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Varietal Differences in the Responses of Yield Components of Rice Plants to Nitrogen-Free Basal Dressing Accompanied with Sparse Planting Density in the Tohoku Region of Japan

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Abstract : Grain yield of rice plants is composed of different yield components that vary with the genotype, environmental condition and cultivation practice. Experiments were conducted in 1999, 2000 and 2001 in the field of Iwate University, Japan to study the responses of yield components to the practice of nitrogen-free basal dressing accompanied with sparse planting density (BNo) in 12 rice cultivars or lines. The results showed that the number of spikelets per panicle (NSp^{-1}), especially in the late-maturing cultivars and in 2001, was often larger in BNo than in the conventional cultivation (CONT). The number of panicle m^{-2} (NPm^{-2}), however, was significantly smaller in BNo than in CONT, resulting in a small number of spikelets m^{-2} (NSm^{-2}) in BNo. The difference between BNo and CONT in NSm^{-2} varied with the cultivar and the year, and it was often smaller in the late-maturing cultivars than in the early- and medium-maturing ones, and was also smaller in 2001 than in 1999 or 2000. The percentage of ripened grains (PRG) was higher in BNo than in CONT in all cultivars, and the average PRG of 12 cultivars in BNo was 14.0%, 9.0% and 4.8% higher than that in CONT in 1999, 2000 and 2001, respectively. Grain weight (1,000-grain weight) was heavier in BNo than in CONT in most cultivars, and the 1,000-grain weight averaged over cultivars and years was 0.8 g (3%) heavier in the former than in the latter. High temperatures during the grain-filling period significantly and adversely affected 1,000-grain weight in CONT, but only slightly in BNo. The stably high PRG and heavy 1,000-grain weight in BNo, especially in the year with unfavorable weather (1999), could compensate for the small NPm^{-2} in BNo so as to achieve a high and stable yield in the Tohoku region.

Key words : Nitrogen-free basal dressing, Rice cultivars, Sparse planting density, Weather conditions, Yield components.

The number of panicles per unit area, the number of spikelets per panicle, the percentage of ripened grains and 1,000-grain weight are four components forming the grain yield of rice plants. Each of these yield components is determined at a certain growth period, contributes to grain yield to a different extent and varies with the genotype, environmental condition and cultivation practice (Yoshida, 1981; Hirano et al., 1997; Truong et al., 1998; Kuroda et al., 1999a and b; Peng et al., 2000). Yield is a result of the interaction among different factors, and yield reduction results from a decrease in any yield component. Thus, producing and maintaining all yield components at a high level for achieving a stable and high grain yield is one of the most difficult tasks in rice production.

The conventional rice cultivation practice based on the basal application of a large amount of nitrogen fertilizer and a close planting density (CONT) has been established for increasing the number of panicles and spikelets, which results in a high grain yield per unit area (Matsushima, 1995). Although this heavily fertilized and close spacing cultivation has been widely used, yield reduction due to sterilized spikelets occurred in years with a cool summer, particularly in 1993 (Oyamada, 1995; Nishiyama, 1996). Such damage by a cool summer seems to be unavoidable in the conventional practice (Murata, 1994; Hirano et al., 1997).

In some paddy fields, however, rice had been planted without a basal application of nitrogen fertilizer, but with sparse planting density (BNo) (Murata, 1994; Hirano et al., 1997; Truong et al., 1998). Although the BNo cultivation method is effective to avoid cool weather damage (Murata, 1994), its use has been limited because of the low grain yield, which was about 5-10% lower than in CONT in normal years (Hirano et al., 1997; Truong et al., 1998). This low yield is caused by a decreased number of spikelets per m^2 (NSm^{-2}), which is attributed to a small number of panicles per m^2 (Hirano et al., 1997).

Grain yield in BNo, however, can be improved to

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Abbreviations : BNo, the practice of nitrogen-free basal dressing accompanied with the sparse planting density of 16.7 hills m^{-2}; CONT, the standard cultivation with the planting density of 22.2 hills m^{-2}; NPm^{-2}, number of panicles m^{-2}; NSm^{-2}, number of spikelets per m^2; NSp^{-1}, number of spikelets per panicle; PRG, percentage of ripened grains.

the same level as that in CONT through the increase in the number of spikelets per panicle (NSp^{-1}) and the percentage of ripened grains (PRG) by a split application of nitrogen fertilizer at the neck node initiation stage (Truong et al., 1998). This once again indicates that a high yield could be achieved not only by producing a large number of panicles per m^2 (NPm^{-2}), but also by improving other yield components, and that a mere increase of NPm^{-2} could not secure a high and stable yield.

In a previous study (Pham et al., 2004), we examined the effect of BNo practice on the growth of tillers and yields of various rice cultivars in years with different weather, and concluded that although the grain yield in BNo was lower than that in CONT in the years with favorable weather (2000 and 2001), it was similar to or higher than that in CONT in the year with unfavorable weather (1999). We also showed that the grain yield of Akitakomachi and Fukuhibiki in BNo was lower, but that of Ouu316 and Hitomebore in BNo was similar to or higher than that in CONT. However, in that study, the responses of yield components to BNo practice were not examined.

In the present study, we examined the yield components of 12 rice cultivars grown in BNo and compared them with those in CONT for three growing seasons (1999, 2000 and 2001). Furthermore, the effects of weather conditions on the yield components were analyzed and discussed.

