Effects of Nitrogen Application and Planting Density on Morphological Traits, Dry Matter Production and Yield of Large Grain Type Rice Variety Bekoaoba and Strategies for Super High-Yielding Rice in the Tohoku Region of Japan

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Abstract: To achieve super high yield of more than 10 t ha\(^{-1}\) in the Tohoku region (colder area of Japan), we conducted a two-year field experiment using a large grain type high-yielding rice variety Bekoaoba. Although high nitrogen application (HN) increased the top dry weight at the full heading stage only slightly, it increased the sink size (single grain weight x the number of spikelets per area), leaf area index and nitrogen content at the full heading stage and accordingly the dry matter production during the ripening period. As a result, the gross hulled rice yield was higher under HN than under standard nitrogen application (SN). Under HN, early topdressing increased not only the number of differentiated spikelets but also the number of degenerated spikelets. As a result, the sink size and gross hulled rice yield of the plants were not changed by the early topdressing. Under HN, the higher planting density increased the number of panicles per area but decreased the number of spikelets per panicle. As a result, the sink size and gross hulled rice yield were not changed with the planting density. In conclusion, HN produced the gross hulled rice yield of more than 9 t ha\(^{-1}\). However, the gross hulled rice yield could not be increased more than 10 t ha\(^{-1}\) by regulation of the timing of topdressing and/or the planting density. We discussed the strategies for super high-yielding rice in the Tohoku region.

Key words: Bekoaoba, High-yielding variety, Large grain, Planting density, Rice, Tohoku region, Topdressing.

Super high-yielding rice having a yield of more than 10 t ha\(^{-1}\) and for multipurpose use is highly desired in Japan. In the Tohoku region (colder area of Japan), Nagata et al. (2007) reported that the large grain type variety Bekoaoba showed the best yield among many kinds of high yielding rice varieties under high nitrogen application (HN). On the other hand, in our previous report (Fukushima et al., 2011) we showed that the morphological traits of Bekoaoba were quite different from those of high yielding indica type variety Takanari but similar to those of the japonica type varieties except for the large grain size of Bekoaoba. We also elucidated that the high rice yield in Bekoaoba could be attributed to the large grain size and the great assimilate remobilization. These results suggest that the cultivation technique suitable for the new high-yielding variety Bekoaoba are different from those for high-yielding indica or japonica type varieties.

There are many studies on the cultivation techniques for high rice yield, such as the ideal rice cultivation (Matsushima, 1973) and the topdressing to the lower soil layer (Tanaka, 1979). However, most of them were focused on conventional japonica type varieties, and there are few studies on the cultivation techniques for the new high-yielding rice varieties such as indica type (San-oh et al., 2004) and large grain type varieties (Mae et al., 2006).

Although HN usually increases the rice yield, the timing of topdressing to produce a high rice yield is not fully understood. Matsushima (1973) noted that the topdressing at 30 days before heading (30 DBH) elongated the lower internodes and upper leaves, resulting in the worse plant type and yield reduction. On the other hand, Matsuba (2000) indicated that the topdressing at 30 DBH did not elongate the lower internodes in a model experiment with japonica type variety Koshihikari. Fukushima (2007) also showed that the topdressing at 30 DBH did not worsen the plant type but did increase the sink size in high-yielding indica variety Takanari. These results suggest that topdressing at 30 DBH (early topdressing) may increase the sink size and the rice yield of the new type rice variety Bekoaoba with the short culm and erect leaf.

Received 24 March 2010. Accepted 27 July 2010. Corresponding author: A. Fukushima (afuku@affrc.go.jp, fax +81-187-66-2639).

Abbreviations: DAH, days after heading; DBH, days before heading; LAI, leaf area index, NSC, nonstructural carbohydrate.
Both high and low planting densities have the potential to increase rice yield. In colder areas such as Tohoku region, where the rice growth before heading is not enough to ensure a high yield, high planting density might increase rice yield. In particular, a high planting density might be suitable for Bekoaoba, since it has narrow erect leaves and fewer shoots, and can receive sunlight effectively under a high planting density. A low planting density also might increase rice yield by the slow early growth and increased crop growth rate during the two weeks just before heading, which is closely related to yield potential (Takai et al., 2006).

Early transplanting usually increases the rice yield of high yielding indica type varieties in warm and temperate areas of Japan (Kabota et al., 1988; Ishikawa et al., 2003). However, it is difficult to introduce early transplanting in the Tohoku region because of its cold weather during the early growth period.

As described above, the method of nitrogen application and planting density suitable for the rice variety Bekoaoba in the Tohoku region are not fully understood. In this study we examined the effects of nitrogen application and planting density on the growth and yield of Bekoaoba. Then, based on the results and our previous report about the varietal differences in growth and yield (Fukushima et al., 2011), we proposed strategies for cultivating super high-yielding rice in the Tohoku region.

