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Soil Fertility Management and Grassland Renovation on Dairy Farms in Japan: Regional Differences between Hokkaido and Other Prefectures

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Abstract

In 2015-2016, we investigated the farmland management procedures used on dairy farms in Japan using a mail-back survey. In Hokkaido, 98% of the surveyed farms had meadows, 53% had pastures, and 49% had forage crop fields. In all other prefectures, 19% of farms had meadows, 10% had pastures, and 90% had forage crop fields. The median area of each field category per farm was greater in Hokkaido than in the other prefectures. In all places, the application rate of organic fertilizer decreased in the following order: forage crop field > meadow > pasture (37, 8.7, and 2.7 Mg-manure ha^{-1} y^{-1}, respectively, in Hokkaido). In forage crop fields, organic fertilizer was applied at lower rates and inorganic fertilizer was applied at higher rates in Hokkaido than elsewhere (37 vs. 69 Mg-manure ha^{-1} y^{-1} and 42 vs. 22 kg-N ha^{-1} y^{-1} respectively). In meadows, organic fertilizer was applied at lower rates in Hokkaido (8.7 vs. 14 Mg-manure ha^{-1} y^{-1}); however, inorganic fertilizer was applied at similar rates. The annual rate of grassland renovation with full-inversion tillage in 2006-2010 was 3.0% in Hokkaido and 1.3% in the other prefectures. In both regions, manure was intensively applied during grassland renovation.

Discipline: Agricultural Environment
Additional key words: farmyard manure, forage crop field, inorganic fertilizer, meadow, pasture

Introduction

Livestock excreta contain nutrients and organic matter and can be used to fertilize crops. The application of livestock excreta as organic fertilizer is crucial to achieve sustainable forage production and to simultaneously promote soil carbon sequestration (Kitamura et al. 2021). Cattle wastes, including excreta and bedding materials, produced by dairy farming in Japan are a significant nutrient source, with annual totals of 196 Gg of nitrogen (N), 27 Gg of phosphorus (P), and 170 Gg of potassium (K) (Kohyama et al. 2006). Inorganic fertilizers are used to supplement the nutrient requirements of forage and common crops. In Japan, the most popular pretreatment of livestock excreta is composting of manure followed by the storage of slurry (GIO 2021).

Hokkaido, which is the second largest island in Japan and the largest and northernmost prefecture, belongs to the subarctic zone, whereas most of the other prefectures belong to the temperate zone (MAFF 2018a). Therefore,

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most of Japan's meadows and pastures with cool-climate grasses are in Hokkaido and at high altitudes in the other prefectures. In the other prefectures, agricultural lowland area is usually used as paddy fields, i.e., there is an insufficient land area for forage production. This is the principal reason that the stocking rate of dairy and beef cattle is lower in Hokkaido than in the other prefectures (Mori et al. 2020). In Hokkaido, meadows for hay harvesting and pastures for animal grazing are intensively used for livestock production, whereas in other prefectures, forage crop fields are intensively used for this purpose. Grassland renovation is necessary to maintain the quality and quantity of herbage by restoring deteriorated vegetation (Tarumi et al. 2021). Consequently, the two regions differ in forage species, farmland area breakdown by field type, soil fertility management, and frequency of grassland renovation; however, few quantitative data are currently available. Government statistics include the amount of manure used by farmers, but the amount of manure application to each field type is unavailable.

With this survey, we intended to capture the whole picture of farmland management on dairy farms in Japan, focusing on farmland area breakdown, soil fertility management, and grassland renovation and to examine the regional differences between Hokkaido and other prefectures.

Materials and methods

1. Distribution and collection of questionnaires

In 2015 and 2016, a mail-back survey was conducted in dairy farms in Japan. With the assistance of dairy cooperatives, public research institutes, and universities, 2000 self-completion questionnaires were distributed by hand or by post to dairy producers. Completed questionnaires were sent by post to Hokkaido University and were then aggregated (Hatano 2017).

