Comparison of Two High-Yielding Rice Varieties, Kita-aoba and Tachijobu, for Hokkaido, Northern Japan, and Effects of Swine Compost Application on the Growth and Grain Yield of Tachijobu

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Abstract: The grain yield of two high-yielding rice varieties, Kita-aoba and Tachijobu, was examined in a field experiment by using swine compost at a rate of 0, 1 and 2 kg m\(^{-2}\) and chemical fertilizer at a rate of 5.25, 7.35, and 10.5 g N m\(^{-2}\) in 2010, and 5.25 and 10.5 g N m\(^{-2}\) in 2011 (Exp. 1). The grain yield of Tachijobu was also evaluated by applying compost at a rate of 0 or 2 kg m\(^{-2}\) and chemical fertilizer at a rate of 5.25, 10.5, and 15.75 g N m\(^{-2}\) from 2011 to 2013 (Exp. 2). Tachijobu had a lower grain yield than Kita-aoba under the same fertilizer management in Exp. 1 due to its lower sink production efficiency, but it showed the highest grain yield of 1085 g m\(^{-2}\) at the highest fertilizer level in Exp. 2. A significant interaction between compost application and nitrogen fertilizer level was observed in grain yield and nitrogen uptake in Tachijobu in Exp. 2, and the nitrogen uptake in Tachijobu reached its maximum at around 15 g m\(^{-2}\) at maturity. In addition, the apparent nitrogen use efficiency of compost (NUE\(_{\text{compost}}\)) was higher at a lower nitrogen fertilizer level. From the nitrogen uptake and NUE\(_{\text{compost}}\) at each fertilizer level, the optimum rates of compost and fertilizer were discussed. The compost also increased the concentration of protein in Tachijobu (significantly in 2013).

Key words: Fertilizer management, Forage rice, Manure.

High-yielding forage rice is important as a substitute for imported, concentrated feed to improve forage self-sufficiency in Japan. In 2008, Kita-aoba (formerly called Hokkaishi308) was released as a high-yielding variety in Hokkaido (Shimizu et al., 2008), and Hayashi et al. (2012) reported that the yield potential of Kita-aoba was more than 1000 g m\(^{-2}\). In 2010, Tachijobu was released as a high-yielding variety in Hokkaido. Tachijobu matures later and is more tolerant to lodging, low temperatures, and blast than Kita-aoba, but its yielding performance needs to be studied.

High-yielding varieties require large amounts of nitrogen (Horie et al., 2005; Mae, 2011). Compost can be used as a source of nitrogen and other nutrients, and its effectiveness has been reported in many crops (Diacono and Montemurro, 2009). The combined use of compost and chemical fertilizers could help reduce the amount of chemical fertilizers used. Effective use of compost from farm-animal wastes is desirable, especially for forage rice, from the viewpoint of nutrient recycling. Another advantage of compost application is that it reduces the negative effects of low temperatures. High concentrations of plant nitrogen from panicle initiation to the young microspore stage aggravate floral sterility due to low-temperature damage (Satake et al., 1987; Tatsuta, 1999). This floral sterility can be reduced by using compost (Amano and Moriwaki, 1984). In Hokkaido, the nitrogen fertilizer for rice, a staple food, has been recommended to be reduced by 1.5 to 2 g m\(^{-2}\) (Department of Agriculture, Hokkaido, 2010). However, there is no information on nitrogen concentrations for high-yielding rice varieties, which would have higher nitrogen fertilizer-use efficiency for biomass production than rice varieties used as a staple food (Taylaran et al., 2009).

Several types of compost from farm-animal wastes are available in Japan. Swine or poultry compost is more easily mineralized in soil and used by rice than cattle compost (Nishida et al., 2005; Nishida, 2011). However, mineralization of organic nitrogen in compost depends on the temperature (Nishida et al., 2008; Nishida, 2011), and nitrogen in compost may not be utilized efficiently in Hokkaido at low temperatures. In this study, we compared the yields of Tachijobu with Kita-aoba, and investigated the nitrogen use efficiency of swine compost for Tachijobu to estimate the suitable combination of compost and fertilizer rate for high grain yield.
Materials and Methods

1. Cultivation management

Two field experiments were conducted in a paddy field (Andosol) at the National Agriculture and Food Research Organization/Hokkaido Agricultural Research Center (NARO/HARC; Sapporo, Hokkaido, Japan; 43°0′ N, 141°25′ E).