Materials and Methods

Experiments were conducted in the paddy field with Wet Aldosols at the Faculty of Agriculture, Iwate University in 1999, 2000 and 2001. Twelve cultivars or lines belonging to different genotypes were used. They were Iwate43 (I43), Hananomai (Ha), Ouu339 (339) and Fukei149 (149) of the early-maturing genotype; Akitakomachi (Ak), Hatajirushi (Hat), Fukuhibiki (Fu) and Iwanan7 (I7) of the medium-maturing genotype; and Menkoina (Me), Okiniiri (Ok), Ouu316 (316) and Hitomebore (Hi) belonging to the late-maturing one. The plant type of each cultivar is shown in Fig. 1.

Seedlings at around the 4th leaf-age stage were transplanted, three seedlings per hill in the middle of May. In CONT, planting density and nitrogen application regimes were the same as in the standard practice in Iwate Prefecture; the planting density was 22.2 hills per m^2 (15 × 30 cm) and the total of nitrogen fertilizer was 11 g m^{-2} (6.5 g as basal dressing, 2.5 g at panicle formation and 2.0 g at heading stages). In BNo, the planting density was 16.7 hills per m^2 (20 × 30 cm) and the amount N was 9 g m^{-2} (3.0 g at the 8th leaf-age stage, 2.0 g at the neck-node initiation stage, 2.0 g at the panicle formation stage and 2.0 g at the heading stage). Phosphorus and potassium fertilizers at 14.0 g m^{-2} and 12.8 g m^{-2}, respectively, were applied as basal dressing in both CONT and BNo.

The experiment was carried out in a split-random block design with two replications. Growth conditions were arranged as main blocks and cultivars as sub-blocks. The sub-block was about 20 m^2 in area. For determining yield components, 27 hills from each replication were harvested at the full-ripening stage, dried under sunlight and then carefully threshed by hand. The grain weight and moisture content were measured, and then grains were separated into four equal groups. The grains in one group were used for further investigation of the number of filled and unfilled grains as well as 1,000-grain weight. The filled grains were selected with a salty solution with a specific gravity of 1.06, and grain weight of the filled grains (1000-grain weight) was adjusted to the moisture content of 14.5%.

The meteorological data during experiments were detailed in our previous report (Pham et al., 2004). Briefly, rice plants in 1999 experienced a high temperature (4~5°C higher than the average value) and high solar radiation from the end of July to mid-August, a warm temperature (1~2°C higher than the average value) and low solar radiation thereafter. In

Table 1. Mean squares from analysis of variance for yield and yield components of twelve rice cultivars grown in CONT and BNo in 1999, 2000 and 2001.

Source of variance	Degrees of freedom	Grain yield (g m^{-2})	NPm^{-2}	NSp^{-1}	NSm^{-2} (10^3 m^{-2})	PRG (%)	1,000-G (g)
Cultivar (C)	11	9123**	34903**	2198**	78**	204**	8.9**
Cultivation practice (CP)	1	10887**	576210**	1991**	1794**	3085**	20.0**
Year (Y)	2	263524**	445ns	599**	122**	1051**	17.0**
C × CP	11	918*	2140**	31**	9*	11ns	0.2**
C × Y	22	2522**	884*	19**	3ns	49**	0.1**
CP × Y	2	3942**	2489**	85**	64**	261**	2.6**
C × CP × Y	22	804*	345ns	9ns	4ns	10ns	0.1**
Error	72	467	457	5	4	7	0.0
Total	143						

1,000-G : 1,000-grain weight. * and ** : significant at 0.05 and 0.01probability levels, respectively; ns : not significant.

2000, the temperature was slightly (1~2°C) higher than the average value during the whole growth period of rice plants, and solar radiation was also higher than the average value from mid-May to the end of August. On the other hand, the temperature in 2001 was similar to or slightly lower than the average value from the beginning of August to mid-September. In this year (2001), solar radiation was markedly lower than the average value from 10 July to 10 August, but was higher than the average value thereafter.

Results

1. Analysis of variance of yield and yield components

Table 1 shows the mean squares from analysis of variance for yield and yield components of twelve rice cultivars grown in CONT and BNo in 1999, 2000 and 2001. Cultivar and cultivation practice significantly affected the yield and all its components, especially NPm^{-2} and NSp^{-1}. The mean squares of NPm^{-2}, NSm^{-2}, PRG and 1,000-grain weight for the cultivation practice, however, were much larger than those for the cultivar, indicating that the cultivation practice had a stronger effect on these yield components than the cultivar. Yearly difference was the major component of the total variation of grain yield, and was highly significant for the NSm^{-2}, the PRG and 1,000-grain weight, but was not significant for the NP m^{-2}. Cultivar and cultivation practice interaction was also significant for the variation of yield and its components, except for that of PRG. The interaction of cultivar and year, on the other hand, was not significant for the variation of NSm^{-2}, but was significant for that of yield and other yield components. Yield and all its components were also significantly affected by the interaction of cultivation practice and year.