2. Questionnaire items and survey period

The survey contained questions regarding (1) management style; (2) farmland area breakdown; (3) manure, slurry, and inorganic fertilizer application rates; (4) areas of fertilizer application; (5) total area of grassland, i.e., meadows, pastures, and meadow/pasture dual-purpose fields; and (6) area of grassland renovation using full-inversion tillage, shallow tillage, or a tine drill. The questionnaire asked for annual data from 2014 or 2015 for questions 1-4 and for decadal data from 2006 to 2015 for questions 5 and 6. Note that grassland renovation with full-inversion tillage is used to reduce radiocesium transfer from soil to herbage (Fesenko et al. 2007). The renovation rate was expected to be temporarily increased following the Fukushima Daiichi Nuclear Power Plant accident in March 2011, and data on renovation rates from 2006 to 2010 were used to indicate the rates under normal conditions.

3. Regional categories

Based on farm addresses, completed questionnaires were divided into two regional categories: (1) Hokkaido and (2) prefectures other than Hokkaido.

4. Farmland categories

Farmlands were classified as (1) forage crop fields, (2) meadows (grass for hay harvesting), (3) pastures (grass for animal grazing), (4) meadow/pasture dual-purpose fields (used for both harvesting and grazing), (5) fallow, (6) rangeland (with native species), (7) forests, (8) paddy fields, and (9) upland fields for common crops. We focused our analysis of management types on 1-3. Note that double-cropped fields—for example, with rotation of annual grass species and silage corn—were included in the forage crop category.

5. Manure, slurry, and inorganic fertilizer application

In each region, the area-weighted means of manure (Mg ha^{-1} y^{-1}), slurry (Mg ha^{-1} y^{-1}), and inorganic fertilizer (kg ha^{-1} y^{-1}) application rates were calculated for each farmland category as follows:

$$Fertilizer\ application\ rate\ = \frac{\sum Fertilizer\ amount}{\sum Farmland\ area},$$

where $\sum$*Fertilizer amount* is the sum of manure (Mg y^{-1}), slurry (Mg y^{-1}), or inorganic fertilizer (kg y^{-1}) applied to one farmland category and $\sum$*Farmland area* is the total area (ha) in the farmland category. Note that $\sum$*Farmland area* includes an unfertilized field area. The application rate of inorganic fertilizer was calculated separately for N, P, K, and magnesium (Mg). Manure, slurry, and inorganic fertilizer application rates associated with grassland renovation were calculated separately, as described in the following section.

6. Manure, slurry, and inorganic fertilizer application associated with grassland renovation

In each region, the area-weighted means of manure (Mg ha^{-1}), slurry (Mg ha^{-1}), and inorganic fertilizer (kg ha^{-1}) application rates associated with grassland renovation were calculated as follows:

$$Fertilizer\ application\ rate\ for\ grassland\ renovation = \frac{\sum Fertilizer\ amount}{\sum Renovated\ area},$$

where $\sum$*Fertilizer amount* is the sum of manure (Mg),

slurry (Mg), or inorganic fertilizer (kg) applied for renovation and ∑*Renovated area* is the total renovated area (ha) of meadows, pastures, and dual-purpose fields. The application rate of inorganic fertilizer was calculated separately for N, P, K, and Mg.

7. Grassland renovation rate

In each region, the grassland renovation rate was calculated annually on an area basis as follows:

$$Grassland\ renovation\ rate = \frac{\sum Renovated\ area}{\sum Grassland\ area},$$

where ∑*Renovated area* is the total renovated area (ha) of meadows, pastures, and dual-purpose fields and ∑*Grassland are*a is the total area (ha) of meadows, pastures, and dual-purpose fields. The annual renovation rate was calculated separately for full-inversion tillage, shallow tillage, and the use of a tine drill. In this study, we excluded newly established grasslands from all the analyses because these areas are negligibly small.

Results

1. Number of responses and management style

Valid responses were obtained from 263 farms (13% of the questionnaires distributed; Table 1). Responses came from all over Japan including several important dairy regions (Fig. 1), for example, Doutou (a leading producer of milk for dairy products; 85 responses) and Kanto (a leading producer of drinking milk for urban residents; 82 responses). The principal management style was private farms, along with a small number of cooperative stock farms (Table 2). The remaining farms were agricultural corporations or educational institutes (e.g., a center for the production of total mixed ration and an experimental farm for training). A small number of returned surveys (34 farms) had no answer for this question.

