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Nitrogen balance and use efficiency on dairy farms in Japan: a comparison among farms at different scales

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Abstract

In recent decades, the rate of milk production per unit land area and per cow has increased with the intensification of the dairy system. The possible environmental risks arising from nutrients surpluses, such as nitrogen (N), are often evaluated using the N balance approach. In Hokkaido, the biggest dairy farming area in Japan, many dairy farms have started introducing a new dairy farming system called the total mixed ration (TMR) and biogas system. Feed and manure are managed at a community scale in these systems while each farm focuses primarily on milking cows. Thus, calculating the N balance for this system is complicated. Therefore, this study aimed to evaluate the N surplus and use efficiency (NUE), focusing mainly on the community-based dairy farming system, as described above. We investigated twenty dairy farms comprising a TMR centre (TMR-based farms) and nineteen conventional dairy farms (conventional farms). The Hokkaido dairy farms had a smaller N surplus and higher NUE than farms in other countries. The whole farm N surplus and NUE ranged from −163 to 701 kg N ha⁻¹ and from 20% to 171% with median values of 40.5 kg N ha⁻¹ and 69.5%, respectively. One of the possible reasons for the smaller N surplus and higher NUE is a lower stocking rate (averaged 1.3 cows ha⁻¹) on Hokkaido dairy farms. There were strong relationships between feed N and N surplus because the studied dairy farms depended on purchased feed. In the comparison between the TMR centre and conventional dairy farms, the milk production level per cow and stocking rate tended to increase, and variations between farms decreased on the TMR-based farms. Increasing the amount of home-grown feed with pasture management is essential to decreasing N surplus for the new dairy farming systems.

1. Introduction

Over the past 50 years, the productivity of dairy farming has dramatically increased worldwide (Food and Agriculture Organization of the United Nations 2017). This increase has been achieved by increased application rates of nutrients, particularly nitrogen (N), as chemical fertiliser used for forage production and protein in animal feed (Stott and Gourley 2016, Chobtang et al 2017). The intensification of dairy farm systems resulted in increased milk production per unit land area and per cow. However, along with intensification, dairy farming has imposed significant nutrient surpluses, particularly of N, to the environment (Gourley et al 2012b, Stott and Gourley 2016, Powell et al 2017).

To date, evaluating the environmental impact of dairy farming and its mitigation options has been widely studied in Oceania, Europe, and the United States of America (USA; Gourley et al 2012b, Powell and Rotz 2015, Buckley et al 2016). However, data from other regions is limited. The major milk-producing countries include India, China and Brazil, which account for 28% of the world’s cow and buffalo milk production (Food and Agriculture Organization of the United Nations 2017). Thus, to understand and provide an overview of the
environmental impacts of dairy farming worldwide, more research is needed in other regions, such as South America and Asia, including Japan.

Hokkaido is the biggest dairy farming area in Japan due to its cool climate and vast farmland, and it accounts for 53% of annual milk production (2016) in the whole country (Statistics Department, Ministry of Agriculture, Forestry and Fisheries 2017a). Hokkaido dairy farming production increased from 6.7 Mt in 1990 to 8.5 Mt in 2018 due to the intensification of the industry. The intensification of dairy production systems was partly achieved through the development of total mixed ration (TMR) centres (Yamada 2005). In general, TMR centres in Hokkaido are operated by a community farming system in which pasture production and utilisation are performed by the community so that conventional farmers can reduce their workload (Yamada 2005). The development of the TMR centres allows the dairy industry to increase its productivity despite the ageing of farmers (Suzuki 2005). In some regions of Hokkaido, TMR centres are coupled with biogas plants and the digestate by-product is used as a high-quality fertiliser along with raw manure and composted manure. Although TMR centres and biogas plants have direct benefits for farmers, their impact on the entire N balance and the environment is unclear.

As we stated above, N loss from dairy systems can be released into the neighbouring environment, such as rivers and the atmosphere, and it can degrade the environment through nitrate leaching (Thurber et al. 2014, Smallbone et al. 2016) and nitrous oxide emission (IPCC 2007). Additionally, N can escape to the atmosphere as ammonia from fertiliser and animal waste. The volatilisation of ammonia from animal waste, particularly from dairy systems, is the major source of ammonia in the atmosphere (ApSimon et al. 1987, Kannari et al. 2001). With an increase in the number of cows and dietary N content, the ammonia burden of the atmosphere has increased (Bussink and Oenema. 1998). In addition, the inefficient use of N can result in the loss of profit (Gourley et al. 2012a, Powell and Rotz 2015).