2. NSp^{-1} and NSm^{-2}

The data of yield and NPm^{-2} are presented in a separate paper (Pham et al., 2004). Fig. 1 shows the NSp^{-1} and the NSm^{-2} of different cultivars grown under CONT and BNo in 1999, 2000 and 2001. Generally, NSp^{-1} in both BNo and CONT was larger in the cultivars of the panicle-weight type, particularly in Fukuhibiki and Ouu316, than in the cultivars of the panicle-number type. NSm^{-2} in both BNo and CONT was also often larger in the cultivars of the panicle-weight type than in the cultivars of the panicle-number type, except in Iwanan7. In comparison with CONT, NSp^{-1} in BNo was larger. The relative increase in NSp^{-1} in BNo was greater in the late-maturing cultivars than in the early- and medium-maturing ones, and was also greater in 2001 than in 1999 or 2000. NSm^{-2}, however, was lower in BNo than in CONT in all cultivars and in all 3 years, and largely varied with the cultivar and the year. The difference between BNo and CONT in NSm^{-2} was not clearly related with the plant type of the cultivar, and it could be small or large in the cultivars belonging to any plant type. The difference, however, was often smaller in the late-maturing cultivars, especially in Ouu316 and Hitomebore, than in the early- and medium-maturing ones, and was also smaller in 2001 than in 1999 or 2000.

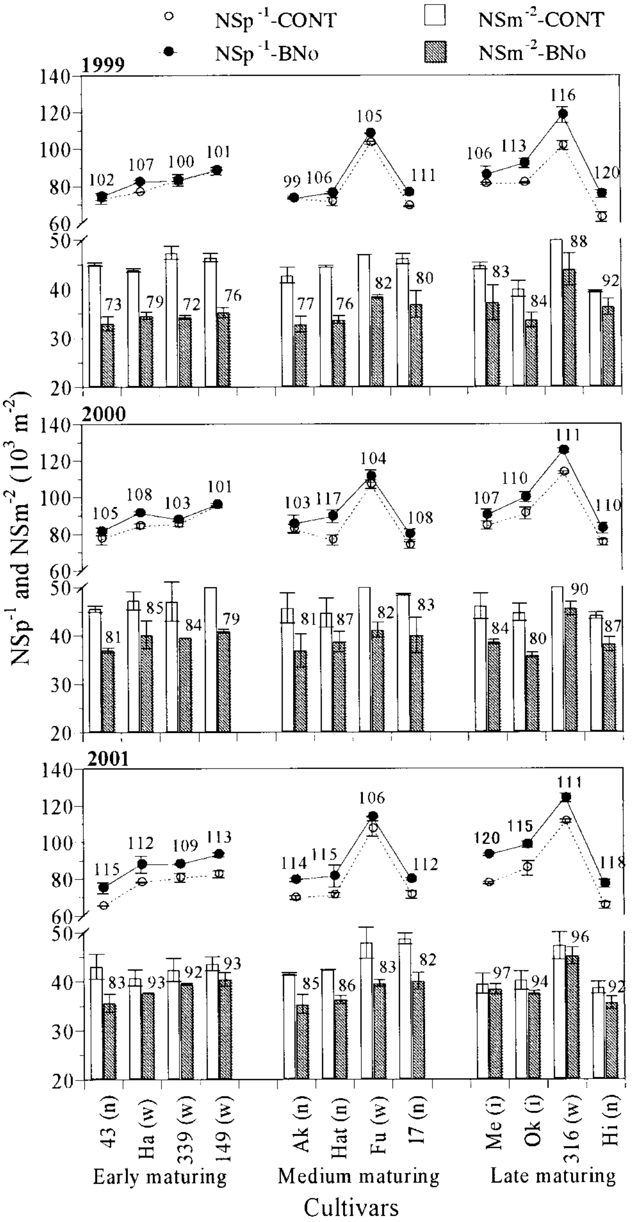

Fig. 1. Number of spikelets per panicle (NSp^{-1}) and per m^2 (NSm^{-2}) of different cultivars under CONT and BNo in 1999, 2000 and 2001.
Numerals above bars and lines indicate the ratio of values in BNo to those in CONT (%). Errors bars indicate standard errors. Letter in ( ) indicate the plant type of cultivars; n = the panicle-number type, i = the intermediate type and w = the panicle weight type.

3. PRG and 1,000-grain weight

Fig. 2 and 3 show the PRG and 1,000-grain weight of different rice cultivars. PRG in both BNo and CONT

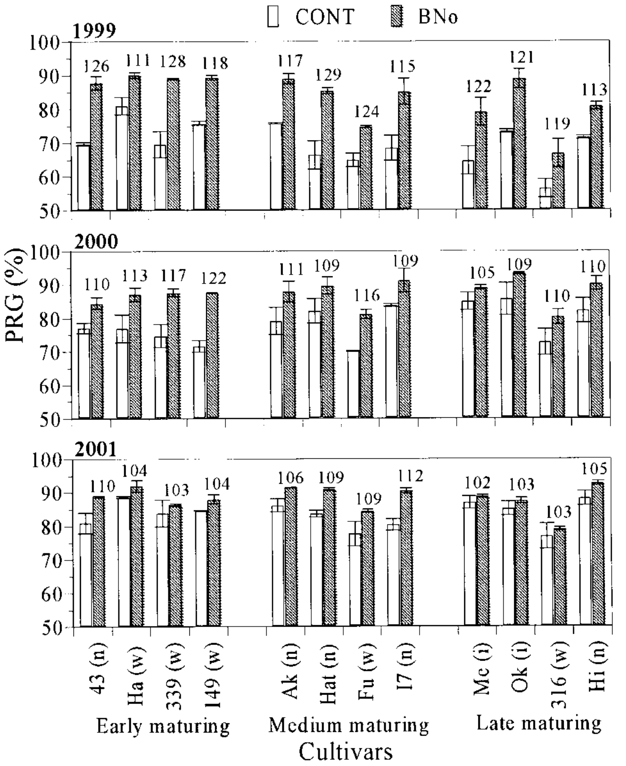

Fig. 2. The percentage of ripened grains (PRG) of different rice cultivars under CONT and BNo in 1999, 2000 and 2001.
Numerals above bars indicate the ratio of values in BNo to those in CONT (%). Error bars indicate standard errors. Letters in ( ) are the same as in Fig. 1.