2. Field area breakdown

In Hokkaido, 98% of the surveyed farms had meadows, 53% had pastures, 49% had forage crop fields, and 23% had dual-purpose fields (Fig. 2a). In the other prefectures, 19% had meadows, 10% had pastures, 90% had forage crop fields, and 28% had paddy fields (Fig. 2b). The median areas of meadow, pasture, and forage crop fields per farm in Hokkaido (36, 12, and 16 ha, respectively, Table 3a) were over double than those in the other prefectures (10, 5.0, and 7.0 ha, respectively, Table 3b). The mean area of pastures in the other prefectures (83 ha) was far greater than the median area (5.0 ha) because the cooperative stock farms contained huge pastures.

3. Manure

In Hokkaido, 58% of farms with meadows, 30% with pastures, 94% with forage crop fields, and 43% with dual-purpose fields applied manure to respective field types (Fig. 3a). In the other prefectures, 36% of farms with meadows, 8% with pastures, 78% with forage crop fields, and 70% with paddy fields applied manure to respective field types (Fig. 3b). In both regions, the application rate of manure decreased in the following order: forage crop field > meadow > pasture (i.e., 37, 8.7, and 2.7 Mg ha^{-1} y^{-1},

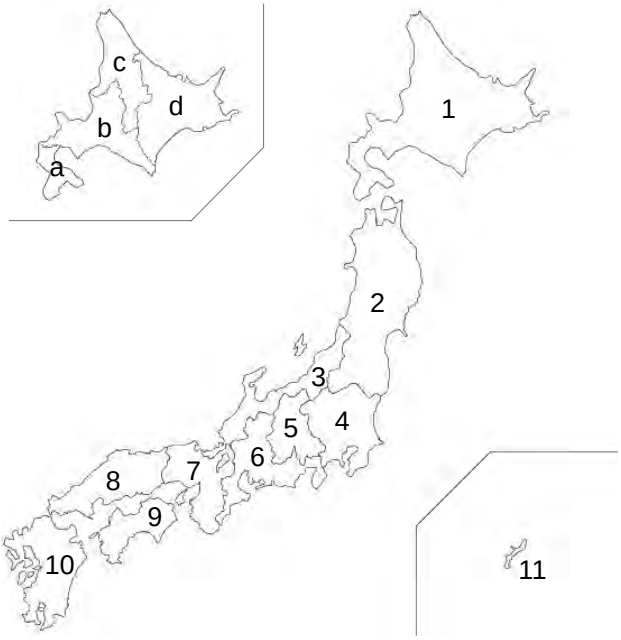

Fig. 1. Geographical division of Japan
1, Hokkaido; 2, Tohoku; 3, Hokuriku; 4, Kanto; 5, Touzan; 6, Toukai; 7, Kinki; 8, Chugoku; 9, Shikoku; 10, Kyusyu; 11, Okinawa; a; Dounan; b; Douou; c, Douhoku; d, Doutou

Table 1. Farm numbers of valid responses in each region

Hokkaido Prefecture				Other prefectures									
130				133									
Dounan†	Douou‡	Douhoku§	Doutou‖	Tohoku	Hokuriku	Kanto	Touzan	Toukai	Kinki	Chugoku	Shikoku	Kyusyu	Okinawa
5	13	27	85	9	0	82	6	1	2	10	6	17	0