The N balance approach is widely applied to minimise the loss of N from dairy systems (Aarts et al. 2000, Powell et al. 2010, Gourley et al. 2012b, Burchill et al. 2016). Nitrogen surplus and N use efficiency (NUE) are frequently used as indicators of optimum levels of the N cycle on dairy farms. Nitrogen surplus indicates the amount of N inputs as fertiliser or feed that is in excess to the amount exported in product (Gourley et al. 2012b), and NUE implies the relative conversion of imported N into products (Gourley et al. 2012b, de Klein et al. 2016, de Klein et al. 2017). The N surplus is calculated as the difference between the total N imported and exported per hectare (kg N ha$^{-1}$ yr$^{-1}$) (de Klein et al. 2017, Quemada et al. 2020). The NUE is calculated as the total exported N in products divided by the total imported N expressed as a percentage (Gourley et al. 2012b, de Klein et al. 2016). The EU Nitrogen Expert Panel (2015) recently proposed the conceptional framework of the N balance approach with a graphical approach to visualise NUE, N output and input as well as to indicate the difference between actual and target values. In the framework, an NUE value of 50% is the lowest value and 90% is the highest value, which indicates the optimum level (Lassaletta et al. 2014). A N surplus of 80 kg N ha$^{-1}$ yr$^{-1}$ was also included to limit the absolute amount of N loss. Combined criteria were used as a ‘desirable range’ for the N balance. This method was used to investigate the environmental impact of dairy farming globally (de Klein et al. 2016, Quemada et al. 2020) and some tools were developed to help farmers meet regulatory requirements. For example, the ‘Dairy Nitrogen Fertiliser Advisor’, which is available online, helps dairy farmers find out how much N to apply to a particular paddock for a particular grazing rotation in Australia (Stott et al. 2016). Additionally, in New Zealand, tools, such as UDDER farm simulator and OVERSEER (https://overseer.org.nz/), have been widely applied to predict the energy and nutrient flows within dairy production systems by calculating the consumption and output of energy and nutrients on a farm (Hart et al. 1998).

Most of these N-balancing tools require users to add the details of all the N inputs, which are primarily feed N, fertiliser N, bedding material N, and cow N, and the N outputs, which are primarily milk-N and cow N, and prompt farmers to balance the N input and output. Compared with other approaches to mitigate specific N-related environmental impacts, the N balance approaches are useful to reduce the multiple N-related environmental risks. Thus, the N balance approach is a way to avoid pollution ‘swapping’, which means that a reduction in one pathway leads to an increase in another pathway in the regulation process (Stevens and Quinton 2009). As an example of the pollution swappings, Fan et al. (2017) showed that manure application had a lower risk of N leaching than liquid dairy effluent, while Chai et al. (2016) suggested that the use of a solid manure system has a more substantial potential for ammonia (NH$_3$) emissions than the use of liquid manure systems. Monaghan and de Klein (2014) also showed that a restricted autumn and winter grazing strategy achieved reductions in N leaching loss, but it was associated with increases in N loss via NH$_3$ volatilisation and N$_2$O emissions from effluents stored in the confinement systems. Thus, it is important to accumulate data associated with N balance in dairy systems, in the regions where the data are scarce.

Therefore, the objectives of this study were two-fold: 1) to calculate N surplus and NUE in Hokkaido dairy farming at different scales: the TMR centre and conventional farms and 2) to explore the differences and controlling factors of N surplus and NUE.
2. Materials and methods

2.1. Farm selection

Nineteen dairy farms and one TMR centre were studied. The study sites were selected from three primary dairy regions: Central Hokkaido (one farm), Eastern Hokkaido (eight farms and one TMR centre) and Northern Hokkaido (six farms). The exact location of each farm is not shown to protect the privacy of farmers. Two farming systems are used in the area: confinement and a grazing system. The confinement system keeps dairy cows in a shed throughout the year and is commonly used by farms with a relatively larger number of cows. Contrastingly, the grazing system is often used by small-scale farms, but generally, grazing is only possible from May to November, due to harsh winter conditions, and cows are confined for approximately six months of the year, even for the farms under ‘grazing’ systems in table 1 (Hokkaido Research Organization 2002). Of the farms sampled in this study, ten farms used the confinement system, and seven farms used the grazing system (table 1).

The TMR centre is composed of twenty dairy farms in a community, and all of these farms have adopted the confinement system. We treated the TMR centre as one big farm because most of the N input and output data, including forage, manure, feed and fertiliser, were managed collectively. Notably, in the TMR system, individual farmers do not have responsibility and authority regarding land management such as the timing of fertiliser application, harvest and pasture renewal. The farmers that belong to the TMR centre focus on animal management. Additionally, the harvested pasture and dent corn from farms within the TMR centre are centralised and mixed with grains and redistributed to each farm. Therefore, most of the cows in the TMR centre are fed the same diet. Thus, it was appropriate to calculate the nutrient balance for the TMR centre as one system. Also, because of the management systems mentioned above, it was extremely difficult to estimate the nutrient balance for each farm within the TMR centre. Detailed information about each farm is presented in table 1. The farms were assigned alphnumeric codes to protect their privacy.