### Table 1. Planting and nitrogen application method used for the rice variety Bekoaoba.

| Nitrogen application | Treatment | Year | Row space (cm) | Hill space (cm) | Plants hill | Basal dressing (N g m\(^{-2}\)) | Total dressing | Topdressing (N g m\(^{-2}\)) |
|----------------------|-----------|------|----------------|-----------------|------------|------------------|----------------|------------------|
| SN                   | ST-SD     | 2008 | 30             | 15              | 3          | 6                | 0              | 0                | 2                | 0                | 0                | 8                |
| HN                   | ST-SD     | 2008 | 30             | 15              | 3          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |
| HN                   | ET-SD     | 2008 | 30             | 15              | 3          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |
| HN                   | ST-HD     | 2008 | 15             | 15              | 3          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |
| HN                   | ET-HD     | 2008 | 15             | 15              | 3          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |
| HN                   | ST-LD     | 2009 | 30             | 15              | 1          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |
| HN                   | ET-LD     | 2009 | 30             | 15              | 1          | 6                | 2              | 0                | 4                | 2                | 2                | 16               |

SN, Standard nitrogen application; HN, High nitrogen application; ST, Standard topdressing; ET, Early topdressing; SD, Standard planting density; HD, High planting density; LD, Low planting density; DAT, Days after transplanting; DBH, Days before heading.

### Table 2. Effects of nitrogen application method and planting density on the morphological traits of main shoots and panicles in the rice variety Bekoaoba.

| Year | Nitrogen application | Treatment | No. of leaves | Panicle length (cm) | Culm length (cm) | No. of spikelets per panicle | degenerated | surviving |
|------|----------------------|-----------|---------------|---------------------|------------------|-----------------------------|-------------|-----------|
| 2008 | SN                   | ST-SD     | 14.9          | 19.8                | 69.8             | 131                         | 20          | 111       |
|      | HN                   | ST-SD     | 15.0          | 20.1                | 71.0             | 129                         | 16          | 113       |
|      |                      | ST-HD     | 14.2          | 19.2                | 65.2             | 114                         | 15          | 99        |
|      |                      | ET-SD     | 14.9          | 20.2                | 69.5             | 141                         | 29          | 112       |
|      |                      | ET-HD     | 14.2          | 19.8                | 65.1             | 122                         | 17          | 106       |
|      | SN vs. HN (ST-SD)    | NS        | NS            | NS                  | NS                | NS                          | NS          | NS        |
|      | Timing of topdressing| NS        | NS            | NS                  | *                 | NS                          | **          | NS        |
|      | Planting density     | **        | *             | **                  | **                | **                          | *           |           |
|      | Interaction           | NS        | NS            | NS                  | NS                | *                           | NS          |           |
| 2009 | SN                   | ST-SD     | 14.3          | 20.9                | 66.4             | 134                         | 15          | 119       |
|      | HN                   | ST-SD     | 14.7          | 20.2                | 69.4             | 139                         | 18          | 120       |
|      |                      | ST-LD     | 15.3          | 22.3                | 69.3             | 164                         | 21          | 144       |
|      |                      | ET-SD     | 14.8          | 20.5                | 68.1             | 149                         | 28          | 120       |
|      |                      | ET-LD     | 15.9          | 21.2                | 72.3             | 179                         | 34          | 145       |
|      | SN vs. HN (ST-SD)    | NS        | NS            | NS                  | **                | NS                          | NS          | NS        |
|      | Timing of topdressing| **        | NS            | NS                  | NS                | **                          | NS          | NS        |
|      | Planting density     | **        | **            | *                   | **                | NS                          | **          | NS        |
|      | Interaction           | *         | NS            | NS                  | NS                | NS                          | NS          | NS        |

*, Significant at the 0.05 level; **, Significant at the 0.01 level; NS, Not significant by t-test and ANOVA.
and high nitrogen application (HN) was 16 g m\(^{-2}\) and the number of surviving spikelets per panicle. Culm length in most cases. It also decreased the number of main shoots and accordingly shortened the panicle and

degenerated spikelets. As a result, there was no significant difference in the number of surviving spikelets between ET and ST. HD decreased the total number of leaves on the main shoots and accordingly shortened the panicle and culm length in most cases. It also decreased the number of differentiating and surviving spikelets per panicle.

The morphological traits of the leaves and stems in 2009 fluctuated due to the difference in total number of leaves on the main shoot, as described by Matsuba (1987). However, at the same total leaf number on the main shoot in 2008, the length and width of the first and second leaf blades were higher in ET (Table 5). HD tended to decrease the width of upper leaves and the diameter of lower internodes.

2. Dry matter production until the full heading stage

HD increased the number of shoots, LAI and top dry weight at the maximum tillering stage (Table 4). However, the differences in dry matter related traits among planting densities were smaller at the full heading stage (Table 5).