† southern; ‡ central; § northern; ‖ eastern

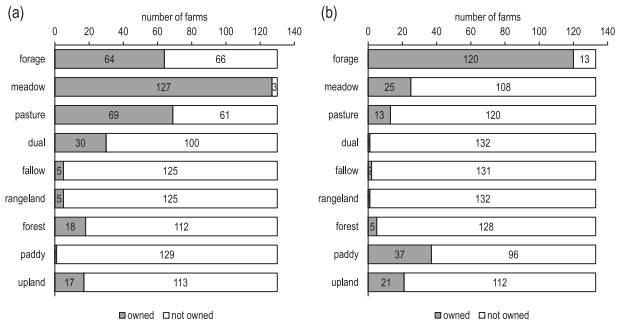

Fig. 2. Field type breakdown in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops

respectively in Hokkaido, Table 4a). The rates of manure application to forage crop fields and meadows were higher in the other prefectures (69 and 14 Mg ha^{-1} y^{-1}, respectively, Table 4b) than in Hokkaido (37 and 8.7 Mg ha^{-1} y^{-1}, respectively, Table 4a), whereas the rate of manure application to pasture was higher in Hokkaido than elsewhere (2.7 vs. 0.2 Mg ha^{-1} y^{-1}, respectively).

4. Slurry

In Hokkaido, 25% of farms with forage crop fields, 52% with meadows, 23% with pastures, and 23% with dual-purpose fields applied slurry to respective field types (Fig. 4a). In the other prefectures, 30% of farms with forage crop fields, 40% with meadows, and 8% with

Table 2. Farm number breakdown based on management style

Classification	Private farms	Co-operative stock farms	Other farms	No answer	Total
Hokkaido Prefecture	101	2	5	22	130
Other prefectures	110	9	2	12	133

Table 3a. Field area breakdown per farm in Hokkaido Prefecture

Classification	Forage†	Meadow	Pasture	Dual‡	Fallow	Rangeland	Forest	Paddy	Upland§	Total
Median (ha)	16	36	12	13	5.0	5.0	5.0	50	3.6	60
Mean (ha)	29	58	22	20	5.2	12	16	50	7.5	92
n	64	127	69	30	5	5	18	1	17	130

† forage crop field; ‡ meadow/pasture dual-purpose field; § upland field for common crops

Table 3b. Field area breakdown per farm in prefectures other than Hokkaido

Classification	Forage†	Meadow	Pasture	Dual‡	Fallow	Rangeland	Forest	Paddy	Upland§	Total
Median (ha)	7.0	10	5.0	20	3.8	0.5	3.0	2.0	0.5	9.0
Mean (ha)	9.0	18	83	20	3.8	0.5	129	7.5	2.2	27
n	120	25	13	78	2	1	5	37	21	133

† forage crop field; ‡ meadow/pasture dual-purpose field; § upland field for common crops

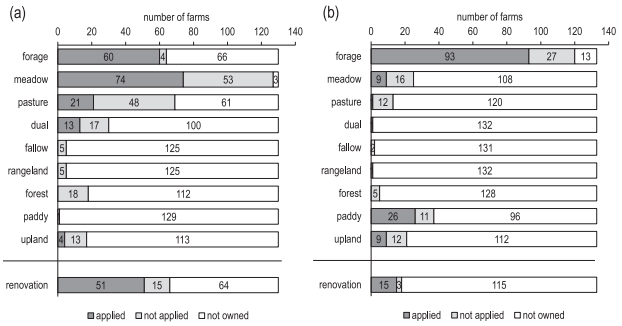

Fig. 3. Number of farms that applied manure in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

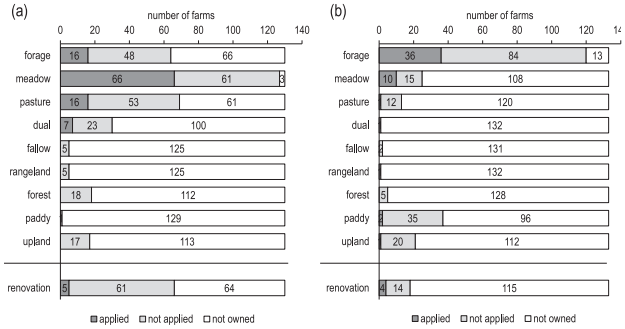

Fig. 4. Number of farms that applied slurry in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

pastures applied slurry to respective field types (Fig. 4b). In both regions, the application rate of slurry decreased in the following order: forage crop field > meadow > pasture (i.e., 16, 9.8, and 4.3 Mg-slurry ha^{-1} y^{-1}, respectively in Hokkaido, Table 4a). The rates of slurry application to forage crop fields and meadows were higher in the other prefectures (21 and 19 Mg ha^{-1} y^{-1}, respectively, Table 4b) than in Hokkaido (16 and 9.8 Mg ha^{-1} y^{-1}, respectively, Table 4a), whereas the rate of slurry application to pasture was higher in Hokkaido than elsewhere (4.3 vs. 0.3 Mg ha^{-1} y^{-1}, respectively).