2.2. Study period

Data were collected over two time-periods. First, we collected the data for farms A to O (except for farm C) from autumn (October or November) 2014 to September or October 2015, except for two farms, which manage their enterprises following the annual calendar: for farm N, the research period was January 2014 to December 2014, and for farm K, the research period was January 2015–December 2015. Next, the data for the TMR centre were collected from January 2018 to December 2018. The data for farm C was collected from October 2017 to September 2018. The data for farms A and B were collected from October 2017 to September 2018 to observe temporal changes in N surplus and NUE.
2.3. The approach used in the current study

We used the farm-gate N balance approach, which assesses N management at the farm level. This approach measures N inputs onto the farm, primarily through imported feed and fertilisers and N output exported from the farm as milk, forage and manure (Buckley et al. 2013). We did not consider the N fertiliser used to grow the purchased feeds because it was difficult to estimate the N used to grow the purchased feeds, as most of the feeds used in Hokkaido dairy farms are imported from overseas. We emphasise this point as a limitation of the study. However, the farm–gate N balance approach still provides useful information for dairy farms systems in this region. All N input and output data were reported as kg N ha$^{-1}$ of farm area year$^{-1}$ (Quemada et al. 2020). As previously mentioned, we considered the TMR centre as one big farm. We calculated N surplus using the ‘productive dairy farm area’ (Stott and Gourley 2016) as the land assigned to feed production, i.e. the land for forage production, crop production and grazing. Thus, the land area for milking sheds and households was not included when we calculated the N surplus.

Natural contributors of the N cycle, such as the N input from N fixation, atmospheric deposition, output through N leaching, the volatilisation of NH$_3$ and emission of N$_2$O and dinitrogen were not included in this study. We did not aim to understand the N cycle completely but to quantify the N input and output with the data available to farmers. Also, we assumed that the effect of natural contributors was small. In Hokkaido, the dominant sward is Timothy grass (Iida et al. 2009), and the coverage of clover is low, with 9% legume pasture contents (Otsuka 2016). Gourley et al. (2012b) reported that based on the 205 legume zones assessed, the median legume content (% dry matter; DM) was 6% (mean 11%, CV 137%), which contributed only 17 kg N ha$^{-1}$ yr$^{-1}$. Thus, the maximum possible contribution of N fixation to the N balance can be up to 17 kg N ha$^{-1}$ yr$^{-1}$ (Gourley et al. 2012b). We discuss the potential losses affecting the results in estimating N surplus and NUE later. The conceptual framework of NUE (the EU Nitrogen Expert Panel 2015) was used to visualise the overall differences between conventional farms and TMR centre.

2.4. Questionnaire and interview

A standard questionnaire was filled in online to collect basic information, including farm size, cow number (lactating and drying cows and calves) and the existence of several input/output types, such as home-grown feeds, beddings and manure. Then, two follow-up visits were conducted per study period to collect more detailed information through interviews.

2.5. Data collection and calculation

2.5.1. Manure and fertiliser

The mass of manure was estimated based on the volume of truckloads used for its delivery. The concentration of N within the manure was obtained from data from a research institution, which farmers cooperated with individually, or from the literature if individual data were not available (National Agriculture and Food Research Organization 2006). For the TMR centre, we considered all the manure deliveries to each farm to the biogas plant and manure shed as outputs. Then, digestate and row manure were considered as nutrients imported to the farms. Notably, the EU nitrogen expert panel used the N output of manure as a negative N input (EU Nitrogen Expert panel 2015). However, in the TMR centre targeted in the current study, the manure was exported from the farms to the biogas plants, and the exported manure was transformed to anaerobic digestate and returned to the farms belonging to the TMR centre. Thus, we decided to express the manure transfer from the TMR centre farms to the biogas plants as ‘output’ and the digestate transfer from the biogas plants to the TMR centre farms as ‘inputs’. Data on the mass transfer of manure to the biogas plant and manure shed and N concentration in digestate were obtained from records of the Japan Agricultural Cooperatives (JA). The mass of chemical fertiliser reported as bills and application rate per hectare were recorded where possible. The standard concentrations provided by their commercial suppliers were used to obtain the nutrient contents of the chemical fertiliser. During the interview, tables of ingredients on the chemical fertiliser package were photographed.

2.5.2. Feed and bedding

The mass of the purchased feed was obtained from available bills, or it was calculated based on the amount of feed given to each cow, presented as kg cow$^{-1}$ day$^{-1}$, based on information from the interview. For the TMR centre, the JA recorded the amount of forage harvested from each farm based on the number of tanks (volume) and the mass of purchased feed. We considered the forage that was exported from farms as the output of nutrients. The total amount of forage and purchased feed used for the TMR preparation was calculated as input.

The mass of the bedding was obtained from the bills and the interview. When the amount of bedding was mentioned as the number of forage rolls, this value was converted into kilograms based on the roll size: diameter and height. When the mass was referred to as volume (e.g. sawdust), the value was converted into kilograms based on the density of 0.55 t m$^{-3}$ (Ministry of Environment, Government of Japan 2006). Some farmers had
sold some bales during the studied period. Thus, the forage output was recorded as roll number, and it was converted into mass using the roll size information.

The N concentration for feed and bedding was calculated using the standard concentration published for Japan (National Agriculture and Food Research Organization 2009), or it was provided by commercial suppliers.

2.5.3. Animal

The N flows related to animal transfers (birth, purchase, sale and death) were recorded from bills and/or livestock insurance records. During the interview, details were obtained about transfers via the calving farm, the weight of the calves and milking cows according to different breeds. The N concentration of livestock was calculated based on their live weight corresponding to breed and age multiplying by N content of 2.8%, which was also used in previous studies (Gourley et al 2012b, Burchill et al 2016).