The number of panicles and top dry weight at the full heading stage was larger in HD than in SD density only in 2008. However, at the same total leaf number on the main shoot in 2008, the length and width of the first and second leaf blades were higher in ET (Table 3). In HN, ET decreased the width of upper leaves and the diameter of lower internodes.

There was no significant difference in the top dry weight at the full heading stage between HN and SN in 2008, but it tended to be larger in HD in 2009. In this case, the effects of HD on LAI, numbers of shoots and panicles per area were stronger than those on the top dry weight. In HD, the timing of topdressing did not affect the dry matter related traits in either year of the study.

Total nitrogen (g m\(^{-2}\)) and leaf nitrogen (%) were clearly higher in HN than in SN. In HD, ET decreased the total nitrogen (g m\(^{-2}\)) in 2008 and the leaf nitrogen (%) in 2009. Planting density affected only the total nitrogen (g m\(^{-2}\)) in 2008. On the other hand, there were no significant differences in the NSC (%) and NSC (g m\(^{-2}\)) of stems and leaf sheaths at the full heading stage between HN and SN or among timings of topdressing and planting densities.

3. Yield and yield components

HN affected neither the number of spikelets per panicle nor thousand grain weight, but it increased the number of panicles per area, compared with SN (Table 6). As a result, the sink size (single grain weight x the number of spikelets per area) and gross hulled rice yield were higher in HN than in SN. The gross hulled rice yield under HN was

Materials and Methods

We used Bekoaoba, a large grain type high-yielding variety for the Tohoku region (Nakagomi et al., 2006) in this study. The cultivation method was almost the same as that described in our previous report (Fukushima et. al., 2011). The dates of seeding and transplanting were April 16 and May 16, respectively, in 2008 and April 15 and May 14, respectively in 2009. The planting density and nitrogen application were designed to obtain a super high-yield (LD) was 22.2 plants m\(^{-2}\) and low planting density (SD) was 66.7 (plant m\(^{-2}\)). The method

The morphological traits of the main shoots and panicles of plants in HD were similar to those of plants in SN (Table 2). In HN, ET increased not only the number of differentiated spikelets but also the number of degenerated spikelets. As a result, there was no significant difference in the number of surviving spikelets between ET and ST. HD decreased the total number of leaves on the main shoots and accordingly shortened the panicle and culm length in most cases. It also decreased the number of differentiated and surviving spikelets per panicle.

The morphological traits of the leaves and stems in

Table 3. Effects of nitrogen application and planting density on the morphological traits of leaves and stems in the rice variety Bekoaoba in 2008.

| Nitrogen application | Treatment | Length of leaf blade (cm) | Width of leaf blade (cm) | Diameter of internode (mm) |
|----------------------|-----------|--------------------------|-------------------------|---------------------------|
|                      | I        | II          | III         | I          | II          | III         | I          | II          | III         | IV          |
| HN                   | ST-SD    | 31.0        | 35.6        | 40.5       | 1.31       | 1.11       | 1.03       | 1.70       | 3.49       | 4.24       | 4.97       |
|                      | ST-HD    | 28.0        | 32.4        | 34.1       | 1.17       | 1.03       | 1.01       | 1.64       | 3.35       | 3.92       | 4.57       |
|                      | ET-HD    | 34.1        | 42.1        | 42.7       | 1.33       | 1.16       | 1.04       | 1.69       | 3.56       | 4.42       | 5.14       |
|                      | ET-SD    | 37.0        | 40.7        | 35.6       | 1.28       | 1.09       | 1.04       | 1.72       | 3.49       | 4.20       | 4.75       |
| SN                   | ST-SD    | NS          | NS          | NS         | NS         | NS         | NS         | NS         | NS         | NS         | NS         |
|                      | ST-HD    | NS          | NS          | NS         | *          | *          | *          | NS         | NS         | *          | NS         |
|                      | ET-HD    | NS          | NS          | NS         | **         | **         | NS         | NS         | NS         | *          | **         |
|                      | ET-SD    | NS          | NS          | NS         | NS         | NS         | NS         | NS         | NS         | NS         | NS         |
|                      | SN vs. HN (ST-SD) | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
|                      | Timing of topdressing | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
|                      | Planting density | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

I, II, III and IV indicate positions of leaves and internodes from the top. * Significant at the 0.05 level; ** Significant at the 0.01 level; NS Not significant by t-test and ANOVA.

