<sub>3</sub><sup>-</sup>) ions in soil is profoundly restricted in the submerged conditions in paddy soil. Typically, the Nr leached from soil is in the form of NO<sub>3</sub><sup>-</sup> because NH<sub>4</sub><sup>+</sup> tends to be adsorbed and retained in soil. In addition, crop NUE<sub>gravel</sub> was greater than crop NUE<sub>upland</sub> because of less Nr leaching in grassland compared with upland fields; grassland is covered year round by the dense roots of grassland plants, whereas plant cover is removed periodically from the soil of upland fields. Crop NUE<sub>upland</sub> was similar in magnitude to the NUE of corn production in the United States (0.65; Leach et al. 2012).

3.2. Milking cow NUEs

Milking cow NUE<sub>other prefab</sub> (0.26) was greater than milking cow NUE<sub>Hokkaido</sub> (0.23) (figure 3). A possible explanation for this result is that concentrated feeds containing easily digestible oil meal, chaff, and bran (JLIA 2009) were fed more in the other prefectures than in Hokkaido prefecture (figure 3 and MAFF 2012b). Undigestible feed-Nr is excreted in the dung. Another possible explanation is increased feed-Nr excretion in the urine due to the feeding of high-moisture grass silages containing soluble protein (Shinoda 2017); given the increased availability of herbage, more silage was fed in Hokkaido prefecture than in other prefectures (figure 3). In Japan, because the number of cows per farm is increasing, most dairy farmers are under time constraints and therefore unable to cut and dry herbage at the optimal time for harvesting and, consequently, tend to cut
at a high-moisture content. This situation is particularly true for Hokkaido prefecture, due to large-scale management of grassland and forage cropping area per farm (Hatano 2017, MAFF 2019). The value for milking cow NUE_nat was comparable to that in the United States (0.25, Leach et al. 2012), suggesting that in modern farms relying on concentrates, milking capacity does not differ markedly between these countries.

From the Japanese feeding standard for dairy cattle (JLIA 2006) and assuming a liveweight of 650 kg, 3.9% milk fat, and milk production of 8470 kg head$^{-1}$ yr$^{-1}$ (MAFF 2015), the calculated feed-Nr required for milking cows is 133 kg-N head$^{-1}$ yr$^{-1}$. Given that milk contains 0.50% Nr (MEXT 2015), the amount of milk produced per year (8470 kg head$^{-1}$ yr$^{-1}$) contains 42 kg-N head$^{-1}$ yr$^{-1}$. The rate of food loss in Japan is 11.1% for all food groups combined (Eguchi and Hirano 2019). Consequently, the milking cow NUE calculated as the consumed-Nr/feed-Nr and by using the JLIA and MEXT data was 0.28. This value is greater than...
the milking cow NUEs that we obtained (figure 3), because feed-Nr for dry milking cows and heifers were not included in the above calculation. The value of milking cow NUE in a previous study (0.30, Godinot et al 2015) was greater than our value because the feed-Nr for heifer was not considered.

### 3.3. Milk NUEs, milk VNFs, and N footprint

*Milk NUE* without trade (0.16) was greater than *milk NUE* Hokkaido (0.14) (figure 4). The feeding ratio of roughage to total fed amount (i.e. silage + hay, inclusive of grazing), which has a moderate crop NUE (figure 2), was greater in Hokkaido prefecture, which contains more than 80% of Japan’s grassland and forage cropping area, whereas the proportion of concentrates was greater in the other prefectures (figure 3). This difference in feed components is due mainly to differences in the stocking rates of cattle: the grassland and forage cropping area per animal in Hokkaido prefecture was greater than that in the other prefectures (MAFF 2019). However, as was mentioned earlier, the feeding of easily digestible concentrates seems to improve milking cattle NUE. Consequently, *milk NUE* Other prefectures was slightly greater than *milk NUE* Hokkaido. The value of milk NUE in previous studies were greater than our values in part because Nr loss in the feed exporting countries was not considered (Daalgard et al, 2012, van Leeuwen et al 2019).

*Milk VNF* without trade (5.6, table 1) was greater than that previously estimated for Japanese milk without trade (3.9, Shibata et al 2014), because we used more detailed data regarding feed flow in multiple feeding types than did the previous estimate (Shibata et al 2014). In addition, *milk VNF* without trade was greater than *milk VNF* with trade (table 5), suggesting that the importation of dairy products has decreased the N footprint of Japanese consumers. The annual protein supply from milk and dairy products produced in Hokkaido prefecture was comparable to that from imported dairy products, but the N footprint of Hokkaido was greater than that of imported dairy products (table 6).