2.5.4. Milk

The amount of milk exported was recorded from the bills. The milk quality of almost all farms (except farm M and O) was analysed on a monthly basis by Hokkaido Dairy Milk Recording & Testing Association, and these data were used to calculate protein contents. Standardised N concentration from Gourley et al (2012b) was used for farm M and O. The N concentration of milk was calculated from its protein contents divided by 6.38 (McDonald et al 2010).

2.5.5. Statistics

Correlations between the calculated N surplus values (kg N ha\(^{-1}\)) and one of the major N flow types (i.e. feed N, chemical fertiliser N and milk-N, expressed as kg N ha\(^{-1}\)) were calculated using the Pearson correlation approach and the statistical software R (ver. 3.6.3) and RStudio (ver. 1.2.5033). We assumed that the relationship between the variables was linear and the data were normally distributed.

3. Results

3.1. N surplus and whole farm NUE and factors controlling the N surplus

The whole farm N surplus ranged from 163 to 701 kg N ha\(^{-1}\) yr\(^{-1}\) with a median value of 40.5 kg N ha\(^{-1}\) yr\(^{-1}\). The whole farm NUE ranged from 20% to 171%, with a median value of 69.5% (table 2). We mapped the whole farm NUE results into the conceptional framework of NUE proposed by the EU Nitrogen Expert panel (2015) (figure 1). The TMR centre was characterised by higher input and output values than the other conventional farms that were studied. Feed and fertiliser were the two major N import sources for all farms (table 2). However, there were variations in export sources. The TMR centre, farm G and K had the most significant component of export N, whereas, for farm A2 and F, it was forage. For farm N, the most significant N export was through animals.

| Table 2. Nitrogen (N) input and output factors, N surplus and whole-farm NUE. Whole farm NUE is the ratio between N outputs in products over N inputs, which is used to evaluate N use outcomes of an agricultural system and/or the risk of environmental N losses. |
|-----------------|-----------------|----------------|----------------|----------------|-----------------|
| TMR             | Fertilizer      | Feed           | Animal-in       | Milk           | Forage          | Output Manure   | Animal-out      | N surplus (kg ha\(^{-1}\)) | Whole farm NUE (%) |
| TMR             | 433             | 532            | 6              | 110            | 112            | 463            | 59              | 228              | 77             |
| A1              | 24              | 45             | 0              | 16             | 4              | 0              | 0               | 48               | 30             |
| B1              | 10              | 23             | 0              | 25             | 2              | 0              | 0               | 5                | 84             |
| C               | 0               | 104            | 0              | 74             | 37             | 0              | 0               | -7               | 107            |
| A2              | 26              | 66             | 0              | 22             | 96             | 0              | 2               | -28              | 130            |
| B2              | 7               | 87             | 0              | 34             | 25             | 0              | 2               | 33               | 65             |
| D               | 55              | 106            | 0              | 85             | 68             | 0              | 3               | 5                | 97             |
| E               | 134             | 372            | 0              | 119            | 0              | 6              | 14              | 367              | 27             |
| F               | 41              | 186            | 0              | 44             | 71             | 0              | 5               | 107              | 53             |
| G               | 100             | 280            | 0              | 88             | 0              | 192            | 7               | 93               | 76             |
| H               | 238             | 631            | 2              | 125            | 0              | 23             | 22              | 701              | 20             |
| I               | 47              | 59             | 0              | 36             | 0              | 32             | 8               | 30               | 72             |
| J               | 45              | 43             | 0              | 27             | 0              | 0              | 4               | 57               | 35             |
| K               | 98              | 128            | 5              | 54             | 41             | 288            | 11              | -163             | 171            |
| L               | 29              | 69             | 3              | 30             | 11             | 0              | 9               | 51               | 50             |
| M               | 5               | 43             | 0              | 26             | 5              | 0              | 1               | 16               | 67             |
| N               | 18              | 101            | 0              | 66             | 0              | 0              | 86              | -33              | 128            |
| O               | 62              | 547            | 10             | 150            | 0              | 9              | 13              | 447              | 28             |
We evaluated the differences in the N balance between the grazing and confinement systems, but we did not find major differences. When evaluating the relationship between the N balance and factors of N input and output, feed, milk and fertiliser showed statistically significant correlations with N surplus \((p < 0.01)\). Feed, in particular, had a strong positive correlation with N surplus \((R^2 = 0.77)\) (figure 2).

### 3.2. TMR-based farms and conventional farms

The farms comprising the TMR centre (TMR-based farms) had higher milk production and stocking rates than conventional farms (figure 3). The average annual milk production was 10316 ± 1350 kg cow\(^{-1}\), and average stocking rate was 1.98 ± 0.49 cow ha\(^{-1}\) on TMR-based farms. However, average annual milk production was 8486 ± 1825 kg cow\(^{-1}\), and the average stocking rate was 1.26 ± 0.78 cow ha\(^{-1}\) on conventional farms.