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Table 5. Effects of nitrogen application and planting density on the dry matter production at the full heading stage in the rice variety Bekoaoba.

| Year | Nitrogen application | Treatment | Heading date | No. of panicles (m\(^2\)) | LAI | Top dry weight (g m\(^{-2}\)) | Total nitrogen (g m\(^{-2}\)) | Leaf nitrogen (%) | NSC (g m\(^{-2}\)) | NSC (%) |
|------|----------------------|-----------|--------------|---------------------------|-----|-----------------------------|---------------------------|------------------|----------------|----------|
| 2008 | SN                   | SD        | 8 Aug.       | 515                        | 4.5 | 275                         | 43.0                      | 5.0              | 791            | 10.0    |
|      | HN                   | SD        | 9 Aug.       | 456                        | 4.9 | 283                         | 48.0                      | 5.1              | 810            | 10.5    |
|      | HD                   | 8 Aug.    | 426          | 4.63                       | 954 | 15.8                        | 32.3                      | 5.6              | 855            | 10.8    |
|      | ET                     | 8 Aug.    | 439          | 5.06                       | 1150| 16.0                        | 44.5                      | 6.0              | 861            | 11.0    |
|      | t-test                | NS        | *            | NS                         | NS  | NS                         | NS                       | NS               | NS             | NS      |
| 2009 | SN                   | SD        | 8 Aug.       | 56.7                       | 437 | 234                         | 37.2                      | 6.0              | 247            | 10.0    |
|      | HN                   | SD        | 6 Aug.       | 56.6                       | 489 | 257                         | 47.2                      | 6.5              | 309            | 10.5    |
|      | LD                   | 9 Aug.    | 356          | 5.17                       | 141 | 200                         | 37.9                      | 6.0              | 200            | 10.0    |
|      | t-test                | NS        | **           | *                          | NS  | NS                         | NS                       | NS               | NS             | NS      |

NSC, Nonstructural carbohydrate in the stem and leaf sheath; *, Significant at the 0.05 level; **, Significant at the 0.01 level; NS, not significant by t-test and ANOVA.

more than 900 kg 10a\(^{-1}\) in both years. In HN, the timing of topdressing scarcely affected yield and yield components. HD increased the number of panicles per area but decreased the number of spikelets per panicle. As a result, sink size and gross hulled rice yield did not differ significantly among planting densities.

4. Ripening process

Top dry weight at maturity was heavier in HN than in SN, although harvest index did not differ between SN and HN (Table 7). The increase in top dry weight during the ripening period (Δ\(W\)) tended to be larger in HN than in SN.

There were no significant differences in the decrease in stem and leaf weights during the early ripening period (Δ\(S_{30}\)) between SN and HN although the increase in stem and leaf weight during the late ripening period (Δ\(S_{30-M}\)) tended to be higher in HN than in SN. The hulled rice weight at 30 DAH (RW30) and the increase in hulled rice weight from 30 DAH to maturity (ΔRW\(_{30-M}\)) was greater in HN than in SN in 2008. As a result, unhulled rice weight at maturity (RWm) was heavier in HN than in SN in both years.

In HN, the timing of nitrogen application and planting density scarcely affected the ripening process, except that
Table 6. Effects of nitrogen application and planting density on yield and yield component in the rice variety Bekoaoba.

| Year | Nitrogen application | Treatment | No. of panicles (m\(^{-2}\)) | No. of spikelets per panicle | Thousand grain weight (g) | Percentage of ripened grain (%) | No. of spikelets (m\(^{-2}\)) | Sink size (g m\(^{-2}\)) | Percentage of sink filling (%) | Gross hulled rice yield (g m\(^{-2}\)) | Hulled rice yield (g m\(^{-2}\)) |
|------|----------------------|-----------|-----------------------------|-----------------------------|-------------------------|-------------------------------|-------------------------------|-----------------------------|--------------------------------|----------------------------------|----------------------------------|
| 2008 | SN                   | ST-SD     | 301                         | 97                          | 34.5                    | 79.3                          | 29219                         | 1097                        | 81.5                           | 818                              | 708                              |
|      | HN                   | ST-SD     | 361                         | 101                         | 35.0                    | 64.2                          | 36419                         | 1275                        | 76.4                           | 974                              | 818                              |
|      |                      | ST-HD     | 418                         | 82                          | 35.5                    | 65.1                          | 34346                         | 1219                        | 79.9                           | 936                              | 793                              |
|      |                      | ET-SD     | 366                         | 101                         | 34.6                    | 64.3                          | 36604                         | 1266                        | 78.2                           | 964                              | 812                              |
|      |                      | ET-HD     | 424                         | 82                          | 35.2                    | 66.6                          | 34889                         | 1226                        | 78.0                           | 957                              | 816                              |
|      | SN vs. HN (ST-SD)    | ** NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Timing of topdressing| NS NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Planting density     | ** **    | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Interaction          | NS NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
| 2009 | SN                   | ST-SD     | 278                         | 98                          | 34.6                    | 73.2                          | 27171                         | 941                         | 82.9                           | 780                              | 689                              |
|      | HN                   | ST-SD     | 356                         | 98                          | 35.0                    | 69.5                          | 54926                         | 1219                        | 78.3                           | 953                              | 845                              |
|      |                      | ST-HD     | 304                         | 120                         | 35.0                    | 68.8                          | 36324                         | 1273                        | 78.4                           | 997                              | 875                              |
|      |                      | ET-SD     | 360                         | 98                          | 34.0                    | 74.1                          | 35120                         | 1194                        | 82.2                           | 981                              | 884                              |
|      |                      | ET-HD     | 311                         | 120                         | 33.9                    | 67.7                          | 37310                         | 1266                        | 78.3                           | 991                              | 856                              |
|      | SN vs. HN (ST-SD)    | ** NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Timing of topdressing| NS NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Planting density     | ** **    | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |
|      | Interaction          | NS NS     | NS                          | NS                          | NS                       | NS                            | NS                            | NS                          | NS                             | NS                               | NS                               |