5. Inorganic fertilizer

In Hokkaido, 66%-75% of farms with forage crop fields, 58%-75% of farms with meadows, and 32%-42% of farms with pastures applied inorganic fertilizers (N, P, K, or Mg) to respective field types (Figs. 5a, 6a, 7a, 8a); the range represents differences among fertilizer components (N, P, K, Mg). In the other prefectures, 12%-38% of farms with forage crop fields, 16%-52% of farms with meadows, and 15%-31% of farms with pastures applied inorganic fertilizers (Figs. 5b, 6b, 7b, 8b).

In Hokkaido, the rate of inorganic fertilizer application, excluding K, decreased in the order of forage crop field > meadow > pasture (i.e., 42, 31, and 13 kg-N ha^{-1} y^{-1}, respectively, Table 4a). In the other prefectures, the rate of inorganic fertilizer application, including K, increased in that order (i.e., 22, 42, and 70 kg-N ha^{-1} y^{-1}, respectively, Table 4b). Pastures in Hokkaido received less inorganic fertilizer than those in the other prefectures (i.e., 13 vs. 70 kg-N ha^{-1} y^{-1}, respectively). In both regions, fallow, rangeland, and forested land received no manure, slurry, or inorganic fertilizer at all.

6. Organic and inorganic fertilizers for grassland renovation

In Hokkaido, 77% of farms that renovated grassland applied manure (88 Mg ha^{-1}) and 8% applied slurry (8.1 Mg ha^{-1}) for renovation (Figs. 3a, 4a; Table 4a). In the other prefectures, 83% of farms that renovated grassland applied manure (41 Mg ha^{-1}) and 22% applied slurry (3.4 Mg ha^{-1}) for renovation (Figs. 3b, 4b; Table 4b). The rate of inorganic fertilizer application for renovation

Table 4a. Organic and inorganic fertilizer application rates in Hokkaido Prefecture (area-weighted average)

Classification	Manure ¶	Slurry ¶	Inorganic N fert.	Inorganic P fert.	Inorganic K fert.	Inorganic Mg fert.
	Mg ha^{-1} $year^{-1}$	Mg ha^{-1} $year^{-1}$	kg-N ha^{-1} $year^{-1}$	kg-P_2O_5 ha^{-1} $year^{-1}$	kg-K_2O ha^{-1} $year^{-1}$	kg-MgO ha^{-1} $year^{-1}$
Forage†	37	16	42	57	21	11
Meadow	8.7	9.8	31	33	34	7
Pasture	2.7	4.3	13	15	15	3
Dual‡	8.6	3.8	14	11	13	3
Fallow	0	0	0	0	0	0
Rangeland	0	0	0	0	0	0
Forest	0	0	0	0	0	0
Paddy	0	0	0	0	0	0
Upland§	7.3	0	79	37	16	3
	Mg ha^{-1}	Mg ha^{-1}	kg-N ha^{-1}	kg-P_2O_5 ha^{-1}	kg-K_2O ha^{-1}	kg-MgO ha^{-1}
Renovation ‖	88	8.1	21	55	33	13

† forage crop field; ‡ meadow/pasture dual-purpose field; § upland field for common crops; ‖ grassland renovation; ¶ raw weight

Table 4b. Organic and inorganic fertilizer application rates in prefectures other than Hokkaido (area-weighted average)