### 4. Discussions

#### 4.1. N surplus and whole-farm NUE

Our results showed that the majority of researched Hokkaido dairy farms had relatively smaller N surplus and higher NUE (table 2 and figure 1) than dairy farms from other studies in other countries. The TMR centre was plotted as an outlier compared to the conventional farms in figure 1 due to differences in the N flow calculation: almost all of the forage and manure produced on the TMR-associated farms was exported from the farm once and imported back again. The N surplus and NUE ranged from 116 to 409 kg N ha\(^{-1}\) and 21% to 42% on grazing dairy farms in New Zealand (Ledgard \textit{et al} 1999, Monaghan and de Klein 2014), 98 to 252 kg N ha\(^{-1}\) and 29% to 42% on commercial dairy farms in the Netherlands (Oenema \textit{et al} 2012) and 140 to 314 kg N ha\(^{-1}\) and 25% to 64% on commercial dairy farms in the USA (Hristov \textit{et al} 2006), respectively. One of the possible reasons behind the smaller N surplus and the higher NUE observed in the current study was the shorter turnover rate of milking
cows in Japan. The average productive life of a dairy cow in Japan is about three years (Ministry of Agriculture, Forestry and Fisheries 2017) while 4.2, 3.7 and 2.7 years have been reported as the average productive life of a dairy cow in New Zealand, the Netherlands and the USA, respectively (Food and Agriculture Organization of the United Nations 2017). Milk production reaches its peak at the third to fourth calving and declines after the fifth calving (Ray et al. 1992). Therefore, the average productive life, which is the time between first calving and culling (Food and Agriculture Organization of the United Nations 2017), can affect the whole farm N flow. Younger milking cows can produce more milk per cow than older cows, which may contribute to better N performance on Hokkaido farms. Supporting this idea, de Klein et al (2016) showed in a case study that the elimination of less productive cows could lead to an increase of NUE and reduction of N surplus.

Another reason for the relatively higher NUE in Japan than previously reported NUE values from other regions could be because the cows were confined for an extended period during the year, even if some farms apply grazing systems. When farmers apply the confinement system, they can easily optimise the crude protein (CP) contents in feed to maximise milk production (Powell et al. 2010, Gourley et al. 2012a), which may improve NUE. To support this, Gourley et al. (2012a) reported that in summer, confinement-based dairy farms in the USA accomplished higher feed NUE than grazing-based dairy farms in Australia.

Additionally, the relatively smaller stocking rate observed in the current study is a reason for higher NUE in Hokkaido than other countries. In New Zealand, 3 cows ha−1 was reported as an average stocking rate in dairy farms (Monaghan et al. 2005, Pinxterhuis et al. 2015) and grazing livestock densities of 3.6, 3.1 and 2.5 cows ha−1 were reported for the Netherlands, Italy and Ireland, respectively (Fangueiro et al. 2008, eurostat 2017). Only two farms in the current study exceeded a density of 2.5 milking cows ha−1 and those farms showed a higher N surplus and lower NUE than the other farms. Previous studies showed that the stocking rate was positively correlated with the N surplus (4.7 to 7.5 cows ha−1 and 0.4 to 3.7 cows ha−1, Fangueiro et al. 2008, Gourley et al. 2012b, respectively). Powell et al. (2010) simulated that an increase in stocking rate can increase N surplus, and N surplus is negatively correlated with NUE. However, Ramirez and Reheul (2010) showed in a model that the stocking rate was negatively correlated with N surplus when the stocking rates varied from 2.98 to 3.18 cows ha−1. Similarly, Huebsch et al. (2013) showed that an increase in stocking rate of 2.25 to 2.88 cows ha−1. The current study showed a similar trend to the models stating that the stocking rate was positively correlated with N surplus (e.g. Fangueiro et al. 2008). This could be because the models that agree with our findings were used to research dairy farms applying the confinement system. As we explained in section 2.1, the cows researched in our study spend at least six months of the year in confinement, as grazing is only possible during spring and summer. In the confinement system, stocking rates can easily be increased by purchasing more feed or by increasing labour as well as the size of cowsheds, whereas in the grazing systems, matching stock feed demands and production is critical to increase stocking rates (Huebsch et al. 2013). Although excess dairy cow numbers per land area increase environmental risks, an appropriate number of dairy cows per unit of land can maximise the utilisation of home-grown feed and potentially contributes to better N management.

For Hokkaido dairy farms, the stocking rate was often controlled by the size of the shed rather than the size of the whole farm. Dairy farms require solidly structured sheds for winter in Hokkaido, and many farmers may not
be able to afford appropriately sized sheds to maximise the NUE. Another factor constraining increased stocking rates on Hokkaido dairy farms is available labour. Individual dairy farms operating as a family business dominate the management systems of Hokkaido farms. Also, the annual working time on dairy farms was 2,025 h person\(^{-1}\) in Hokkaido (Statistics Department, Ministry of Agriculture, Forestry and Fisheries 2017b) while the value of all employment in Japan was 1,719 h person\(^{-1}\) (The Japan Institute for Labour Policy and Training 2017). Thus, appropriate stocking rates can only be achieved with the consideration of optimising the working hours of farmers.