### 3.4. Beef cattle NUEs

The age at slaughter depends on the type of cattle, due to the differences in fattening period (figure 1). Beef cattle NUE decreased in the order of *beef cattle NUE* dairy bullock (0.19) > *beef cattle NUE* crossbred (0.15) > *beef cattle NUE* beef breed (0.11) (figure 5). This relationship was in reverse order to the

![Figure 3. Feed- and milk-Nr and milking cow NUE in Hokkaido prefecture, in other prefectures, and for Japan overall scale. Feed-Nr was the sum of concentrate-, silage-, hay-, grazing-, and other-Nr; ‘other’ includes milk (as feed for calves), straw, and green forage. Milking cow NUE was calculated as the ratio of milk-Nr/feed-Nr. Concentrates mainly contain grain, oil meal, chaff and bran. Silage, hay and grazing grass are produced in grassland. Straw is produced in upland and paddy fields as a by-product.](image-url)

| Food category | NUE | VNF |
|---------------|-----|-----|
| Milk          |     |     |
| Hokkaido      | 14  | 5.9 |
| Other prefectures | 16  | 5.4 |
| Japan overall | 15  | 5.6 |
| Beef          |     |     |
| Beef-breed cattle | 2.4 | 41.5 |
| Dairy bullocks | 4.0 | 24.2 |
| Crossbred cattle | 3.2 | 29.8 |
| Overall       | 3.7 | 26.3 |

**Table 1.** Nitrogen use efficiency (NUE, %) and virtual nitrogen factor (VNF) of milk and beef produced in Japan.
Figure 4. Nr flows of milk production (kg-N head$^{-1}$ yr$^{-1}$). Percentages of Nr as compared with new-Nr are in parentheses. New-Nr is the sum of synthetic-Nr + BNF-Nr. Applied-Nr is the sum of new-Nr + manure-Nr. Feed-Nr is the sum of Nr in feed inclusive of main and by-product feed. Milk-Nr and consumed-Nr are the Nr in produced and consumed milk, respectively.

|                | new-Nr | applied-Nr | feed-Nr | milk-Nr | consumed-Nr |
|----------------|--------|------------|---------|---------|-------------|
| Hokkaido       |        |            |         |         |             |
| prefecture     | 244 (100) | 257 (105) | 172 (70) | 40 (16) | 35 (14) |
|                |         |            |         |         | manure-Nr 13 |
| Other          |        |            |         |         |             |
| prefectures    | 240 (100) | 246 (102) | 163 (68) | 42 (18) | 38 (16) |
|                |         |            |         |         | manure-Nr 6 |
| Japan overall  |        |            |         |         |             |
|                | 240 (100) | 250 (104) | 166 (69) | 41 (17) | 36 (15) |
|                |         |            |         |         | manure-Nr 9 |

*animals’ slaughter ages (MAFF 2012b), namely beef breeds (29.2 months) > crossbred cattle (26.6 months) > dairy bullocks (21.0 months), suggesting that the length of the feeding period was an important determinant of beef cattle NUE. A prolonged fattening period is necessary to develop marbling, which enhances the juiciness, flavor, and tenderness of beef. The variation in marbling might explain the differences in whole-body cattle-Nr among breeds (figure S1) (available online at stacks.iop.org/ERL/15/125007/mmedia), because fat contains less Nr than red meat (MEXT 2015). Moreover, calf production by breeding cattle contributed to the lower beef cattle NUE$^{beef,breed}$, whereas the utilization of dairy bullock calves and crossbred calves (i.e. by-products of milk) promoted the greater values for beef cattle NUE$^{dairy,bullock}$ and beef cattle NUE$^{cross,bred}$. Beef cattle NUE$^{dairy,bullock}$ was similar in magnitude to the beef cattle NUE in the United States (0.20, Leach et al 2012), whereas beef cattle NUE$^{beef,breed}$ and beef cattle NUE$^{cross,bred}$ were lower than the United States value, mainly due to the longer fattening period needed to develop marbling in Japan. The France value (0.15, Godinot et al 2015) for beef cattle NUE$^{beef,breed}$ seems to be greater than our value due to the younger slaughter age (i.e. 16 months). It is true that a prolonged fattening period is essential to meet the demand of marbled beef, but the preference of less marbled beef is also receiving growing popularity in recent years.