Classification	Manure ¶	Slurry ¶	Inorganic N fert.	Inorganic P fert.	Inorganic K fert.	Inorganic Mg fert.
	Mg ha^{-1} $year^{-1}$	Mg ha^{-1} $year^{-1}$	kg-N ha^{-1} $year^{-1}$	kg-P_2O_5 ha^{-1} $year^{-1}$	kg-K_2O ha^{-1} $year^{-1}$	kg-MgO ha^{-1} $year^{-1}$
Forage†	69	21	22	19	12	9
Meadow	14	19	42	28	23	13
Pasture	0.2	0.3	70	37	37	17
Dual‡	30	0	18	12	6	20
Fallow	0	0	0	0	0	0
Rangeland	0	0	0	0	0	0
Forest	0	0	0	0	0	0
Paddy	13	2.1	4	3	3	0
Upland§	95	0	0	0	0	0
	Mg ha^{-1}	Mg ha^{-1}	kg-N ha^{-1}	kg-P_2O_5 ha^{-1}	kg-K_2O ha^{-1}	kg-MgO ha^{-1}
Renovation ‖	41	3.4	4.2	3.7	3.7	8.4

† forage crop field; ‡ meadow/pasture dual-purpose field; § upland field for common crops; ‖ grassland renovation; ¶ raw weight

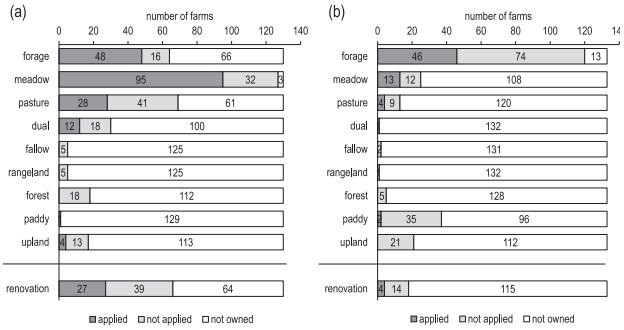

Fig. 5. Number of farms that applied inorganic nitrogen fertilizer in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

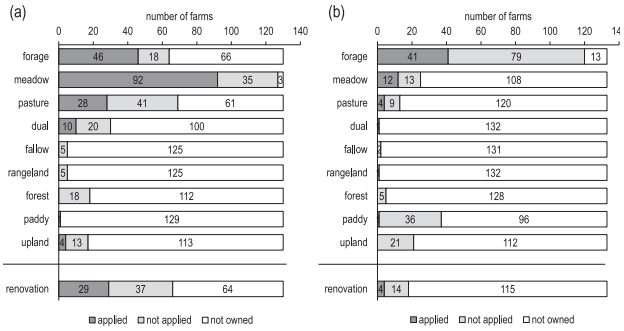

Fig. 6. Number of farms that applied inorganic phosphorus fertilizer in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

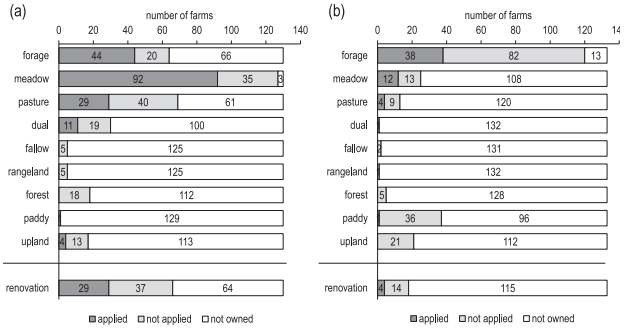

Fig. 7. Number of farms that applied inorganic potassium fertilizer in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

was greater in Hokkaido than in the other prefectures (i.e., 21 vs. 4.2 kg-N ha^{-1}, respectively, Tables 4a, 4b).

7. Grassland renovation rate

In Hokkaido, the renovation rate increased slightly from 2006 to 2015 (Fig. 9a). Outside Hokkaido, the renovation rate with full-inversion tillage increased and rates of shallow tillage and use of a tine drill decreased in the years after the Fukushima Daiichi Nuclear Power Plant accident (Fig. 9b). From 2006 to 2010, the average rates of renovation by full-inversion tillage, shallow tillage, and tine drill were 3.0%, 0.17%, and 0.02% in Hokkaido and 1.3%, 0.39%, and 0.85%, respectively, in the other prefectures.