In contrast to other studies, a negative value for N surplus (>100% of NUE) was found for some farms in the current study (table 2), suggesting that some of the Hokkaido dairy farms had smaller inputs than outputs than farms in other countries. The negative N surplus values indicate N mining from the land, which leads to N depletion in soils (Chen et al. 2016, Quemada et al. 2020). Additionally, the negative value of the N surplus might indicate the possible overestimation of the N exports in the current study. The possible poor documentation of manure transport might lead to under and/or overestimation of N surplus and NUE.

4.2. Limitations and sensitivities of the data

Poor documentation and possibly inaccurate information might have caused errors in this study. For example, the amount of manure exported to other farms was often roughly estimated using the number of truckloads. The nutrient contents of manure depend on the age of the manure, which was hard to accurately estimate. Additionally, the printed CP values of purchased feeds in Japan, which were used as the N values of the feeds in the current study, are guaranteed minimums, meaning that the actual CP values for the feed could be higher. Thus, the CP values of feeds should ideally be measured regularly to provide better data. Additionally, the impacts of the management of feeds and manure on each farm were unknown. For example, there are some losses of feeds within cowsheds because not all the feeds go into the mouths of cows. Steinshamn et al. (2004) argued that 6% to 10% of offered feed N can be feed loss. If all the offered feed was eaten, for instance, feeding the residues from the cows to the heifers would have improved N utilisation. Similarly, not all the manure produced is stored on-farm because some of the manure can be lost during transportation from cowsheds to manure storage areas. Future studies should perform error and sensitivity analyses on N balance data calculated based on the bills and interviews with farmers, as performed in the current study. Additionally, microbial activities related to the N cycle, such as N fixation, were not considered in the current study. In Hokkaido, the dominant sward is Timothy grass (Iida et al. 2009), and the coverage of clover is relatively low. For example, a previous study showed that the legume contents were averaging 9% in Hokkaido pastures (Otsuka 2016). Similarly, Gourley et al. (2012b) reported that, based on the 205 legume zones assessed in Australia, the median legume content (DM) was 6%, which contributed only 17 kg N ha\(^{-1}\) yr\(^{-1}\). In the current study, the median N inputs of chemical fertiliser plus manure averaged 43 kg N ha\(^{-1}\) yr\(^{-1}\). Therefore, the contribution of N fixation to the overall N balance might be important for farms not to rely on the use of chemical fertilisers. Thus, The Nitrogen Expert Panel (2015) suggested to include biological N fixation by legumes to the N balance approach. Further research is required to determine N flow driven by legumes.

Additionally, for the TMR centre data, substantial amounts of N were exported from the farms to the biogas plants as manure whereas the N was returned from the biogas plants to the farms as anaerobic digestate. We expected that the amount of N transfer between the farms and the biogas plants was roughly the same. However, our calculations suggested that the N returned from the biogas plants to the farms as digestate was much smaller than that exported from the farms to the biogas plants as manure. This could be because of the overestimation of the N transported from farms to the biogas plants because it was difficult to estimate the N content of the manure from each farm within the TMR centre: we used one value for the N contents of the manure from the whole TMR centre. Also, the N could be lost and diluted during the storage of the digestate at the biogas plants, as the biogas plants had open-top digestate storage tanks and N could be volatilised and diluted by rainfall and snow.

4.3. The controlling factor for N surplus

Feed was the most important factor for N surplus in Hokkaido dairy farms (figure 2). However, Gourley et al. (2012b) reported that there was no significant relationship between feed and N surplus but rather stated that the amount of N fertiliser used on the farms was related to the N surplus. The studies overseas often reported that the N input as fertiliser was larger than the N input as feed (Gourley et al. 2012b, Buckley et al. 2016). The median values for fertiliser N and feed N were 104.5 kg N ha\(^{-1}\) and 71.3 kg N ha\(^{-1}\) in Australia (Gourley et al. 2012b) whereas, they were 43 kg N ha\(^{-1}\) and 102.5 kg N ha\(^{-1}\) in this study, indicating that Hokkaido dairy farms depend more on purchased feed than home-grown feed. In Japan, the feed self-efficiency ratio was 12%, 77% and 25% for concentrate feed, roughage (i.e. silage) and total feeds used for dairy production, respectively (Ministry of Agriculture, Forestry and Fisheries 2020). Yet, the milk production levels were relatively higher in Australia.
(10,866 kg fresh milk ha$^{-1}$) than the targeted farms in the current study (9,153 kg fresh milk ha$^{-1}$) when median values were compared.

These values suggest that the targeted farms in Hokkaido might be able to reduce the N inputs from purchased feeds while increasing the N inputs as chemical fertiliser N. To achieve this, Hokkaido farmers could aim to produce silage with relatively higher CP, then the silage can be the sole (or dominant) feed used to produce milk. A previous study reported that the yield of milk and protein maximised when cows were fed a diet with a CP of 16.5% (Colmenero and Broderick 2006). This could be achieved by optimising or increasing cutting timings for grass to produce silage because the grass is often harvested at its heading stage in Hokkaido, and the quality of the silage is not optimal when grass is harvested at the heading stage (Miyaji et al. 2020). The CP value of Timothy grass-based silage declined with delayed harvest timings (166, 145 and 113 g kg DM$^{-1}$, harvested at the end of May, the beginning of June and the middle of June, respectively). Similarly, the CP value of Timothy grass-based silage was reported as 139, 153 and 129 g kg DM$^{-1}$ for the first cut at late vegetative, early bloom and bloom stages, respectively (National Agriculture and Food Research Organization 2009). Thus, we suggest producing silages using grass harvested earlier to reduce N imports to Hokkaido dairy farms.