(1) Exp. 1: Comparison of Kita-aoba and Tachijobu

A field experiment was conducted in 2010 and 2011. We used a strip-split plot design, with three replications. The horizontal factor was variety (Kita-aoba and Tachijobu), and vertical factor was swine compost levels (0, 1, and 2 kg m⁻²). The chemical properties of swine compost are listed in Table 1. As the subplot factor, three basal chemical fertilizer levels (5.25, 10.5, and 15.75 g N m⁻²) were used in 2010, and two levels (5.25, and 10.5 g N m⁻²) in 2011. The fertilizer contained 14:17:12% of N:P₂O₅:K₂O (a mixture of urea and ammonium, no control-release fertilizer was included), and the amount of P₂O₅ and K₂O paralleled that of N. The size of each subplot was 3.5 × 4 m. The sowing dates were April 14 and 13, in 2010 and 2011, respectively, and the transplanting dates were May 20 and 19, respectively. Plants were transplanted using a transplanting machine. Planting density was 18.4 and 20.9 hills m⁻² in 2010 and 2011, respectively. Standing water was maintained from the time the plants were transplanted to the end of August (mid-grain-filling stage), at a depth of approximately 5 cm.

(2) Exp. 2: Compost and fertilizer management for Tachijobu

A field experiment was conducted from 2011 to 2013. The experimental design was a split plot design, with three replications. The main factor was swine compost application (0 and 2 kg m⁻²). The compost application of 1 kg m⁻² was omitted in Exp. 2 since the effect of compost on rice growth was not large in Exp. 1. The chemical properties of swine compost are shown in Table 1. In 2011, the same fertilizer used in Exp. 1 (14:17:12% of N:P₂O₅:K₂O) was used, and the amount of P₂O₅ and K₂O paralleled that of N. In 2012 and 2013, only nitrogen (ammonia sulfate) was applied. The size of each subplot was 3.5 × 4 m. The dates of sowing and transplanting were the same as in Exp. 1 in 2011. The sowing dates were April 11 and 10, in 2012 and 2013, respectively, and the transplanting dates were May 21 and 23, respectively. Planting density was 20.2 and

Table 1. Chemical properties of the swine compost applied from 2010 to 2013.

|                | 2010 | 2011 | 2012 | 2013 |
|----------------|------|------|------|------|
| Moisture content (%) | 65   | 55   | 62   | 63   |
| Total N (%)        | 0.39 | 0.64 | 0.78 | 0.60 |
| NH₄N (ppm)         | n.m. | 51   | 607  | 132  |
| NO₃-N (ppm)        | n.m. | 39   | 608  | 134  |
| P₂O₅ (%)           | n.m. | 1.5  | 1.5  | 1.0  |
| K₂O (%)            | n.m. | 1.1  | 1.1  | 1.0  |
| Total C (%)        | 13   | 14   | 12   | 14   |
| C/N ratio          | 33   | 21   | 16   | 24   |
| Mn (ppm)           | n.m. | 150  | 135  | 109  |
| Zn (ppm)           | n.m. | 142  | 115  | 325  |
| Cu (ppm)           | n.m. | 121  | 36   | 68   |

Concentration is expressed as wet basis.
n.m. indicates the property was not measured.

Table 2. Mean air temperature and solar radiation from 2010 to 2013, and the average values for 1981 to 2010.

|                | 2010 | 2011 | 2012 | 2013 | Average of 1981 to 2010 |
|----------------|------|------|------|------|-------------------------|
| Mean air temperature (°C) |      |      |      |      |                         |
| May             | 10.8 | 10.1 | 11.8 | 10.0 | 10.9                    |
| June            | 17.6 | 16.2 | 15.4 | 16.2 | 21.1                    |
| July            | 20.8 | 20.5 | 20.1 | 20.8 | 18.9                    |
| August          | 23.2 | 21.9 | 21.9 | 21.6 | 20.7                    |
| September       | 18.3 | 17.8 | 20.8 | 17.3 | 16.6                    |
| October         | 14.1 | 10.6 | 11.7 | 11.5 | 10.3                    |
| Average of May to October | 17.5 | 16.2 | 16.9 | 16.2 | 15.4                    |
| Solar radiation (MJ m⁻² day⁻¹) |      |      |      |      |                         |
| May             | 15.6 | 15.6 | 19.6 | 15.5 | 17.7                    |
| June            | 21.3 | 21.3 | 22.2 | 18.9 | 20.9                    |
| July            | 19.8 | 19.8 | 19.3 | 17.1 | 18.9                    |
| August          | 14.2 | 14.2 | 14.2 | 15.6 | 15.6                    |
| September       | 12.2 | 12.2 | 12.2 | 12.9 | 12.9                    |
| October         | 8.9  | 8.9  | 8.9  | 9.3  | 9.3                     |
| Average of May to October | 15.3 | 14.7 | 15.3 | 15.3 | 15.3                    |

Table 3. Heading date and harvest date across years and varieties.

| Year | Variety       | Heading date | Harvest date   |
|------|---------------|--------------|----------------|
| 2010 | Kita-aoba     | 27 July      | 24 September   |
|      | Tachijobu     | 1 August     | 1 October      |
| 2011 | Kita-aoba     | 1 August     | 29 September   |
|      | Tachijobu     | 7 August     | 3 October      |
| 2012 | Tachijobu     | 6 August     | 2 October      |
| 2013 | Tachijobu     | 5 August     | 2 October      |