was lower in Fukuhiki and Ouu316 than in other cultivars. In comparison with CONT, PRG in BNo was higher in all cultivars and in all 3 years. The difference between BNo and CONT in PRG was 14.0% (BNo/CONT=120.1%) in 1999, 9.0% (BNo/CONT=111.5%) in 2000 and 4.8% (BNo/CONT=105.7%) in 2001 (Fig. 2). In 1999, PRG in CONT was very low and ranged from 56.3 % in Ouu316 to 80.9 % in Hananomai. PRG in 1999 in BNo was higher than in CONT in all cultivars, and the difference ranged from 9.1% in Hananomai (BNo/CONT=111.3%) to 19.0% in Hatajirushi (BNo/CONT=128.7%). In 2000, PRG, particularly in CONT, was higher than that in 1999, and ranged from 70.1% in Fukuhibiki to 85.6 % in Okiniiri in CONT, and from 80.3 % in Ouu316 to 93.2 % in Okiniiri in BNo. PRG in 2000 was also higher in BNo than in CONT in all cultivars, and the difference ranged from 4.1% in Menkoina (BNo/CONT=104.8%) to 16.0% in Fukei149 (BNo/CONT=122.4%). In 2001, PRG was high in both CONT (from 77% in Ouu316 to 88.7% in Hananomai) and BNo (from 79% in Ouu316 to 92.7% in Hitomebore). In this year, the PRG of Hananomai, Ouu339, Fukei149, Menkoina, Okiniiri and Ouu316 was only slightly higher in BNo than in CONT.

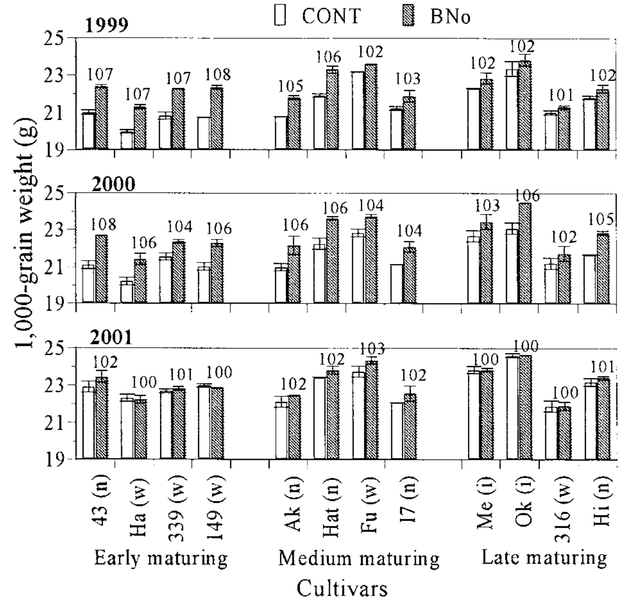

Fig. 3. 1,000-grain weight of different rice cultivars under CONT and BNo in 1999, 2000 and 2001.
Numerals above bars indicate the ratio of values in BNo to those in CONT (%). Error bars indicate standard errors. Letters in ( ) are the same as in Fig. 1.

Cultivars with a heavy 1,000-grain weight in CONT possessed a heavy 1,000-grain weight in BNo (Fig. 3). The grain weight (1,000-grain weight) did not relate with the plant type or the earliness of cultivars. It was always light in Hananomai or Ouu 316, but was heavy in Fukuhibiki and Okiniiri. The difference between BNo and CONT in 1,000-grain weight was similar to that in PRG. The 1,000-grain weight averaged over cultivars and years was 22.8 g in BNo, and 22.0 g in CONT (BNo/CONT=103%). Grain weight (1,000-grain weight) was light in CONT in both 1999 and 2000. It ranged from 20.0 g in Hananomai to 23.4 g in Okiniiri in 1999 and from 20.2 g in Hananomai to 23.1 g in Okiniiri in 2000. The 1,000-grain weight was heavier in BNo than in CONT, and the difference ranged from 0.3 g (1%) in Ouu316 to 1.6 g (8%) in Fukei149 in 1999, and from 0.5 g (2%) in Ouu316 to 1.6 g (8%) in Iwate43 in 2000 (Fig. 3). In 2001, the 1,000-grain weight of all cultivars in CONT was heavy (from 21.9 g in Ouu316 to 24.6 g in Okiniiri), but the difference between BNo and CONT was not significant in any cultivar.