3.5. Beef NUEs, beef VNFs, and N footprint

Beef NUE (figure 6) decreased in the order of beef NUE$^{dairy,bullock}$ (0.040) > beef NUE$^{cross,bred}$ (0.032) > beef NUE$^{beef,breed}$ (0.024), reflecting the differences in beef cattle NUE. The feeding period of beef breeds was longer than those of dairy bullocks and crossbred cattle. Breeding cattle that produce beef-breed calves are fed substantial amounts of silage, straw, and hay (inclusive of grazing; figure 5), which have moderate crop NUEs (figure 2); however, beef NUE$^{beef,breed}$ was the smallest among the three types of cattle, in part because calves of dairy bullocks and crossbred cattle were considered as by-products. The dressing percentage (i.e. wt. % of carcass to liveweight) in Japan (63%, MAFF 2010) is almost the same as that in the United States (62%–64%, National Cattlemen’s Beef Association 2014), demonstrating that meat yield does not differ markedly between these countries. Beef-Nr of marbled beef tends to be smaller than that of lean beef (MEXT 2015); the protein contents of the flank, chuck roll, sirloin, and rib were in the order of imported beef > dairy bullock > crossbred cattle > beef breeds (table 2), but the protein contents of the other parts varied only slightly among cattle types (MEXT 2015). Red meat comprises 56 wt. % and 87 wt. % of carcass and dressed beef, respectively (table 3), whereas flank, chuck roll, sirloin, and rib collectively contain only 38 wt. % of red meat (table 4). These combined results suggest that the length of the feeding period to develop marbling, rather than the degree of marbling itself (i.e. less Nr in marbled beef than in lean beef), contributed to the lower beef NUE in Japan than the United States.

Beef NUE$^{dairy,bullock}$ was similar in magnitude to the beef NUE obtained from feedlots in Australia (0.038, Liang et al 2016), but beef NUE$^{beef,breed}$
Figure 5. Feed- and cattle-Nr and beef cattle NUE for beef breeds, dairy bullocks, and crossbred cattle. Feed-Nr was the sum of concentrate-, hay-, straw-, silage-, and other-Nr; ‘other’ includes green forage, grazing grass, and milk (as feed for calves). Beef cattle NUE was calculated as the ratio of cattle-Nr/feed-Nr. Concentrates mainly include grain, oil meal, chaff and bran. Hay, silage and grazing grass are produced in grassland. Straw is produced in upland and paddy fields as a by-product.

Table 2. Protein contents of beef (g 100 g$^{-1}$).

| Cut         | Beef-breed cattle | Dairy bullocks | Crossbred cattle | Imported |
|-------------|-------------------|----------------|------------------|----------|
| Chuck       | 20.2              | 19.9           | 20.0$^{b}$       | 20.4     |
| Chuck roll  | 16.5              | 19.1           | 17.8$^{b}$       | 19.7     |
| Rib         | 14                | 18.8           | 16.7             | 21.7     |
| Sirloin     | 17.1              | 21.1           | 19.1$^{b}$       | 22       |
| Flank       | 11                | 12.8           | 12.2             | 14.4     |
| Inside round| 21.3              | 21.9           | 19.3             | 21.2     |
| Outside round| 20.7             | 21.3           | 21.1$^{b}$       | 21.2     |
| Rump        | 19.2              | 22             | 20.6$^{b}$       | 21.6     |
| Fillet      | 19.1              | 20.8           | 19.0             | 20.5     |

$^{a}$The name for cuts are based on the Japanese standard.
$^{b}$Estimated as an average of beef breeds and dairy bullocks.

Table 3. Weight breakdowns of carcass and dressed beef per animal (%).

|               | Red meat | Fat | Bone |
|---------------|----------|-----|------|
| Carcass       | 56       | 32  | 12   |
| Beef          | 87       | 13  | 0    |

and beef NUE$^{crossbreed}$ were smaller than the Australian value. When the percentage components of slaughtered cattle in Japan (MAFF 2012a) were included in the calculation (figure S3), beef NUE$^{overall}$ and beef VNF without trade were estimated to be 0.037 and 26.3. Beef VNF without trade was similar to that previously estimated for Japanese beef without trade (27.3, Shibata et al 2014). Beef VNF without trade was greater than beef VNF with trade (table 5), suggesting that the importation of beef has reduced the N footprint in Japan. The annual protein supplied from imported beef was more than three times greater than that from beef-breed cattle, but the N footprints were comparable (table 7). This situation accounts for the relatively greater N footprint of Japan (OECD 2008) despite its lower beef consumption per capita (i.e. nearly one-quarter of that in the United States).