Exp. 1: 2010 and 2011.
Exp. 2: Tachijobu in 2011, 2012 and 2013.
Table 4. Biomass production, grain yield, yield components, and nitrogen uptake in 2010 in Exp. 1.

| Variety | Compost application (kg m\(^{-2}\)) | Chemical fertilizer application (g N m\(^{-2}\)) | Heading Maturity (g m\(^{-2}\)) | Grain yield (g m\(^{-2}\)) | Harvest index (%) | Panicle number (m\(^{-2}\)) | Spikelet number per panicle (10\(^{3}\) m\(^{-2}\)) | Spikelet number per area (10\(^{3}\) m\(^{-2}\)) | Percentage of ripened grains (%) | 1000-grain weight (g) | Nitrogen uptake (g m\(^{-2}\)) |
|---------|-------------------------------------|-----------------------------------------------|---------------------------------|-----------------------------|-------------------|---------------------------|---------------------------------|--------------------------------|-----------------------------|-----------------|----------------------|
| Kita-aoba | 0                                   | 5.25                                          | 499                             | 1211                         | 50.7              | 363                       | 101                             | 36.9                          | 84                          | 22.4            | 10.3                 |
|         | 1                                   | 7.35                                          | 486                             | 1256                         | 51.7              | 380                       | 106                             | 40.3                          | 81                          | 22.2            | 11.1                 |
|         | 2                                   | 10.5                                          | 537                             | 1283                         | 50.2              | 389                       | 99                             | 38.4                          | 83                          | 22.0            | 11.2                 |
| Tachijobu | 0                                   | 5.25                                          | 520                             | 1277                         | 50.6              | 360                       | 101                             | 36.3                          | 89                          | 22.4            | 10.8                 |
|         | 1                                   | 7.35                                          | 536                             | 1267                         | 51.7              | 328                       | 115                             | 37.7                          | 87                          | 22.2            | 10.7                 |
|         | 2                                   | 10.5                                          | 557                             | 1332                         | 50.2              | 394                       | 101                             | 39.6                          | 84                          | 22.2            | 12.5                 |
|         | 0                                   | 5.25                                          | 438                             | 1281                         | 51.2              | 390                       | 98                             | 37.8                          | 88                          | 22.0            | 11.1                 |
|         | 1                                   | 7.35                                          | 537                             | 1332                         | 49.9              | 396                       | 103                             | 40.5                          | 82                          | 22.0            | 12.0                 |
|         | 2                                   | 10.5                                          | 558                             | 1357                         | 49.8              | 456                       | 96                             | 45.5                          | 76                          | 22.0            | 13.2                 |
|         | 0                                   | 5.25                                          | 438                             | 1281                         | 44.0              | 334                       | 97                             | 32.4                          | 87                          | 22.9            | 10.0                 |
|         | 1                                   | 7.35                                          | 537                             | 1332                         | 45.7              | 417                       | 95                             | 39.3                          | 80                          | 22.4            | 11.8                 |
|         | 2                                   | 10.5                                          | 558                             | 1357                         | 45.0              | 374                       | 102                             | 37.9                          | 82                          | 22.4            | 11.2                 |
|         | 0                                   | 5.25                                          | 577                             | 1196                         | 44.9              | 320                       | 95                             | 30.6                          | 88                          | 23.0            | 8.9                  |
|         | 1                                   | 7.35                                          | 626                             | 1307                         | 45.9              | 348                       | 99                             | 34.3                          | 88                          | 22.8            | 9.8                  |
|         | 2                                   | 10.5                                          | 574                             | 1311                         | 45.0              | 371                       | 95                             | 35.4                          | 85                          | 22.4            | 11.3                 |
|         | 0                                   | 5.25                                          | 585                             | 1282                         | 45.0              | 358                       | 99                             | 35.2                          | 83                          | 22.7            | 10.3                 |
|         | 1                                   | 7.35                                          | 633                             | 1325                         | 44.0              | 346                       | 104                             | 36.1                          | 81                          | 22.7            | 10.8                 |
|         | 2                                   | 10.5                                          | 658                             | 1375                         | 47.6              | 370                       | 109                             | 40.3                          | 82                          | 22.4            | 11.7                 |

| Variety | Average of variety | Kita-aoba | 530 b | 1291 a | 770 a | 50.7 a | 384 a | 102 a | 39.0 a | 84 a | 22.2 a | 11.4 a |
|---------|---------------------|-----------|-------|--------|-------|--------|-------|-------|--------|------|--------|--------|
|         |                     | Tachijobu | 597 a | 1312 a | 697 b | 45.1 b | 360 a | 99 b | 35.7 b | 84 a | 22.6 a | 10.7 a |