4. Correlation of PRG with NS m^{-2}

Since the correlation of PRG with NSm^{-2} in 2000 was similar to that in 2001, the combined data of these two years were used for analyzing the relationship between PRG and NSm^{-2}. PRG significantly and negatively correlated with NSm^{-2}, and the correlation coefficient (r) was –0.895 ($P<0.01$) in 1999, –0.888 ($P<0.01$) in 2000+2001 and –0.703 ($P<0.01$) overall (Fig. 4). The

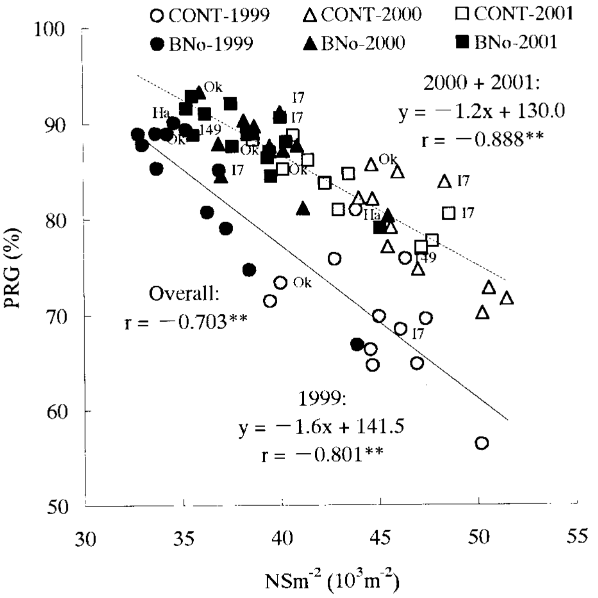

Fig. 4. Correlation of the percentage of ripened grains (PRG) with the number of spikelets m^{-2} (NSm^{-2}).
Letters and numerals beside symbols indicate the abbreviated cultivar names. ** : significant at 0.01 probability level.

slope coefficient was significantly steeper in 1999 (−1.6) than in 2000+2001 (−1.2), indicating that an increase in NSm^{-2} caused a larger decrease in PRG in the former than in the latter years. At the same level of NSm^{-2}, PRG in 1999 was lower than that in 2000 and 2001, except for Hananomai and Fukei149. Among cultivars, the PRG of Iwanan7 and that of Okiniiri was also often higher than that of other cultivars with the same NSm^{-2}.

5. Correlation of the difference between BNo and CONT in PRG with that in NSm^{-2}

The difference in PRG significantly and positively correlated with that in NSm^{-2}, and the correlation coefficient (r) was 0.644 ($P<0.05$) in 1999, 0.828 ($P<0.01$) in 2000+2001 and 0.803 ($P<0.01$) overall (Fig. 5). At the same level of the difference in NSm^{-2}, the increase in PRG in BNo, however, was greater in 1999 than in 2000 and 2001 in most cultivars, except in Hananomai, Fukei149, Akitakomachi and Fukuhibiki. In 1999, the increase in PRG in the late-maturing cultivars (Menkoina, Okiniiri, Ouu316 and Hitomebore) in BNo was considerably large although the difference in NSm^{-2} was small.

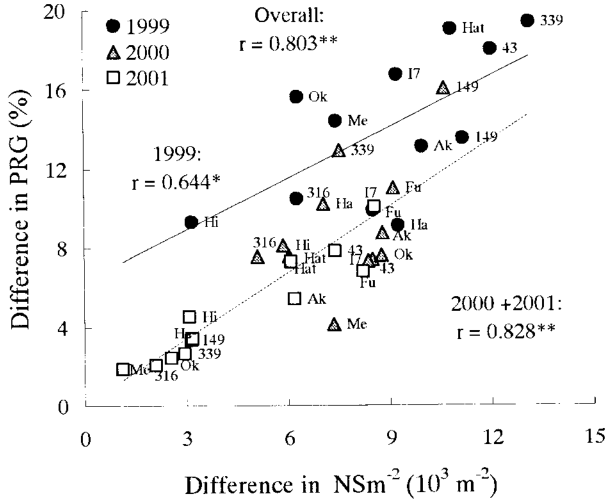

Fig. 5. Correlation of the difference between BNo and CONT in the percentage of ripened grains (PRG) with that in the number of spikelets m^{-2} (NSm^{-2}).
Letters and numerals beside symbols indicate the abbreviated cultivar names.* and ** : significant at 0.05 and 0.01 probability levels, respectively.

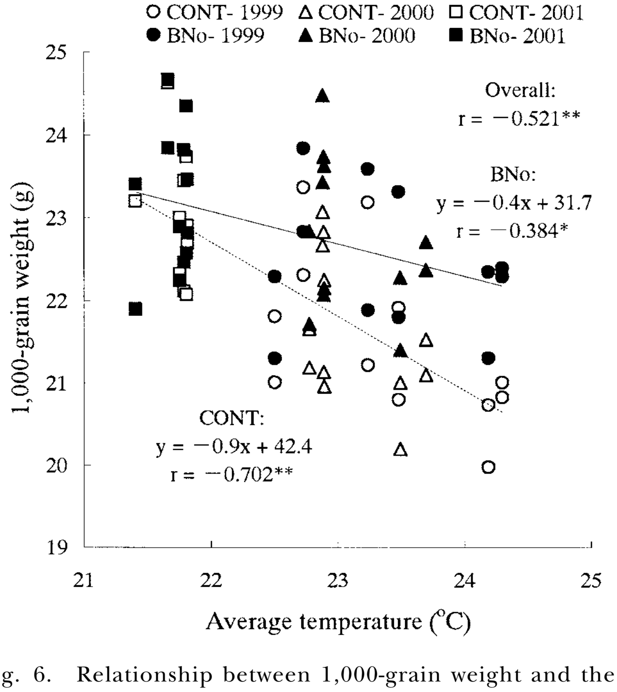

Fig. 6. Relationship between 1,000-grain weight and the average temperature during the whole grain filling period (40 days after full heading).
* and ** : significant at 0.05 and 0.01 probability levels, respectively.