Sink size = single grain weight × the number of spikelets per area, Percentage of sink filling = gross hulled rice yield / sink size. *, Significant at the 0.05 level; **, Significant at the 0.01 level; NS, Not significant by t-test and ANOVA.

Table 7. Effects of nitrogen application and planting density on the ripening traits in the rice variety Bekoaoba.

| Year | Nitrogen application | Treatment | TDWm (g m\(^{-2}\)) | Harvest index | ΔW (g m\(^{-2}\)) | ΔS30-30 DAH (g m\(^{-2}\)) | ΔS30-M (g m\(^{-2}\)) | RW30 (g m\(^{-2}\)) | ΔRW30-M (g m\(^{-2}\)) | RWm (g m\(^{-2}\)) |
|------|----------------------|-----------|----------------------|---------------|------------------|---------------------------|---------------------|-------------------|---------------------|------------------|
| 2008 | SN                   | ST-SD     | 1323                 | 0.55          | 332              | –274                     | 14                  | 619               | 116                | 734              |
|      | HN                   | ST-SD     | 1544                 | 0.57          | 525              | –246                     | 47                  | 654               | 222                | 875              |
|      |                      | ST-HD     | 1548                 | 0.54          | 451              | –262                     | 31                  | 684               | 155                | 839              |
|      |                      | ET-SD     | 1567                 | 0.55          | 556              | –217                     | 53                  | 646               | 218                | 864              |
|      |                      | ET-HD     | 1628                 | 0.53          | 479              | –264                     | 39                  | 704               | 155                | 859              |
|      | SN vs. HN (ST-SD)    | ** NS     | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
|      | Timing of topdressing| NS *      | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
|      | Planting density     | NS **    | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
|      | Interaction          | NS NS     | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
| 2009 | SN                   | ST-SD     | 1251                 | 0.56          | 393              | –186                     | 13                  | 556               | 144                | 701              |
|      | HN                   | ST-SD     | 1475                 | 0.58          | 507              | –235                     | 35                  | 658               | 220                | 858              |
|      |                      | ST-HD     | 1509                 | 0.60          | 601              | –219                     | 75                  | 648               | 256                | 905              |
|      |                      | ET-SD     | 1556                 | 0.57          | 600              | –211                     | 74                  | 688               | 203                | 891              |
|      |                      | ET-HD     | 1514                 | 0.60          | 546              | –234                     | 49                  | 615               | 265                | 901              |
|      | SN vs. HN (ST-SD)    | ** NS     | *                    | NS            | NS               | NS                        | NS                  | NS                | NS                  | **               |
|      | Timing of topdressing| NS *      | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
|      | Planting density     | NS NS     | NS                   | NS            | NS               | NS                        | NS                  | NS                | NS                  | NS               |
|      | Interaction          | * NS      | *                    | NS            | *                | NS                        | NS                  | NS                | NS                  | NS               |

TDWm, TDW at maturity; Harvest index, Unhulled rice weight at maturity / TDWm; ΔW, TDWm - TDW at the full heading stage; ΔS30-30 DAH, Stem and leaf weight at 30 DAH - stem and leaf weight at the full heading stage; ΔS30-M, Stem and leaf weight at maturity - stem and leaf weight at 30 DAH; RW30, Unhulled rice weight at 30 DAH; ΔRW30-M, RWm-RW30; RWm, Unhulled rice weight at maturity. *, Significant at the 0.05 level; **, Significant at the 0.01 level; NS, Not significant by t-test and ANOVA.
Discussion

1. Effects of nitrogen application and planting density on morphological traits

HN hardly affected most of the morphological traits of the panicles, leaves and stems, compared with SN (Tables 2, 3), although HN generally elongated the culm and leaves of rice plants. In Bekoaoba, HN increased the number of shoots per area, instead of affecting the morphological traits of individual shoots.