| Variety | Average of compost application | 0 kg m\(^{-2}\) | 540 a | 1293 a | 725 a | 47.7 a | 376 ab | 100 a | 37.5 a | 83 a | 22.4 ab | 10.9 a |
|---------|---------------------------------|-----------------|-------|--------|-------|--------|--------|-------|--------|------|--------|--------|
|         | 1 kg m\(^{-2}\)                | 562 a | 1283 a | 727 a | 48.1 a | 354 b | 101 a | 35.6 a | 87 a | 22.5 a | 10.7 a |
|         | 2 kg m\(^{-2}\)                | 587 a | 1328 a | 748 a | 47.9 a | 386 a | 101 a | 38.9 a | 82 a | 22.3 b | 11.5 a |

| Variety | Average of chemical fertilizer | 5.25 g N m\(^{-2}\) | 528 b | 1257 b | 706 b | 47.7 a | 354 b | 98 a | 34.9 b | 86 a | 22.6 a | 10.2 c |
|---------|---------------------------------|---------------------|-------|--------|-------|--------|-------|------|--------|------|--------|--------|
|         | 7.35 g N m\(^{-2}\)            | 575 a | 1307 ab | 759 ab | 48.2 a | 369 b | 104 a | 38.0 a | 85 b | 22.4 b | 11.0 b |
|         | 10.5 g N m\(^{-2}\)            | 586 a | 1340 a | 755 a | 47.9 a | 392 a | 100 a | 39.2 a | 82 b | 22.2 b | 11.9 a |

Different alphabets indicate the significant effect of variety, compost application, or chemical fertilizer concentrations at the 5% level, according to the LSD test.

21.6 hills m\(^{-2}\) in 2012 and 2013, respectively.

2. Measurements

Air temperature was measured at the meteorological station in NARO/HARC. Six hills of rice were taken from the ground level to determine shoot dry matter at heading stage (50% of the panicles showed heading). Nitrogen uptake at heading was also measured in 2012 and 2013. At maturity when 90% of the spikelets became yellow, lodging was scored on a scale of 0 (no lodging) to 5 (complete lodging), and the plants in an area of 3 m\(^2\) were harvested at ground level to determine shoot dry matter, gross hulled-grain yield (moisture content, 15% w w\(^{-1}\); hereafter referred to as “grain yield”), yield components (number of panicles per area, number of spikelets per panicle, percentage of ripened grains, and weight of the ripened grain), and nitrogen uptake. Hulled grains thicker than 1.8 mm were regarded as ripened grains. Sink capacity, percentage of sink filled, sink production efficiency, and apparent nitrogen-use efficiency of compost (NUE\(_{\text{compost}}\)) was calculated using the following equations:

\[
\text{Sink capacity} = (\text{Spikelet number per area}) \times (\text{Weight of a single grain thicker than 1.8 mm})
\]

\[
\text{Percentage of sink filled} = (\text{Grain yield}) / (\text{Sink capacity}) \times 100
\]

\[
\text{Sink production efficiency} = (\text{Sink capacity}) / (\text{Shoot dry matter at heading})
\]
NUE compost = ([Nitrogen uptake with compost application] – [Nitrogen uptake without compost application]) / (Nitrogen content in applied compost) × 100

Analysis of variance (ANOVA) for the strip-split plot design (Exp. 1) and split plot design over years (Exp. 2) was conducted, using the method of Gomez and Gomez (1984). Fisher’s least significant difference (LSD) test and Tukey’s honestly significant difference (HSD) test was used for significant main effects and interactions detected by ANOVA, respectively. Statistical analysis was conducted by SYSTAT 13 for Windows (SYSTAT, Software Inc., Chicago, IL, USA).

Results

The mean air temperature during the cropping season was generally higher than the average value for 1981 to 2010 (Table 2). Especially, those in 2010 and 2012 were high, and the temperature in September in 2012 was higher than the average in August. Solar radiation in 2010 was low in July, but its average value from May to October was equal to the average of 30 years. In 2011, solar radiation was slightly lower than the average value, except in July and August. Solar radiation in 2012 was generally higher than the average, and was the highest of the 4 years (2010 – 2013). Heading dates and harvest dates of Kita-aoba and Tachijobu in 2010 – 2013 are shown in Table 3.

1. Exp. 1: Comparison of Kita-aoba and Tachijobu

Although Kita-aoba showed severe lodging (score = 5.0) at the late grain-filling stage in all treatments, it produced a significantly higher grain yield than Tachijobu because of its larger spikelet number per area in 2010 (Table 4). The application of more chemical fertilizer resulted in higher nitrogen uptake, more shoot dry matter at maturity, and higher grain yield due to more panicles and spikelets per area.