6. Relationship between 1,000-grain weight and the average air temperature during the grain-filling period

The average temperature during the grain-filling period was lower in 2001 (21.4~21.8°C) than in 2000 (22.8~23.7°C) or 1999 (22.5~24.3°C) (Fig. 6). As temperature increased, 1,000-grain weight decreased, and 1,000-grain weight significantly and negatively correlated with the average temperature in both CONT (r=−0.702, $P<0.01$) and BNo (r=−0.384, $P<0.05$). The slope coefficient, which indicates the degree of the change in 1,000-grain weight with the change in temperature, however, was much steeper (statistically significant at 0.05 probability level) in the former (−0.9) than in the latter (−0.4).

Discussion

1. The large NSp^{-1} in BNo and varietal differences in the responses of NSp^{-1} and NSm^{-2} to BNo practice

NS m^{-2} is a product of NPm^{-2} and NSp^{-1}. Therefore, a change in NPm^{-2} or NSp^{-1} could result in a variation in NS m^{-2}. In this study, NSm^{-2} was smaller in BNo than in CONT (Fig. 1) despite the fact that NSp^{-1} in BNo is possibly increased by nitrogen top-dressing at the neck node initiation stage (Matsushima, 1995; Hashikawa, 1996; Truong et al., 1998). This is because NPm^{-2} was significantly smaller in BNo than in CONT as has been reported previously (Pham et al., 2004).

We also found that the difference between BNo and CONT in NPm^{-2}, particularly in the number of panicles on the secondary tillers, varied with the plant type of cultivar (Pham et al., 2004). The difference was often smaller in the cultivars of the panicle-weight type than in the cultivars of the panicle-number type. The difference between BNo and CONT in NSm^{-2}, however, did not clearly differ with the plant type of cultivar because an increased NPm^{-2} often resulted in a decreased NSp^{-1} (the correlation coefficient in the correlation between NPm^{-2} and NSp^{-1} was significant at 0.01 probability level, and was -0.858 in CONT and −0.833 in BNo) (data not shown). The difference between BNo and CONT in NSm^{-2}, nevertheless, varied with the earliness of cultivars, and it was often smaller in the late-maturing cultivars, particularly in Ouu316 and Hitomebore, than in the early- and medium-maturing ones due to a larger increase in NSp^{-1} in the former cultivars (Fig. 1). Truong et al. (1998) also demonstrated that an increased NSp^{-1} was necessary to achieve a large NSm^{-2} and a subsequent high grain yield in BNo.

The effect of growth duration on yield and yield components has been reported (Yoshida, 1981; Wada and Cruz, 1989). Yoshida (1981) suggested that a close spacing and an early application of nitrogen fertilizer were essential for the early-maturing cultivars, which are short of vegetative growth, to produce high grain yield. In the present study, the shortage of vegetative growth might have caused the small NSm^{-2} in BNo for the early- and medium-maturing cultivars, especially in 1999, when the growth duration of all cultivars was about 6~7 days shorter than that in normal years (Pham et al., 2004) and the leaf number was 0.5 smaller than that in 2000 and 2001 (data not shown). On the other hand, the late-maturing cultivars with a long vegetative growth period, a large biomass and a large leaf area index at the panicle initiation stage could absorb more nutrients, and produce more photosynthates. Thus, they had larger NSp^{-1} and NSm^{-2} than the early- and medium-maturing ones under the BNo condition. The smaller difference in NSm^{-2} between BNo and CONT in the late-maturing cultivars, particularly in Ouu316 and Hitomebore, as compared with the early- and medium-maturing cultivars, could be the main reason for the small yield difference in the late-maturing cultivars (Pham et al., 2004). This also indicates that BNo practice could be more effective for the cultivation of the late-maturing cultivars in the Tohoku region.

The difference in NSm^{-2} between BNo and CONT also significantly varied with the year (Table 1), and was smaller in 2001 than in 1999 or 2000 (Fig. 1). Kumura (1995) stated that dry-matter production per glumaceous flower in the period from glumaceous flower initiation to full heading was the main factor affecting the number of degenerated spikelets. Low solar radiation during this period causes a decrease in dry-matter production, increasing the number of degenerated primordia, and subsequently reduces NSp^{-1} or NSm^{-2} (Ishii and Kumura, 1987). In the present study, during the period from 10 July to 10 August in 1999 and 2000 (corresponding to the period from 30 days before full heading to full heading), solar radiation was high (18.0 and 17.7 MJ m^{-2} day^{-1}), and was 13% and 11% higher than that in normal years, respectively (Iwate Meteorological Monthly Report). Rice plants in CONT with a larger leaf area index, as compared with those in BNo (Hirano et al., 1997), could absorb more sunlight, producing more photosynthates, and subsequently produced a larger NSm^{-2}. On the other hand, low solar radiation during the period of this growth stage in 2001 (14 MJ m^{-2} day^{-1} and was 12% lower than that in normal years), might have caused a reduction in photosynthates thereby reducing the number of spikelets in CONT in this year. The smallest difference in NSm^{-2} between BNo and CONT in 2001, as compared with those in 1999 and 2000, indicated that rice plants in BNo characterized by a smaller number of stems, a smaller leaf area index and a better light intercepting canopy (Hirano et al., 1997), were less affected by low solar radiation during the panicle formation stage than those in CONT.