However, it is often impossible to apply early harvesting strategies in Hokkaido because the grass growth rates are extremely fast in early spring in Hokkaido and farmers (or harvesting contractors) cannot optimise harvest timings even if their machines are fully operating. We often find dairy farmers in Hokkaido selling extra silage, particularly those farmers who harvest late and end up with low-quality silage and needing to purchase concentrated feeds. This situation is not ideal, both regarding N flow and optimising profits for farms.

Grassland in Hokkaido has been markedly degraded by the invasion of quackgrass and reed canary grass (Iida et al. 2009, Deguchi 2016). Thus, the improvement of pasture quality based on pasture compositions and the appropriate timing of harvesting may be essential to decrease N inputs for Japanese farmers.

4.4. Characteristics of Hokkaido dairy farms

The studied Hokkaido dairy farms varied substantially in farm characteristics and management, including land and herd size, resulting in N surplus markedly varying from −163 to 701 kg N ha$^{-1}$ yr$^{-1}$. Comparing milk production and stocking rates between the conventional and TMR-based farms showed a reduction in the variation among farms and an increase in the values for the TMR-based farms (figure 3). Generally, the TMR centre aims to reduce working hours for feed production and improve milk productivity (Kubota et al. 2014). The TMR centre achieved these aims by outsourcing feed production.

However, the feed production costs for the TMR centre tend to be larger than those for conventional dairy farming because of the commission fee (Kubota et al. 2014). Fujita (2014) argued the importance of the thoroughness of farm management and feed formulation to achieve a high profit for TMR centres. Some TMR centres hold seminars for farmers on topics, such as appropriate feeding and herd management, to maximise the profit of TMR centres. Farmers can apply similar management strategy because they use the same quality of feed. These characteristics of the TMR centre might contribute to reducing the variation in the performance between farms.

5. Conclusion

Hokkaido dairy farms had a smaller N surplus and higher NUE than previous studies in other countries. In the current study, the mean value for N surplus was 40.5 kg N ha$^{-1}$ yr$^{-1}$ and the NUE was 69.5%. The lower stocking rate contributed to a relatively higher NUE on Hokkaido farms. Only two farms in the current study exceeded a stocking rate of 2.5 milking cows ha$^{-1}$. This might be because of the limitation of the size of the shed but not the size of the farm constraining the number of cows per farm. Feed N was the most substantial N input factor, and it had a strong relationship with N surplus. It was because the studied farms highly depended on purchased feed. Increasing home-grown feed with the improvement of pasture quality could be essential to decreasing the N inputs. Compared with the TMR-based farms and conventional farms, the annual milk production per cow and the stocking rate increased, and the variation between farms decreased on the TMR-based farms. The development of the TMR centre and biogas plants to manage feeds and manure intensively rather than by a conventional farm can help farming communities reduce the risk of labour shortages, but careful management is necessary to minimise excess increases in N surplus.

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**References**

Aarts H F M, Habekotte B and van Keulen H 2000 Nitrogen (N) management in the ‘De Marke’ dairy farming system *Nutr Cycl Agroecosys.* 56 231–40 [https://doi.org/10.1023/A:1007146.30000](https://doi.org/10.1023/A:1007146.30000)

ApSimon H M, Kruse M and Bell J N B 1987 Ammonia emissions and their role in acid deposition *Atmos. Environ.* 21 1939–46

Buckley C, Murphy P and Wall D P 2013 Farm-gate N and P balances and use efficiencies across specialist dairy farms in the Republic Ireland *Rural Economy and Development Programme, Teagasc (Working Papers)* 1302

Buckley C, Wall D P, Moran B, O’Neill S and Murphy P N C 2016 Farm gate level nitrogen balance and use efficiency changes post implementation *Nutr Cycl Agroecosys.* 104 1–13

Burchill W, Lanigan G J, Li D, Williams M and Humphreys J 2016 A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions *Agr Ecosyst Environ.* 220 262–10

Bussink D W and Oenema O 1998 Ammonia volatilization from dairy farming systems in temperate areas: a review *Nutr Cycl Agroecosys.* 33 19–33

Chai L, Krobel R, MacDonald D, Bittman S, Beauchemin K A, McGinn S M and Vanderzant A 2016 An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: mitigation potential of diet and manure management practices *Atmos. Environ.* 126 1–14

Chen D, Lam S K, Mosier A R, Eckard R and Vitousek P 2016 Should soil nitrogen be managed? *Proc. of the 2016 Int. Nitrogen Initiative Conf., Solutions to improve nitrogen use efficiency for the world* (4–8 December 2016) (Melbourne, Australia)

Chobtang J, Ledgard S F, McLaren S J and Donaghy D J 2017 Life cycle environmental impacts of high and low intensification pasture-based milk production systems: a case study of the Waikato region, New Zealand *J. Clean. Prod.* 140 664–7