In 2011, Kita-aoba tended to show higher grain yield than Tachijobu, but the difference was not significant (Table 5). The effect of compost on grain yield was not detected, but more fertilizer application increased shoot dry matter, panicle or spikelet number, and nitrogen uptake. Lodging (score = 3.0) was observed in Kita-aoba when 2 kg m$^{-2}$ of swine compost and a high level of chemical fertilizer were applied; however, a lodging score of 1.0 or more was not observed in the other treatments.

The relationship between shoot dry matter at heading

| Variety | Compost application (kg m$^{-2}$) | Chemical fertilizer application (g N m$^{-2}$) | Shoot dry matter (g m$^{-2}$) | Grain yield (g m$^{-2}$) | Harvest index (%) | Panicle number (m$^{-2}$) | Spikelet number per panicle (10$^{3}$ m$^{-2}$) | Spikelet number per area (10$^{3}$ m$^{-2}$) | Percentage of ripened grains (%) | 1000-grain weight (g) | Nitrogen uptake (g m$^{-2}$) |
|---------|----------------------------------|-----------------------------------------------|-----------------------------|-------------------------|-------------------|-----------------------------|------------------------------------------|-------------------------------------|----------------------------------|-------------------|-----------------------------|
| Kita-aoba | 0 | 5.25 | 469 | 1212 | 704 | 49.4 | 344 | 94 | 32.3 | 90 | 23.9 | 8.9 |
| | 10.5 | 628 | 1452 | 840 | 49.2 | 427 | 109 | 45.9 | 78 | 22.9 | 11.4 |
| | 0 | 5.25 | 585 | 1283 | 745 | 49.4 | 371 | 93 | 34.5 | 90 | 23.8 | 9.2 |
| | 10.5 | 636 | 1398 | 814 | 49.5 | 384 | 116 | 44.4 | 76 | 23.4 | 10.4 |
| | 2 | 5.25 | 566 | 1278 | 774 | 51.5 | 369 | 99 | 36.2 | 89 | 23.5 | 10.0 |
| | 10.5 | 644 | 1442 | 823 | 48.5 | 450 | 114 | 51.3 | 67 | 23.2 | 11.4 |
| Tachijobu | 0 | 5.25 | 546 | 1170 | 640 | 46.5 | 318 | 105 | 33.4 | 81 | 23.6 | 8.2 |
| | 10.5 | 889 | 1509 | 794 | 44.8 | 379 | 132 | 50.2 | 70 | 22.7 | 11.1 |
| | 1 | 5.25 | 674 | 1292 | 659 | 45.4 | 325 | 98 | 32.1 | 89 | 23.0 | 8.6 |
| | 10.5 | 912 | 1384 | 714 | 43.8 | 364 | 107 | 39.0 | 81 | 22.5 | 9.8 |
| | 2 | 5.25 | 754 | 1341 | 720 | 45.7 | 349 | 106 | 37.2 | 85 | 22.8 | 9.8 |
| | 10.5 | 871 | 1538 | 846 | 46.8 | 414 | 115 | 47.5 | 79 | 22.2 | 12.2 |

Average of variety

Kita-aoba | 588 a | 1344 a | 783 a | 49.6 a | 391 a | 104 a | 40.8 a | 82 a | 23.4 a | 10.2 a |
| Tachijobu | 774 a | 1362 a | 729 a | 45.5 b | 358 a | 111 a | 39.9 a | 81 a | 22.8 a | 9.9 a |

Average of compost application

0 kg m$^{-2}$ | 633 a | 1336 a | 744 a | 47.4 a | 367 a | 110 a | 40.5 a | 80 a | 23.3 a | 9.9 a |
| 1 kg m$^{-2}$ | 702 a | 1324 a | 733 a | 47.0 a | 361 a | 104 a | 37.5 a | 84 a | 23.2 a | 9.5 a |
| 2 kg m$^{-2}$ | 709 a | 1399 a | 791 a | 48.1 a | 395 a | 108 a | 43.1 a | 80 a | 22.9 a | 10.9 a |

Average of chemical fertilizer

5.25 g N m$^{-2}$ | 599 b | 1252 b | 707 b | 48.0 a | 346 b | 99 b | 34.3 b | 87 a | 23.4 a | 9.1 b |
| 10.5 g N m$^{-2}$ | 763 a | 1454 a | 805 a | 47.1 a | 403 a | 115 a | 46.4 a | 75 b | 22.8 b | 11.0 a |

Different alphabets indicate the significant effect of variety, compost application, or chemical fertilizer concentrations at the 5% level, according to the LSD test.
and sink capacity showed that Kita-aoba produced sink more efficiently than Tachijobu (Fig. 1). At all compost and chemical nitrogen levels, Kita-aoba had better sink production efficiency than Tachijobu in both years, and it resulted in a significantly larger spikelet number per area in 2010. Tachijobu showed slightly more shoot dry matter at maturity than Kita-aoba at the same nitrogen uptake level in 2010, but Kita-aoba showed a higher grain yield than Tachijobu (Fig. 2).