2. Heavy and stable 1,000-grain weight in BNo

The 1,000-grain weight is a stable varietal character (Yoshida, 1981; Matsushima, 1995), and was reported to be decreased by high temperature during ripening (Suzuki and Nakamura, 1978; Morita, 2000). Suzuki and Nakamura (1978) showed that 1,000-grain weight significantly and negatively correlated with the average temperature during 3 weeks after full heading ($r=-0.932$, $P<0.01$). In the present study, we also found that high temperature in 1999 and 2000 caused the reduction in 1,000-grain weight in both BNo and CONT, and that 1,000-grain weight significantly and negatively correlated with the average temperature during the whole grain filling period (during 40 days after full heading) in both BNo (r=−0.384, P<0.05) and CONT (r=−0.702, P<0.01) (Fig. 3 and 6). In comparison with CONT, 1,000-grain weight in BNo was heavier in the hot years of 1999 and 2000 (Fig. 3). The slope coefficient of the regression line between 1,000-grain weight and the average temperature, which indicates the degree of changes in 1,000-grain weight with the change of temperature, was also much smaller in BNo (−0.4) than in CONT (−0.9) (Fig. 6). These results suggested that 1,000-grain weight in BNo was less affected by high temperature during the grain filling period than in CONT. In other words, 1,000-grain weight in BNo was often heavier and more stable than in CONT, but that in CONT largely varied with the change of temperature.

3. The high and stable PRG in BNo and factors affecting PRG

PRG was significantly higher in BNo than in CONT in all 3 years and in all cultivars (Fig. 2, Table 1). The interaction of cultivar with cultivation practice for PRG was not significant, indicating that the magnitude of increase in PRG in BNo was similar in all cultivars. The increase in PRG in BNo in all cultivars, thus, may compensate for the small NSm^{-2} in BNo (Truong et al., 1998).

The magnitude of increase in PRG in BNo, however, was larger in 1999 than in 2000 or 2001, causing a significant interaction of cultivation practice with year (Table 1). In previous study (Pham et al., 2004), we showed that the grain yield in 1999 of the early- and medium-maturing cultivars was similar, but that of the late-maturing ones was higher in BNo than in CONT. A large increase in PRG in BNo in 1999, especially in the late-maturing cultivars (Fig. 2, 4 and 5), might have totally compensated for the small NSm^{-2}. Thus, the grain yield in BNo in 1999 was similar to or higher than that in CONT. On the other hand, a small increase in PRG in BNo in 2000 and 2001 (Fig. 2, 4 and 5) could not be large enough to compensate for the small NSm^{-2}. As a result, in 2000 and 2001, the grain yield in BNo was lower than that in CONT in most cultivars (Pham et al., 2004).

The negative correlation of PRG with NSm^{-2} was previously reported (Wada, 1969; Kuroda et al., 1999b). This relationship was again confirmed in this study (Fig. 4), suggesting that a low PRG in the cultivars with a large NSm^{-2}, and the small NSm^{-2} in BNo might also be a reason for the high PRG in BNo. The higher PRG in Iwanan7 and Okiniiri compared with other cultivars with the same NSm^{-2}, and the higher PRG of rice plants in 2000 and 2001 compared with 1999 (Fig. 4), however, indicated that NSm^{-2} is not the only reason for a low or high PRG among cultivars and years. Furthermore, at the same level of the difference in NSm^{-2} between BNo and CONT, the magnitude of increase in PRG in BNo was often greater in 1999 than in 2000 or 2001 (Fig. 2 and 5). These also suggested that the higher PRG in BNo than in CONT was not due to only the low NSm^{-2} in BNo. Thus, besides examining the effects of NSm^{-2}, the elucidation of the effect of other factors on grain filling is thought to be necessary.

A high temperature or low solar radiation during the grain filling period causes a decrease in PRG (Yoshida and Parao, 1976; Kobata et al., 2000; Morita, 2000). Temperature higher or lower than 21.5°C will reduce grain yield by affecting grain filling, but high solar radiation can compensate for the detrimental effects of low or high temperature (Matsushima and Manaka, 1957; Murata, 1964; Yoshida, 1981; Saitoh et al., 1998). On the other hand, a combination of a high temperature and low solar radiation can seriously impair ripening (Matsushima and Manaka, 1957; Yoshida, 1981). For finding the combined effect of low solar radiation and high temperature on PRG, the correlation of PRG with the ratio of the average solar radiation to the average air temperature (S/T) during the whole grain-filling period (40 days after full heading) was calculated. Because PRG significantly correlated with NSm^{-2} (Fig. 4), and the range of NSm^{-2} in CONT was large (from 38,674 in Hitomebore in 2001 to 51,519 in Fukei149 in 2000, Fig. 1 and 4), the data were separated into three groups based on NSm^{-2} in CONT : group 1 with NSm^{-2}<43,000; group 2 with NSm^{-2} of 43,000~47,000; and group 3 with NSm^{-2}>47,000. The correlation of PRG with S/T was