Discussion

We received valid responses from 2.0% of the 6,490 dairy farms in Hokkaido and from 1.3% of the 10,500 dairy farms in the other prefectures (Tables 1, 2) (MAFF 2018b). These percentages may be small, but a key feature of Hokkaido relative to the other prefectures can be understood. In Hokkaido, most farms had meadows (Table 3a; Fig. 2a), whereas in the other prefectures, most farms had forage crop fields (Table 3b; Fig. 2b), which shows that the forage production system differs considerably between the two regions. In both areas, manure and slurry were intensively applied to forage crop fields, and application rates were greater in the other prefectures owing to double cropping than in Hokkaido (i.e., 69 vs. 37 Mg-manure ha^{-1} y^{-1}, respectively, Tables 4a, 4b). The higher stocking rate of cattle outside Hokkaido may explain this pattern (Mori et al. 2020); a large amount of animal waste can be applied

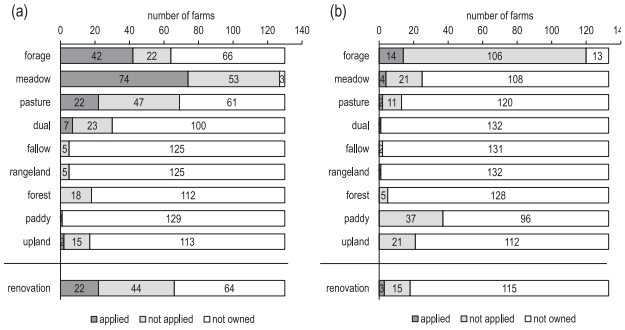

Fig. 8. Number of farms that applied inorganic magnesium fertilizer in (a) Hokkaido and (b) other prefectures
forage, forage crop field; dual, meadow/pasture dual-purpose field; upland, upland field for common crops; renovation, grassland renovation of meadow, pasture, and dual-purpose field

using a plow and a rotovator. This also explains the lower rates of application of inorganic fertilizer to forage crop fields in the prefectures other than Hokkaido (22 vs. 42 kg-N ha^{-1} y^{-1}, respectively). This result suggests that manure application to double cropping fields in the other prefectures promotes soil carbon sequestration. The rates of manure and slurry application to meadows (but not pastures) were also greater in the other prefectures than in Hokkaido (14 vs. 8.7 Mg-manure ha^{-1} y^{-1}, respectively), reflecting the higher stocking rates outside Hokkaido. In the other prefectures, pastures tend to be used for extensive fixed grazing of depositing heifers; most of the dung and urine are excreted on the pasture. In Hokkaido, however, pastures tend to be used for intensive rotational grazing of cows fed with supplemental concentrates; a portion of the dung and urine is excreted in cowsheds, composted/stored, and then applied to the pastures. In the other prefectures, manure and slurry were also applied to paddy fields as part of a diversified farming system (13 and 2.1 Mg ha^{-1} y^{-1}, respectively, Table 4b). Whole-crop rice silage and rice for feed and food were produced with less use of inorganic fertilizer (i.e., 4 kg-N ha^{-1} y^{-1}). A substantial amount of manure (95 Mg ha^{-1} y^{-1}) was applied to upland fields with no inorganic fertilizer. A portion of the manure was exported to other farms, e.g., vegetable farms.

In both regions, rates of organic and inorganic fertilizer application in forage cropping fields, meadows, and pastures did not correlate, which suggests that farmers do not always consider the nutrient contents of manure and slurry when planning inorganic fertilizer use (Smith et al. 2001). However, the amount of fertilizer necessary for forage production depends on variations in biological N fixation by legumes and target yield. Farmland area breakdown is another factor controlling the rates of organic and inorganic fertilizer application (Ren et al. 2019), but this relationship was not clear in our results. A decision support system should be introduced to optimize the rates of organic and inorganic fertilizer application within a farm and to achieve sustainable forage production (Matsunaka et al. 2009).