2. Exp. 2: Compost and fertilizer management for Tachijobu
A significant interaction between compost and nitrogen fertilizer rate was detected in grain yield and panicle number in 2011 – 2013 (Fig. 3). Grain yield increased with nitrogen fertilizer in the plots without compost, but there was no difference among the three nitrogen fertilizer levels applied with 2 kg m$^{-2}$ of compost. The effect of nitrogen fertilizer on panicle number was also larger in the plots.
without compost. This interaction in panicle number was reflected in spikelet number per area, showing a similar tendency ($P = 0.103$). The significant interaction with grain yield was also attributed to the biomass production during the grain-filling stage. Shoot dry matter at heading significantly increased with the application of nitrogen fertilizer (Fig. 4). Compost tended to increase shoot dry matter at heading. A significant interaction was observed between compost application and nitrogen fertilizer rate in the increment of biomass after heading. Biomass production after heading was higher in the plots with a higher rate of nitrogen fertilizer in the plots without compost, but nitrogen fertilizer did not affect biomass production in the plots with compost. There was an interaction between compost and chemical fertilizer rate in nitrogen uptake at maturity (Fig. 5). The effect of nitrogen fertilizer on nitrogen uptake was large in the plots without compost, but the effect of nitrogen fertilizer was small in the plots with compost. The nitrogen uptake obtained in the plots with 10.5 g N m$^{-2}$ fertilizer and 2 kg m$^{-2}$ of compost was similar to that obtained in the plots...
Table 6. Shoot dry matter, nitrogen uptake, grain yield and lodging score in Exp. 2.

| Year | Compost application (kg m\(^{-2}\)) | Chemical fertilizer application (g N m\(^{-2}\)) | Shoot dry matter (g m\(^{-2}\)) | Nitr

| Heading (a) | Maturity (b) | b–a | Heading (c) | Maturity (d) | d–c | Grain yield (g m\(^{-2}\)) | Lodging score |
|---|---|---|---|---|---|---|---|
| 2011 | 0 | 5.25 | 546 | 1170 | 623 | n.m. | 8.2 | n.m. | 640 | 0.0 |
| | 10.5 | 889 | 1509 | 620 | n.m. | 11.1 | n.m. | 736 | 0.0 |
| | 15.75 | 925 | 1697 | 774 | n.m. | 14.8 | n.m. | 886 | 0.0 |
| | 5.25 | 754 | 1341 | 586 | n.m. | 9.8 | n.m. | 720 | 0.0 |
| | 10.5 | 871 | 1538 | 666 | n.m. | 12.2 | n.m. | 846 | 0.0 |
| | 15.75 | 1026 | 1625 | 597 | n.m. | 14.2 | n.m. | 822 | 0.0 |
| | 0 | 5.25 | 848 | 1238 | 391 | 8.1 | 8.9 | 0.8 | 728 | 0.0 |
| | 10.5 | 957 | 1492 | 535 | 11.2 | 11.2 | -0.0 | 850 | 0.0 |
| | 15.75 | 975 | 1977 | 1002 | 15.0 | 17.0 | 2.0 | 1085 | 0.0 |
| | 5.25 | 560 | 1264 | 704 | 4.9 | 8.7 | 3.8 | 636 | 0.0 |
| | 10.5 | 752 | 1534 | 782 | 8.0 | 12.2 | 4.1 | 774 | 0.0 |
| | 15.75 | 868 | 1603 | 735 | 11.3 | 14.3 | 3.0 | 778 | 0.0 |
| | 0 | 5.25 | 725 | 1596 | 871 | 7.1 | 12.6 | 5.5 | 785 | 0.0 |
| | 10.5 | 863 | 1595 | 732 | 10.3 | 14.6 | 4.3 | 701 | 1.0 |
| | 15.75 | 941 | 1464 | 523 | 11.5 | 15.6 | 4.1 | 609 | 1.3 |
| 2012 | 0 | 5.25 | 813 | 1498 | 685 | 8.7 | 9.8 | 2.0 | 728 | 0.0 |
| | 10.5 | 912 | 1591 | 725 | 8.9 | 13.0 | 4.1 | 714 | 0.4 |
| | 15.75 | 941 | 1698 | 576 | 11.5 | 14.3 | 2.8 | 609 | 1.3 |
| | 5.25 | 730 | 1531 | 721 | 7.7 | 9.8 | 2.5 | 722 | 0.0 |
| | 10.5 | 896 | 1584 | 689 | 10.4 | 12.6 | 2.7 | 820 | 0.2 |
| | 15.75 | 962 | 1698 | 736 | 12.9 | 15.2 | 2.7 | 847 | 0.2 |

n.m. indicates not measured.
Different alphabets indicate the significant effect of variety, compost application, or chemical fertilizer concentrations at the 5% level, according to the LSD test.