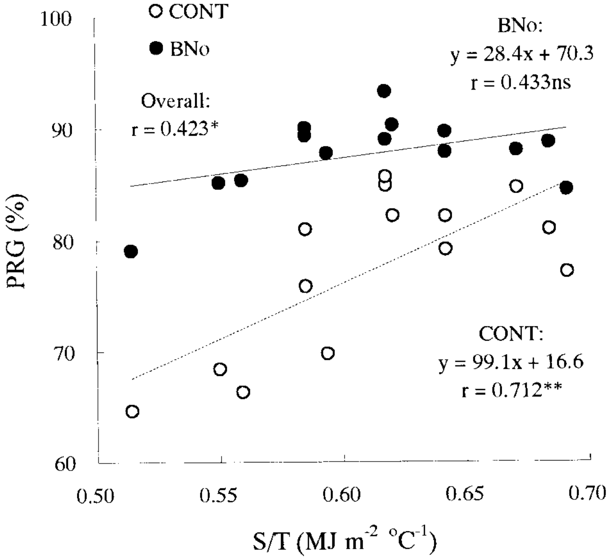

Fig. 7. Relationship between the percentage of ripened grains (PRG) with the ratio of the average solar radiation to the average temperature (S/T) during the whole grain filling period (during 40 days after full heading).
* and ** : significant at 0.05 and 0.01 probability levels, respectively; ns : not significant.
Note : NSm^{-2} in CONT was 43,000~47,000, and that in BNo was 75.7~92.7% of that in CONT.

then calculated for each group. Since similar results were obtained for all 3 groups, only the correlation in group 2 (NSm^{-2} was 43,000~47,000 in CONT) is presented in Fig. 7. PRG significantly correlated with S/T in CONT ($r=0.712$, $P<0.01$), but not in BNo ($r=0.433$). The larger correlation coefficient (0.712) and the significantly steeper slope coefficient (99.1) in CONT compared with those in BNo (0.433 and 28.4, respectively) indicated that PRG in CONT highly associated and largely varied with the change of temperature and solar radiation. On the other hand, PRG in BNo was less affected by this change and always remained at a high level.

Although the reason for the stable PRG and 1,000-grain weight in BNo with the change of temperature and solar radiation is not clear, it would be worth noting that under a high temperature and low solar radiation, a large number of stems, a large leaf area index and a large biomass cause the increased respiration rate that impairs grain filling (Murata and Iyama, 1958; Saitoh et al., 2000). Rice plants in CONT with such characteristics (Hirano et al., 1997; Truong et al., 1998) would be more affected by a high temperature and low solar radiation. On the other hand, rice plants in BNo with a small number of stems, a small leaf area index, but with heavy specific leaf weight and better light intercepting characteristics (Hirano et al., 1997; Truong et al., 1998) could tolerate better such unfavorable weather conditions, and subsequently had a higher PRG and heavier 1,000-grain weight than the plants in CONT.

As mentioned above, PRG and 1,000-grain weight, especially in CONT, largely varied with the change of temperature and solar radiation. The large variation of PRG and 1,000-grain weight might have caused the large variation of grain yield among the years (Table 1). On the other hand, although NSm^{-2} was significantly smaller in BNo than in CONT (Table 1 and Fig. 1), PRG was higher and 1,000-grain weight was heavier in the former than in the latter (Table 1, Fig. 2 and 3). The high PRG and heavy 1,000-grain weight in BNo, thus, could almost compensate for the small NSm^{-2}, and consequently brought about a small difference in grain yield between BNo and CONT. In a previous study (Pham et al., 2004) we found that the yield averaged over the years and cultivars was only about 3% smaller in BNo than in CONT, but the yield averaged over 12 cultivars in both BNo and CONT was much smaller in 1999 (670 g m^{-2} in BNo and 663 g m^{-2} in CONT) than in 2000 (778 g m^{-2} in BNo and 822 g m^{-2} in CONT) or 2001 (776 g m^{-2} in BNo and 830 g m^{-2} in CONT).

Before bringing a particular cultivation practice into use, its merits and demerits need to be examined. The present study showed that although the use of BNo practice could result in a small panicle number, which further leads to a small NSm^{-2}, such a problem could be lessened by using late-maturing cultivars such as Ouu316 and Hitomebore. Furthermore, the stably high PRG and stably heavy 1,000-grain weight in BNo could compensate for the small NSm^{-2} so as to secure a high and stable yield, particularly in years with unfavorable weather like 1999. Although this study was conducted in the Tohoku district, a cool region in the northeast of Japan, we consider that BNo practice could be applied in the southwestern part, where rice plants are often affected by a high temperature during the grain filling period (Murata, 1964; Suzuki and Nakamura, 1978; Morita, 2000). It can also be used for cultivating rice in the tropical regions, particularly in the wet season, where low solar radiation and high temperature are two of the main factors adversely affecting grain yield (Satake and Yoshida, 1978; Yoshida, 1981). To elucidate the reason for a stably high PRG as well as a stably heavy 1,000-grain weight of rice plants in BNo, it is important to examine the dry matter production process relating to yield and yield components.

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* In Japanese with English abstract or summary.

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