Colmenero J J and Broderick G A 2006 Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows *J. Dairy Sci.* 89 1704–12

Deguchi K 2016 Invasion of Rhizomatous Grasses on Timothy Grassland in Hokkaido *Jpn J Grassl Sci.* 62 153–7

de Klein C A M, Monaghan R M, Alfaro M, Gourley C J P, Oenema O and Powell J M 2016 Realistic nitrogen use efficiency goals in dairy production systems: a review and case study examples *Proc. of the 2016 Int. Nitrogen Initiative Conf., Solutions to improve nitrogen use efficiency for the world* (4–8 December 2016) (Melbourne, Australia)

de Klein C A M, Monaghan R M, Alfaro M, Gourley C J P, Oenema O and Powell J M 2017 Nitrogen performance indicators for dairy production systems *Soil Res.* 55 679–88

EU Nitrogen Expert Panel and 2015 Nitrogen Use Efficiency (NUE) – an indicator for the utilization of nitrogen in agriculture and food systems (Altern, Wageningen, Netherlands: Wageningen University)

eurostat 2017 Agri-environmental indicator - livestock patterns. eurostat Statistics Explained [http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_livestock_patterns](http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_livestock_patterns). Accessed 04 January 2018

Fan J et al 2017 Effect of application of dairy manure, effluent and inorganic fertilizer on nitrogen leaching in clayey fluvo-aquic soil: a lysimeter study *Sci. Total Environ.* 592 206–14

Fangueiro D, Pereira J, Coutinho J, Moreira N and Trindade H 2008 NPK farm-gate nutrient balances in dairy farms from Northwest Portugal *Eur. J. Agron.* 28 625–617

Food and Agriculture Organization of the United Nations 2017 Livestock primary. FAOSTAT. Accessed 18 November 2017 [http://faostat.fao.org/faostat/en/#data/QL](http://faostat.fao.org/faostat/en/#data/QL)

Forster P, Ramaswamy V, Artaxo P, Bernsten T, Betts R, Fahey D W, Haywood J, Lean J, Lowe D C, Myhre G, Nagawa J, Prinn R, Raga G, Schulz M and Van Dol Run D 2007 Changes in Atmospheric Constituents and in Radiative Forcing *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averny, M Tignor and H L Miller (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) [https://ipcc.ch/publications_data/ar4/wg1/en/ch2s2-10-2-2.html](https://ipcc.ch/publications_data/ar4/wg1/en/ch2s2-10-2-2.html)

Fujita 2014 Business model for dairy farming to have high returns and spare time and lightening of labour by TMcentes National Agricultural Research Center for Hokkaido Region farm management Research. 111 39–55

Gourley C J P, Arons S R and Powell J M 2012a Nitrogen use efficiency and manure management practices in contrasting dairy production systems *Agr Ecosyst Environ.* 147 73–81

Gourley C J P, Dougherty W J, Weaver D M, Arons S R, Avitz I M, Gibson D M, Hannah M C, Smith A P and Peverill K I 2012b Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms *Anim Prod Sci.* 52 929–44 [http://turf-www1.massey.ac.nz/~flrc/publications_and_data/art4/vgl/en/ch2x2-10-2-2.html](http://turf-www1.massey.ac.nz/~flrc/publications_and_data/art4/vgl/en/ch2x2-10-2-2.html)

Hart R P S, Larcombe M T, Sherlock R A and Smith L A 1998 Optimisation techniques for a computer simulation of a pastoral dairy farming system *Comput. Electron. Agric.* 19 282–93

Hristov A N, Hazen W and Ellsworth JW 2006 Efficiency of use of imported nitrogen, phosphorus, and potassium and potential for reducing phosphorus imports on Idaho dairy farms. *J. Dairy Sci.* 89 3702–12

Huebsch M, Horan B, Blum P, Richards K G, Grant J and Fenton O 2013 Impact of agronomic practices of an intensive dairy farm on nitrogen concentrations in a karst aquifer in Ireland *Agr Ecosyst Environ.* 179 187–99

Iida K, Deguchi K and Hawaii H 2009 A report on the grassland vegetation in Tokachi region *Journal of Hokkaido Society of Grassland Science.* 43 44 Japan Waste Information Center 2016 Count unit and quantity conversion factor of industrial waste, ver. 1.3. Japan Waste Information Center [http://jwnet.or.jp/jwnet/pdf/gyouseihoukoku_jyuryoukanzaisou.pdf](http://jwnet.or.jp/jwnet/pdf/gyouseihoukoku_jyuryoukanzaisou.pdf). Accessed 01 February 2018

Ibara Sumio, Takeda Yoshihiko, Nakano Chodoruboru, Ishida Toru, Hazama Nonoru, Kiso Seiji, Minekazi Yasuhiro, Toutsui Mitsuaki, Okumura Masatoshi and Hokkaido research organization, Agricultural Research Department, Dairy Research Centre Tenpoku Sub Centre 2002 Monthly Management in Grazing Farm *Tempoku Grazing Guide* (Soya, Hokkaido: Hokkaido Government Sousya)