Discussion

Grain yield was significantly lower (Table 4, 2010) or tended to be lower (Table 5, 2011) in Tachijobu than in Kita-aoba under the same fertilizer management. Lower sink production efficiency in Tachijobu (Fig. 1) may be one cause of this slightly lower grain yield. Tachijobu with a

with 15.75 g N m\(^{-2}\) fertilizer without compost. The nitrogen uptake obtained in the plots with 5.25 g N m\(^{-2}\) fertilizer with compost was similar to that obtained with 10.5 g N m\(^{-2}\) fertilizer without compost. NUE (Nitrogen Use Efficiency) was around 0% in the plots with 15.75 g N m\(^{-2}\) fertilizer, but increased in the plots with 5.25 and 10.5 g N m\(^{-2}\) fertilizer. Although Tachijobu was a lodging-tolerant variety, lodging was observed in the plots with compost in 2013, with nitrogen uptake of 15 to 16 g m\(^{-2}\), and yield was low in those plots (Table 6). Excluding the plots with lodging, there was a linear regression between nitrogen uptake and grain yield (Fig. 6). The grain yield was highest (1085 g m\(^{-2}\)) in the plots with 15.75 g N m\(^{-2}\) fertilizer without compost in 2012 (Table 7). The high grain yield was attributed to large spikelet number per area, derived from the large number of panicles per area and large panicle size, i.e., many spikelets per panicle. Application of nitrogen fertilizer significantly increased the concentration of protein in brown rice in all 3 years (Fig. 7). Although there was no significant difference in the effect of compost and the interaction between compost and nitrogen fertilizer in the average of 3 years, compost application resulted in significantly higher protein concentration in 2013. Compost tended to increase protein concentration also in 2011 (P=0.092).
Table 7. The highest grain yield and yield-related factors achieved in Exp. 2.

| Factor                        | Value   |
|-------------------------------|---------|
| Maximum grain yield           | 1085 g m$^{-2}$ |
| Shoot dry matter              | 1977 g m$^{-2}$ |
| Harvest index                 | 47%     |
| Nitrogen uptake               | 17.0 g m$^{-2}$ |
| Panicle number                | 594 m$^2$ |
| Spikelet number               | 117 panicle$^{-1}$ |
| Spikelet number               | $69.5 \times 10^3$ m$^{-2}$ |
| Percentage of ripened grains  | 70%     |
| 1000 grains weight            | 21.5 g  |
| Sink capacity                 | 1492 g m$^{-2}$ |
| Percentage of sink filled     | 72%     |

The highest grain yield was achieved in 2012, with the fertilizer level of 15.75 g N m$^{-2}$ without compost.

Fig. 6. Relationship between nitrogen uptake at maturity and grain yield in Exp. 2. –C and +C indicates plots without and with compost, respectively. Linear regression was drawn for plots without severe lodging. *** indicates the regression was significant at $P = 0.001$ level.

later heading date had more shoot dry matter than Kita-aoba at heading, as reported previously (Nakano et al. 2008; Nakano and Morita 2009). However, spikelet number per area was smaller in Tachijobu than in Kita-aoba (significantly 2010 and tendency in 2011). This lower sink production efficiency could be due to the panicle number which tended to be smaller in Tachijobu than in Kita-aoba in both 2010 and 2011. Although the shoot dry
matter was highest at heading, less biomass was produced during the grain-filling stage in Tachijobu than in Kita-aoba (significantly in 2011 and not significantly in 2010), and shoot dry matter at maturity did not differ significantly between the two varieties.

However, the linear relationship between nitrogen uptake and grain yield of Tachijobu suggested that grain yield could be further increased by increasing nitrogen uptake. Actually, Tachijobu showed the highest grain yield of 1085 g m$^{-2}$ in the plot with 15.75 g N m$^{-2}$ (Table 7), and showed a high yield potential with sufficient nitrogen application. This highest grain yield was similar to that of Kita-aoba (1081 g m$^{-2}$) reported previously (Hayashi et al., 2012) in spite of the smaller number of spikelet per area and higher percentage of ripened grains in Tachijobu. The use of compost to replace chemical fertilizer will help reduce the fertilizer cost in forage rice, which is an important issue, especially for varieties like Tachijobu, which requires higher level of nitrogen uptake.