3.6. Reducing Nr losses in milk production

The presence of leftover feed-Nr and excess feed-Nr consumption likely contributed to the low milk ing cow NUEs we obtained, because it is a common practice for farmers to feed slightly more than the minimum requirement. To reduce the amount of leftover feed and to prevent feed overconsumption, the feed dosage for each cow should be changed in response to her milk production by using, for
Table 4. Weight breakdown of red meat per animal (%).

| Cut          | Flank | Chuck | Chuck roll | Brisket | Sirloin | Inside round | Thick flank |
|--------------|-------|-------|------------|---------|---------|--------------|-------------|
| Outside round| Neck  | 6.5   | 5.6        | 5.4     | 4.3     | 3.9          | 2.6         |
|              | Rump  |       |            |         |         |              |             |
|              | Rib   |       |            |         |         |              |             |
|              | Hindshank |     |            |         |         |              |             |
|              | Fillet |       |            |         |         |              |             |
|              | Foreshank |    |            |         |         |              |             |

The names for various cuts are based on the Japanese Standard.

Table 5. Annual protein supply (g-N capita\(^{-1}\) yr\(^{-1}\)), self-sufficiency rate (SSR), virtual nitrogen factor (VNF) and N footprint (kg-N capita\(^{-1}\) yr\(^{-1}\)) of animal products.

| Milk and dairy products | Beef |
|-------------------------|------|
| Annual protein supply   | 456  |
| SSR                     | 0.65 |
| VNF                     | 5.6  |
| N footprint             | 2.6  |
| with trade              | 5.0  |
| without trade           | 2.3  |
| with trade              | 4.1  |
| without trade           | 2.9  |

Table 6. Breakdown of annual protein supply (g-N capita\(^{-1}\) yr\(^{-1}\)) and N footprint (kg-N capita\(^{-1}\) yr\(^{-1}\)) of milk and dairy products.

| Japan overall | 296 | 1.7 |
| Hokkaido prefecture | 163 | 1.0 |
| Other prefectures | 133 | 0.7 |
| Imported       | 160 | 0.6 |

Table 7. Breakdown of annual protein supply (g-N capita\(^{-1}\) yr\(^{-1}\)) and N footprint (kg-N capita\(^{-1}\) yr\(^{-1}\)) of beef.

| Overall | 65 | 1.7 |
| Beef-breed cattle | 26 | 1.1 |
| Dairy bullocks | 13 | 0.3 |
| Crossbred cattle | 12 | 0.4 |
| Culled cattle | 14 | –   |
| Imported       | 89 | 1.2 |

Figure 6. Nr flows of beef production (kg-N head\(^{-1}\)). Percentages of Nr as compared with new-Nr are in parentheses. New-Nr is the sum of synthetic-Nr + BNF-Nr. Applied-Nr is the sum of new-Nr + manure-Nr. Feed-Nr is the sum of Nr in feed inclusive of main and by-product feed. Beef-Nr and consumed-Nr are the Nr in produced and consumed meat, respectively.

Table 4. Weight breakdown of red meat per animal (%).

| Cut          | Flank | Chuck | Chuck roll | Brisket | Sirloin | Inside round | Thick flank |
|--------------|-------|-------|------------|---------|---------|--------------|-------------|
| Outside round| Neck  | 6.5   | 5.6        | 5.4     | 4.3     | 3.9          | 2.6         |
|              | Rump  |       |            |         |         |              |             |
|              | Rib   |       |            |         |         |              |             |
|              | Hindshank |     |            |         |         |              |             |
|              | Fillet |       |            |         |         |              |             |
|              | Foreshank |    |            |         |         |              |             |

The names for various cuts are based on the Japanese Standard.

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| Dairy bullocks | 13 | 0.3 |
| Crossbred cattle | 12 | 0.4 |
| Culled cattle | 14 | –   |
| Imported       | 89 | 1.2 |

example, automatic feeding and milking systems. However, by maintaining the optimal activity of rumen microbes, the ratio of roughage to concentrate is also important for increasing the milking cow NUE. Furthermore, to manage increasing numbers of cows per dairy farm, most dairy farmers in Japan rely on feeding silage, due to the humid climate and their busy schedules. To optimize silage digestibility by cutting, drying, and harvesting herbage at the appropriate times, the labor involved needs to be divided between contractors (crop management) and dairy farmers (animal management). Appropriate division of labor might also help to promote manure recycling by improving manure and crop management and by closely monitoring and appropriately managing milking cows to minimize the duration of the dry period. Alternatively, utilization of fallow fields for forage production (Hojito et al 2003).
and recycling of food waste as feed are other options to reduce Nr loss.