In HN, ET increased the number of differentiated spikelets per panicle and the length of upper leaves. These morphological responses to ET were almost coincident with those reported in a previous study in a warmer area of Japan (Fukushima 2007), indicating that these responses were not dependent on varieties. However, Fukushima (2007) has also discovered a higher response of the number of spikelets and the length of leaf blade to ET in Takanari, compared with a conventional japonica-type variety Hinohikari and a high yielding japonica type variety Akenohoshi. The morphological response to ET in Bekoaoba seemed to be lower than that in Takanari (Fig. 1).

In HN, the higher the planting density, the larger the number of panicles per area, the lower the number of spikelets per panicle and the thinner the diameter of internodes, but the length of leaves was hardly changed by the planting density.

Timing of topdressing and/or planting density affected some morphological traits, but it was difficult to evaluate how these changes affected the gross hulled rice yield, since timing of topdressing and/or planting density did not affect significantly the sink size or gross hulled rice yield (Table 6). Regulation of morphological traits by the timing of topdressing might be useful for improvement of rice yield in conventional japonica varieties in SN (Matsushima, 1973). However it might not be effective in high-yielding rice varieties in HN.

2. Effects of nitrogen application and planting density on yield, yield components and dry matter production

Although top dry weight at the full heading stage in HN was only 1.08 times the sink size, the DW was 1.42 times larger in HN (Tables 5, 7). In HN, the sink size was 1.27 times larger, LAI was 1.21 times larger, total nitrogen (g m⁻²) was 1.61 times higher and leaf nitrogen (%) was 1.30 times higher. These results suggest that HN caused only a small increase in the top dry weight at the full heading stage but caused a large increase in ΔW, LAI and nitrogen content at the full heading stage, resulting in an increased gross hulled rice yield.

In HN, timing of topdressing and planting density affected neither the sink size nor the gross hulled rice yield (Table 6). This was at least partly because ET not only increased the number of differentiated spikelets but also increased the number of degenerated spikelets, and HD not only increased the number of panicles per area but also decreased the number of spikelets per panicle.

Although leaf nitrogen (%) in 2009 and total nitrogen (g m⁻²) in 2008 were higher in ST than in ET (Table 5), there was no difference in gross hulled rice yield between ET and ST. This result suggests that very high nitrogen content at the full heading stage does not increase gross hulled rice yield, although it is difficult to evaluate the effect of nitrogen content on gross hulled rice yield precisely, since topdressing affects not only the nitrogen content but also the other yield related traits. On the other hand, the NSC content of stems and leaf sheaths at the full heading stage was hardly affected by the timing of topdressings and planting density. Nagata et al. (2001) also reported that HN did not affect NSC content at heading in the high-yielding indica type variety Takanari.

HN was considered to increase unhulled rice weight per area during the early and late ripening periods (Table 7),
resulting in a high gross hulled rice yield. In HN, the lower the planting density, the heavier the unhulled rice weight during the late ripening period (ΔRW30-M) in 2008. This is probably because the low planting density increased the number of late heading panicles and high order spikelets, which grew later. However, the planting density did not affect the final gross hulled rice weight (RWm), probably because of a negative relation between the rate and the duration of rice growth.

3. Strategies for super high-yielding rice in the Tohoku region

In this study we elucidated that although HN produced the gross hulled rice yield of more than 9 t ha\(^{-1}\) in a large grain-type rice variety Bekoaoba, it was difficult to produce the gross hulled rice yield of more than 10 t ha\(^{-1}\) by the regulation of the timing of topdressing and/or the planting density. In the plants with a low-yielding potential, optimization of nitrogen application and planting density might be very useful. In order to achieve a super high rice yield of more than 10 t ha\(^{-1}\), we need to create new types of rice as well as improve the cultivation technology. Based on the varietal differences in the growth and yield reported previously and the responses to nitrogen application and planting density in this study, we discuss here some strategies for super high-yielding rice producing a yield of more than 10 t ha\(^{-1}\) in the Tohoku region.

1) Dry matter production

The top dry weight of Bekoaoba in HN, which was about 10 t ha\(^{-1}\) at the full heading stage and about 15.5 t ha\(^{-1}\) at maturity (Tables 5, 7), seems to be too light to achieve a gross hulled rice yield of 10 t ha\(^{-1}\). The results of the present study showed that it was difficult to increase the top dry weight at the full heading stage by HN in comparison with other traits such as sink size, LAI and nitrogen content (Tables 5, 6). HD increased top dry weight at the full heading stage, but not at maturity. Nagata et al. (2007) reported that the top dry weight at the yellow ripe stage was closely related to the cumulative solar radiation regardless of variety, and Bekoaoba showed a relatively high ratio of dry matter to cumulative solar radiation in the Tohoku region. Yoshinaga et al. (2006) also reported that late heading varieties had a heavy top dry weight at the full heading stage and also at maturity in the Tohoku region. These results suggest that the dry matter production is mainly dependent on the growing duration and that the use of late heading varieties is effective in increasing dry matter production.