A significant interaction between compost application and nitrogen fertilizer level was observed in the grain yield of Tachijobu in Exp. 2 (Fig. 3). This was attributed to its panicle number and nitrogen uptake (Fig. 5) which showed similar interactions. Nitrogen uptake at the highest nitrogen fertilizer level with compost was around 15 g m$^{-2}$, and did not significantly differ from that without compost application. This suggested that nitrogen uptake of Tachijobu reached its maximum at around 15 g m$^{-2}$. This limitation in nitrogen uptake might be due to excessive growth at the highest nitrogen fertilizer level with compost. Although not significant, compost tended to increase shoot dry matter at heading, and that at the highest nitrogen fertilizer level reached 1000 g m$^{-2}$ (Fig. 4). However, biomass production in the grain-filling stage was not increased. Another reason was that lodging occurred after the heavy rain (70.5 mm day$^{-1}$) during the mid-grain-filling stage in 2013 in the plot with compost and high nitrogen fertilizer rate (15.75 g N m$^{-2}$). Although Tachijobu is a lodging-tolerant variety, lodging might occur when nitrogen uptake reaches 15 g m$^{-2}$ (Fig. 6). These results suggested that the combination of 2 kg m$^{-2}$ of compost and 10.5 g m$^{-2}$ of nitrogen fertilizer was appropriate in the combinations examined in the present study from the viewpoints of grain yield and nitrogen uptake. Compost also increased the concentration of protein in brown rice (Fig. 7, significantly in 2013). A high concentration of protein is desirable for forage rice as concentrated feed. This was in contrast to a previous report that compost had no effect on the concentration of protein (Saha et al., 2007).

NUE$_{\text{compost}}$ was the highest (19%) at the lowest fertilizer level (5.25 g N m$^{-2}$) in this study, and 2 kg of compost (0.68% of nitrogen, average of 3 years) could supply 2.5 g of nitrogen to rice (Fig. 5). Since the nitrogen uptake in the plot with 5.25 N m$^{-2}$ fertilizer was 8.6 g m$^{-2}$ without compost, application of approximately 5 kg m$^{-2}$ of compost with 5.25 g N m$^{-2}$ fertilizer may increase the nitrogen uptake to 15 g m$^{-2}$. However, the effect of compost on rice growth depends on the percentage of inorganic nitrogen. The concentration of inorganic nitrogen in the compost used in the present study greatly varied with the year (Table 1). This variation could be due to the maturity of compost (C/N ratio), and the inorganic nitrogen level was highest in 2012 which had a low compost C/N ratio. The quality of compost as a nitrogen source should be investigated prior to application. In addition, nitrogen from compost is generally utilized in a later growth period in rice (Nishida et al., 2008). Also in the present study, the rate of nitrogen uptake from compost tended to be higher in the grain-filling stage 3.0 and 2.3 g m$^{-2}$, in the plots with compost and without compost, respectively, than at the heading stage, 10.9 and 9.8 g m$^{-2}$, respectively, the difference being 32 and 12%, respectively (Table 6). This result suggested that the increase of compost and reduction of chemical nitrogen could reduce the nitrogen supply in the earlier growth stage and affect the yield components determined earlier such as panicle number. The effects of residual nitrogen (discussed below), surplus minerals, and the accumulation of heavy metals should also be taken into consideration when applying more compost than the rate examined in the present study.

Compost was applied every year for 4 years (application starting from 2010, a year before the beginning of Exp. 2) in Exp. 2, and NUE$_{\text{compost}}$ was 5.6, 7.6 and 20.9% in 2011, 2012 and 2013, respectively, showing a tendency of increase with the year. Nitrogen uptake at maturity in plots with compost also tended to increase from 2011, especially in the plot with 5.25 g N m$^{-2}$, while that without compost was relatively stable (Table 6). Total nitrogen in soil measured after the harvest in 2013 also tended to be higher in plots with compost (0.30%) than in those without compost (0.27%). Although not significant ($P = 0.188$ by ANOVA with 3 replications), these results suggested the residual effect of swine compost. Mineralization of organic nitrogen under low-temperature conditions is suppressed (Nishida et al., 2005; Nishida, 2011), and the residual effects of compost have been reported to be larger in an area with lower temperatures (Ueno and Yamamura, 2001; Matsuyama et al., 2003; Nishida et al., 2008). These findings suggested that the amount of applied fertilizer could be reduced by long use of compost. The effect of long-term application requires further study. Although an excess of manganese, zinc, and copper in the soil sometimes occurs with swine compost application (Hsu and Lo, 2000), an excess of those elements was not observed in the present study (data not shown). However, the effect of long-term application on the accumulation of heavy metals should be carefully
investigated, together with the residual effect of nitrogen.

Conclusions

Grain yield was significantly lower or tended to be lower in Tachijobu than in Kita-aoba under the same fertilizer management in Exp. 1. However, Tachijobu showed the highest grain yield of 1085 g m$^{-2}$ at the fertilizer level of 15.75 g N m$^{-2}$ in Exp. 2. A significant interaction between compost application and nitrogen fertilizer level was observed in grain yield and nitrogen uptake of Tachijobu in Exp. 2, and the nitrogen uptake of Tachijobu reached its maximum at around 15 g m$^{-2}$ at maturity. NUE$_{\text{compost}}$ was higher at a lower nitrogen fertilizer level. From the nitrogen uptake and NUE$_{\text{compost}}$ at each fertilizer level, the optimum rate of compost and fertilizer was discussed. Compost also increased the concentration of protein in Tachijobu.

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