3.7. Reducing Nr losses during beef production

Beef NUE is greater in the United States (11%, Leach et al 2012) than in Japan (2.4%–4.0%). In Japan, the lengths of the fattening periods for beef breeds, dairy bullocks, and crossbred cattle are 20, 13, and 19 months, respectively. In the United States, these times are much shorter—only 3–8 months. Besides, cattle being raised or fattened are fed concentrates mainly in Japan. In contrast, calves in the United states and Australia are fed more forage (Drouillard 2018). The length of the fattening period for grass-finished cattle (2–4 years) is longer than that for grain-finished cattle (2–5 months), but beef NUE in grazing (11.9%) was greater than that in feedlots (3.8%) in Australia, because more manure is recycled during grazing than in feedlots (Liang et al 2016). These results collectively suggest that the total concentrate dosage per animal may be an important determinant of beef NUE. Therefore, shortening the fattening period when grains are fed predominantly could reduce Nr losses. Beef NUE in animals grazing on an organically managed beef farm in Japan (Hojito et al 2016) was the same as that in animals grazing in Australia (Liang et al 2016). In light of the factors affecting beef NUE and VNF, it may be important to promote consumer preferences for less marbled beef, to reduce Nr losses associated with beef production (table 1). Alternatively, feeding a low-protein diet supplemented with synthetic amino acids, utilization of fallow fields for forage production (Hojito et al 2003) and recycling of food waste as feed are other options to reduce Nr loss.

3.8. Subjects for future study

Milk and beef production in Japan rely heavily on feed concentrates (figures 3 and 5), most of which are derived from imported feed grain. In the cases of milk and beef, respectively, 47%–89% (depending on region) and 78%–98% (depending on type of beef cattle) of Nr applied was estimated to be used in feed exporting countries, suggesting that the Nr loss in these countries need to be refined (Liang et al 2018). In our study, Nr losses associated with the production of oil meals, straw, chaff, and bran were all attributed to milk and beef production and not to the production of plant oils, rice, or wheat. Similarly, Nr losses associated with the production of dairy bullock and crossbred calves and culled milking cow were all attributed to milk production. However, the choice of whether to attribute Nr losses to main products only, to by-products only, or to both could alter the NUEs of milk and beef. For example, when the Nr loss associated with milk production was attributed to both milk and beef, milk NUE was expected to increase and beef NUE was expected to decrease. Similarly, when the Nr loss associated with the production of by-product feeds (e.g. oil meals, straw, chaff, and bran) was assumed to be zero, milk NUE and beef NUE were expected to increase. This effect is in line with the smaller N footprint previously estimated for Japan, in which the Nr loss associated with the production of by-product feeds was assumed to be zero (Shindo and Yanagawa 2017). Consideration for manure recycling to produce crops other than forage is another explanation for the smaller N footprint as described below.

NUE needs to be calculated carefully when manure-Nr is exported from one farm to another (De Klein et al 2017). In Japan, a substantial portion of manure is composted and then recycled to produce crops other than forage (e.g. high-quality vegetables). This is particularly true to livestock farms in the other prefectures due to the relatively high stocking rates. Manure export reduces the Nr surplus within a farm (Dalgaard et al 2012). In our calculations, manure applied for forage crop production was not considered as a Nr loss; however, manure applied for other crop (excluding forage) production was considered to be a source of Nr loss from milk and beef production. Therefore, Nr flows through by-products and inter-farm recycling of manure need to be accurately accounted for to better understand the overall Nr flows in the environment of livestock. In addition, the quantification of BNF-Nr from legumes needs to be improved to refine crop NUE. The same is applicable to soybeans, because the concentrates fed in Japan contain substantial amounts of defatted soybean meal. In this study, we calculated the NUE values based on the national statistics only with mean values. The spatial and temporal variations in field and animal managements result in a fluctuation in NUE of animal products (van Leeuwen et al 2019) and the average of farm Nr surplus is a crucial indicator of Nr loss to the environment in agricultural landscapes (Dalgaard et al 2012). Besides, the capacity for manure recycling varies in different geographic regions. This is especially true for the other prefectures with high stocking rates. Farm size could be another NUE determinant (Wu et al 2018, Ren et al 2019). It is a subject of future study to consider data uncertainty by using a large number of farmscale data, and then discuss the NUE and VNF values and fine-tuning of agricultural practice at field level. Integrated strategies for statistical extraction of representative farms and collection of robust farm Nr inventory are essential to achieve better results.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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