The dry matter production during the ripening period of Bekoaoba was small in Bekoaoba (Fukushima et al., 2011), indicating that the increase in dry matter production during the ripening period may be increased by the improvement of plant type and photosynthetic ability, as described below.

2) Sink size

The sink size of Bekoaoba under HN, which was more than 12 t ha\(^{-1}\), seems enough to achieve a gross hulled rice yield of 10 t ha\(^{-1}\). The sink size of Bekoaoba is attributed to its large spikelet size (Fukushima et al., 2011). However Takita (1988) suggested that the extra large spikelet size might restrict grain filling, since the grain width could not exceed 3.6 mm even if the spikelet width increased to more than 4.3 mm. Thus, the most suitable combination of the spikelet size and the number of spikelets per area has to be elucidated. The cross of a variety with a high potential ability of spikelet production such as Takanari and a variety with large grain size such as Bekoaoba might be effective in selecting the most suitable combination of the spikelet size and the number of spikelets per area. The response of the number of differentiated spikelets per panicle to ET varied with the variety (Fukushima, 2007) and it was not high in Bekoaoba in this study (Fig. 1). Varieties with a high response to ET such as Takanari might be a useful genetic resource in this respect.

3) Vascular system

To achieve a super high yield, we should improve the conductivity of the vascular system in the panicles and neck internodes, although the conductivity was not found to limit the rice yield in the Tohoku region at the present level of high yield (Fukushima et al., 2011). The vascular system of panicles in indica type varieties is quite different from that of panicles in japonica type varieties (Fukushima and Akita, 1997). Introduction of the large number of large vascular bundles in neck internodes from indica type varieties into the large grain type varieties is one promising strategy (Fukushima et al., 2009).

4) Plant type

Most of the morphological traits of panicles, stems and leaves can be regulated more easily by the selection of varieties than by the method of nitrogen application (Fukushima, 2007). The cross of a variety with long flag leaf and not fully emerged panicle such as Takanari and a variety with bending panicles such as Bekoaoba might improve light intercept characteristics and simultaneously strengthen lodging resistance by lowering the center of gravity.

5) Single leaf photosynthesis

Leaf nitrogen content, which was closely related to photosynthesis, was changed by the method of nitrogen application more than by the selection of varieties (Table 4). This suggests that the method of nitrogen application might be more effective in improving single leaf photosynthesis. For example, topdressing at heading might activate single leaf photosynthesis during the ripening period. On the other hand, the leaf conductance, which is also closely related to the photosynthesis, is larger in high-yielding indica varieties than in japonica varieties (Maruyama and Tajima, 1990). However, varieties with large stomatal aperture such as indica varieties are easily
damaged by cool temperatures (Nishiyama et al., 1987). The role of leaf conductance for high yielding needs to be elucidated in colder areas such as the Tohoku region.

(6) Remobilization

The NSC content of stems and leaf sheaths and the decrease in stem and leaf weight during the ripening period did not vary with the method of nitrogen application and/or planting density (Table 5) but varied with the variety (Fukushima et al., 2011). This suggests that the breeding of varieties or lines with a high remobilization ratio might be possible, although these traits are not always related to hulled rice yield (Nagata et al., 2001; Ishikawa et al., 2003; Fukushima et al., 2011).

(7) Ripening duration

Although varietal differences in gross hulled rice yield were largely determined by the factors before 30 DAH in the Tohoku region (Fukushima et al., 2011), an increase in the rice yield after 30 DAH was important for high yield in the warmer areas of Japan (Fukushima et al., 2006). In order to obtain a super high yield in the Tohoku region, the increase in the rice yield at the late ripening period might be important. Since HN elongated the ripening period (Table 7), the super high-yielding variety in HN is expected to have a longer ripening period. However, the temperature and solar radiation decrease rapidly during the late ripening period in the Tohoku region. Therefore, genetic resources, allowing high ripening ability under low temperatures and low solar radiation, are awaited.

(8) Conclusion

We proposed some strategies for super high-yielding rice having a yield of more than 10 t ha⁻¹; to expand sink size, improve the vascular system and regulate the plant type by the cross of varieties with differential morphological traits; to increase top dry weight by delaying heading date; to increase the remobilization ratio; and to keep ripening ability high under low temperature and low solar radiation conditions. To prove the feasibility and effectiveness of these strategies, we need to compare and evaluate the yielding ability of many varieties or lines with different traits or developmental patterns under various cultivation conditions in the Tohoku region.