Outside Hokkaido, the renovation rate with full-inversion tillage temporarily increased after 2011 (Fig. 9b) to reduce radiocesium contents in herbage (Onda et al. 2020). In Hokkaido, which is located more than 500 km from the power plant, the renovation rate increased slightly to improve the quality and quantity of grass silage (Fig. 9a). The renovation rate before the accident was low, indicating that an extremely limited field area within a farm was renovated annually under normal conditions. Full-inversion tillage was the principal method; however, easier methods were also adopted, especially outside Hokkaido (Fig. 9b). Meadows and pastures in Japan were established mainly in the 1960s to the 1990s, owing to a national policy to promote the livestock industry; some of these fields have not been renovated since they were

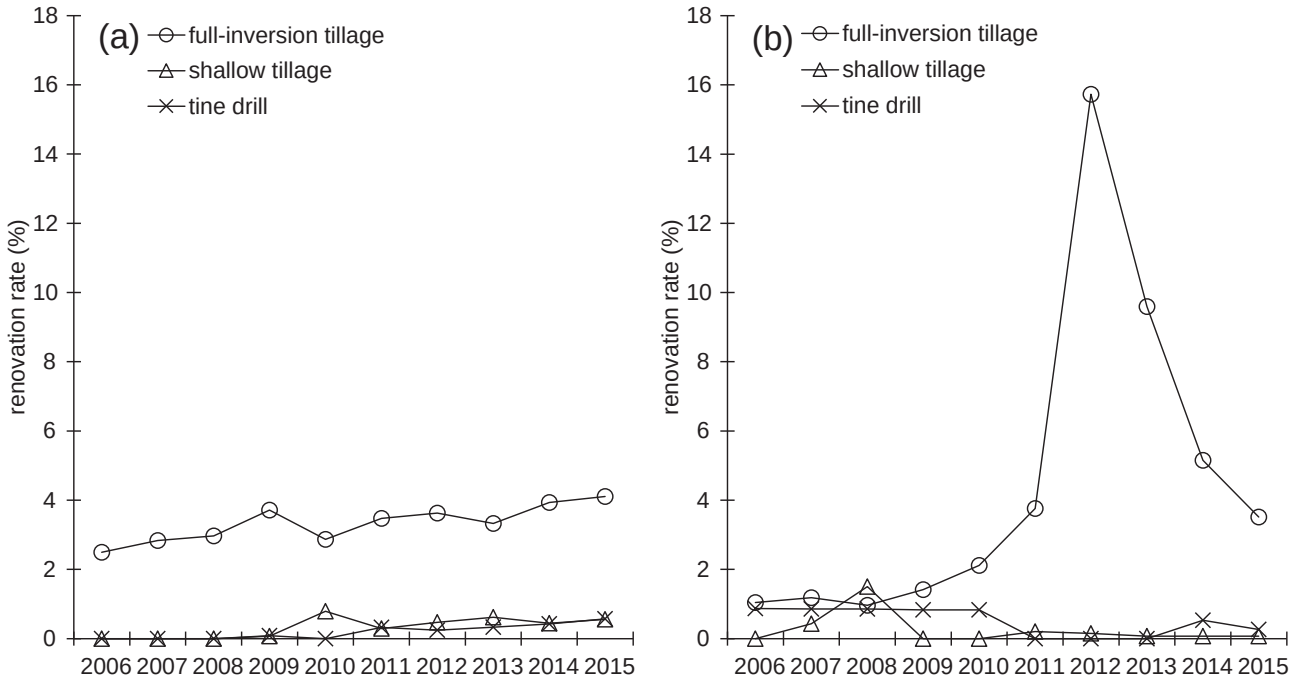

Fig. 9. Grassland renovation rate in (a) Hokkaido and (b) other prefectures

established. Nevertheless, in Hokkaido, the rate of manure application for grassland renovation was more than 10 times that for meadow fertilization; outside Hokkaido, it was three times, showing that manure was intensively applied for grassland renovation. These results suggest that manure application for grassland renovation is crucial to achieve sustainable forage production and promote soil carbon sequestration.

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