References

Fukushima, A. and Akita, S. 1997. Varietal differences of the course and differentiation time of large vascular bundles in the racise of rice. *Jpn. J. Crop Sci.* 66: 24-28*.
Fukushima, A., Kusuda, O., Nakano, H., and Morita, S. 2006. Analysis of high-yielding ability in a rice cultivar Akiyakura. *Plant Prod. Sci.* 9: 360-372.
Fukushima, A. 2007. Effects of timing of nitrogen topdressing on morphological traits in different rice varieties. *Jpn. J. Crop Sci.* 76: 18-27*.
Fukushima, A., Fukuda, A., Shiratsu, H., and Yamaguchi, H. 2009. Panicle traits of P2 plants derived from the cross between large grain rice Bekooba and indica rice Takanari. *Tohoku J. Crop Sci.* 52: 23-24*.
Fukushima, A., Shiratsu, H., Yamaguchi, H. and Fukuda, A. 2011. Varietal differences in morphological traits, dry matter production and yield of high yielding rice in the Tohoku region of Japan. *Plant Prod. Sci.* 14: 47-53.
Ishikawa, T., Fujimoto, H., Kihaki, N., Murayama, S. and Akita, S. 2003. Effect of temperature and solar radiation on dry matter production and translocation during the ripening period in rice cv. Takanari. *Jpn. J. Crop Sci.* 72: 339-344*.
Kobata, F., Tanaka, N. and Arima, S. 1988. Study on productive ecology of a high yielding japonica-indica hybrid rice cultivar ‘Sukinoo258’. *Jpn. J. Crop Sci.* 57: 267-277*.
Mae, T., Iwahara, A., Kaneta, Y., Masaki, S., Suehi, M., Aizawa, M., Okawa, S., Hasegawa S. and Makino A. 2006. A large-grain rice cultivar, Akita 63, exhibits high yields with physiological N-use efficiency. *Field Crop Res.* 97: 227-237.
Matsuba, K. 1987. Morphological studies on the regularity of shoots development in rice plants 1. Different growth types indicated by total leaf number on the main stems in the same plot. *Jpn. J. Crop Sci.* 56: 313-321*.
Matsuba, K. 2000. A new morphogenetic model on the most suitable leaf-internode unit and developmental stage for controlling plant type in rice cultivation. *Jpn. J. Crop Sci.* 69: 293-300*.
Matsushita, S. 1973. Technology for improving rice cultivation. Yokoendo, Tokyo. 1-393*.
Murayama, S. and Tajima, K. 1990. Leaf conductance in japonica and indica rice varieties. I. Size, frequency and aperture of stomata. *Jpn. J. Crop Sci.* 59: 801-808.
Nagata, K., Yoshimagawa, S., Takanashi, J. and Terao, T. 2003. Effects of dry matter production, translocation of nonstructural carbohydrate and nitrogen application on grain filling in rice cultivar Takanari, a cultivar bearing a large number of spikelets. *Plant Prod. Sci.* 4: 173-183.
Nagata, K., Yoshimagawa, S., Terashima, K. and Fukuda, A. 2007. Growth, yield and dry matter production of rice varieties for whole-crop silage bred for Tohoku region of Japan. *Bull. Natl. Res. Cent. Tohoku Reg.* 107: 63-70*.
Nakagomi, K., Yamaguchi, M., Kato, K., Nishio, T., Taki, M., Higashijima, M., Kato, H. and Tamura, Y. 2006. Breeding of a new rice cultivar, “Bekooba”, for whole-crop silage adapted to direct-seeding cultivation. *Bull. Natl. Agric. Res. Cent. Tohoku Reg.* 106: 1-14*.
Nishiyama, I., Lee, M. H. and Yun, D. Y. 1987. Varietal difference in stomatal aperture in rice seedlings in relation to the cool temperature susceptibility in Tongril group varieties. *Jpn. J. Crop Sci.* 56: 482-490.
Sakai, Y., Mano, Y., Okada, T. and Hiro, T. 1984. Comparison of dry matter production and associated characteristics between direct-sown and transplanted rice plants in a submerged paddy field and relationships to planting patterns. *Field Crop Res.* 87: 43-58.
Takai, T., Masunara, S., Nishio, T., Otsumi, A., Shirahata, T. and Horie, T. 2006. Rice yield potential is closely related to crop growth rate during late reproductive period. *Field Crop Res.* 96: 328-335.
Takita, T. 1988. Grain ripening of a high yielding rice cultivar with very large grains. *Jpn. J. Breed.* 38: 443-448.
Tanaka, M. 1979. Rice cultural technology in the future. Basis of a method of nitrogen topdressing applied to a deep soil layer. Hikarimoe, Tokyo. 1-398*.
Yoshinaga, S., Nagata, K. and Fukuda, A. 2006. Characteristics of seedling emergence and dry matter production of direct-seeded rice cultivars for whole-crop silage in Tohoku region. *Bull. Natl. Res. Cent. Tohoku Reg.* 105: 63-71*.

* In Japanese.
** In Japanese with English summary.
*** In Japanese with English abstract.