Analysis of Lodging-Resistant Characteristics of Different Rice Genotypes Grown under the Standard and Nitrogen-Free Basal Dressing Accompanied with Sparse Planting Density Practices

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Abstract: Field experiments were carried out in 2001 and 2002 to examine the lodging-resistance characteristics of various rice cultivars bred for the Tohoku region of Japan including the widely-cultivated cultivars (WCC) and the newly-released cultivars (NRC). The difference in these characteristics between the plants grown under standard (CONT) and nitrogen-free basal dressing accompanied with sparse planting density (BNo) practices was also analyzed. The lengths of the lower internodes and culms were often shorter in NRC than in WCC. Bending moment by whole plant was not different between NRC and WCC, but the breaking strength at the basal internode (IV) with leaf sheaths was often larger in NRC than in WCC. As a result, the lodging index was smaller in the former than in the latter. Breaking strength at the basal internode (IV) without leaf sheaths was also often larger in NRC than in WCC due to a larger cross section modulus or bending stress in NRC. Although the lengths of the upper internodes (I+II+III) were not different between BNo and CONT, the lower internodes (IV+V) were shorter in BNo, resulting in the shortened culms in BNo, especially in the long-culm cultivars. Breaking strength at the basal internode (IV) with leaf sheaths was significantly larger in BNo than in CONT, and thus the lodging index was smaller in BNo. The breaking strength at the basal internode (IV) without leaf sheaths and its two components, cross section modulus and bending stress, were also significantly larger in BNo than in CONT, particularly in the long-culm cultivars. These results suggest that besides creating new cultivars with short and stiff lower internodes, cultivation with sparse planting density accompanied with application of a small amount of nitrogen fertilizer in the early growth stage like BNo may also effectively increase the lodging resistance in rice plants.

Key words: Breaking strength, Lodging, Lower internodes, Nitrogen-free basal dressing, Rice cultivars, Sparse planting density.

One of the major constraints to rice production is lodging. In a lodged plant community, the normal canopy structure is deteriorated resulting in a reduced photosynthetic ability and a reduction in dry-matter production. Severe lodging prevents the transport of water, nutrients and assimilate through the xylem and phloem, resulting in a reduction of assimilate for grain filling. High moisture levels in a lodged plant community may be favorable for the growth of some fungi and for the development of diseases, which have detrimental effects on grain quality of platability and appearance. The grains of lodged plants may also easily germinate on the ear, especially in cultivars with weak seed dormancy. As a result, lodging causes great losses in both grain quantity and quality. Furthermore, it also brings about difficulties in harvest operations, increases demand for grain drying, and consequently results in an increased production cost (Kono, 1995).

Lodging resistance of rice plants is determined by two main factors: genetic traits and growth conditions. Most of the recently created cultivars with short culms are more tolerant to lodging caused by a high level of nitrogen fertilizer than the old ones with long culms and heavy panicles (Ookawa and Ishihara, 1992). Growth conditions, especially cultural practices, also have great effects on lodging resistance of rice plants. The heavy fertilization, particularly nitrogen fertilizer, at the early growth stage and high planting density in the common cultivation practice often result in spindly growth of lower internodes, and consequently cause lodging (Matsuba, 2000).

Although many studies and techniques for prevention of lodging have already been conducted (Takaya and Miyasaka, 1981; Matsuda et al., 1982;
Hossain et al., 1999; San-Oh et al., 2001), lodging is still an important factor limiting the further increase of rice yield, quality, and economical profit of rice growers (Hoshikawa and Wang, 1990). Thus, more studies on new cultivars and new cultivation techniques, which are suitable for a particular cultivar, are necessary to improve lodging resistance in rice plants.

Previously, Kuroda et al. (1997) reported that some newly-released rice cultivars or lines (NRC) bred for the Tohoku region of Japan were more tolerant to lodging than the widely-cultivated ones (WCC). However, the responses of some important morphological and physical characteristics relating to lodging, such as the length, the stiffness of lower internodes of culms, to different growth conditions have not been examined. On the other hand, Hirano et al. (1997) and Truong et al. (1998) mentioned that rice plants grown under the practice of nitrogen-free basal dressing accompanied with sparse planting density (BNo) not only produced a high grain yield, and resisted cold damage, but also did not lodge, even in the years with strong storms and heavy rain at the ripening period. The mechanism of lodging resistance in rice plants in these studies, nevertheless, remains unknown. The present study, therefore, was conducted to identify the lodging resistance characteristics of various rice cultivars grown under BNo and the standard cultivation (CONT). Furthermore, the differences among cultivars in lodging responses to growth conditions are also discussed.

Materials and Methods

Field experiments were carried out in the paddy field with Wet Aldosols at the Faculty of Agriculture, Iwate University, Japan in 2001 and 2002. Materials used were 12 cultivars or lines in 2001, and 9 cultivars or lines in 2002 (Table 1).

Seedlings at around the 4th leaf-age stage were transplanted in the middle of May, three seedlings per hill. In CONT, rice plants were transplanted at a standard planting density of 22.2 hills m$^{-2}$ (15×30 cm), and with a nitrogen fertilizer application of 11 g m$^{-2}$ (6.5 g as basal dressing, 2.5 g at a bout 25-20 days before heading and 2.0 g at heading stages). In BNo, the planting density was 16.7 hills m$^{-2}$ (20×30 cm), and the amount of nitrogen fertilizer 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 about 25-20 days before heading 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 experiments were conducted in a split-random block design with two replications in 2001 and three replications in 2002. Growth conditions (BNo and CONT) were arranged as main blocks and cultivars as sub-blocks. The sub-block was about 20 m$^2$ in area.

Standard management was carried out during the whole growth period. At the maximum tiller number stage, mid-season drainage was carried out in CONT for a period of 7 to 10 days, but a water level at 5-8 cm was kept in BNo to prevent excessive loss of nitrogen.

For determining lodging resistance, we randomly sampled seven to eight hills from each plot at about 30-35 days after heading. Twenty main culms with average growth were then selected. We measured their length, and then equally separated them into two groups (10 culms per group). The leaf sheaths were taken out from culms in one group, but culms in the other group were left intact. Physical characteristics relating to lodging resistance of culms were then measured on the culms of both groups by using a tensile tester apparatus (ORIENTEC STA-1150). Since the lower internodes are most sensitive to lodging (Seko, 1962; Hoshikawa, 1989; Hoshikawa and Wang, 1990), only internode IV counted from the top (peduncular internode was regarded as internode I) was used for measurement. Lodging resistance parameters were calculated by the following formulas (Ookawa and Ishihara, 1992).

1. Bending moment by whole plant (g cm)=$\text{Length from broken point to panicle tip (cm)} \times \text{Fresh plant weight of the plant part above broken point (g)}$.
2. Breaking strength (g cm)=$1/4 \times \text{Breaking load} \times \text{Distance between fulcra}$.
3. Lodging index=Bending moment by whole plant/Breaking strength.
4. Cross section modulus (mm$^3$)=$\pi/4 \times (a_1^3 b_2-a_2^3 b_1)/a_1$, where $a_1$, $b_1$ were the short radius (mm) and long radius (mm) of the outside, and $a_2$, $b_2$ were the

| Name of cultivars and lines | Year released | Plant type |
|-----------------------------|--------------|------------|
| Hannonoii (Ha)★             | 1987         | Panicle weight type [w] |
| Akitaomachi (Ak)★           | 1984         | Panicle number type [n] |
| Hitomebori (Hi)★            | 1991         | Panicle number type [n] |
| Okinii                       | 1996         | Intermediate type [i] |
| Hatajiroshi (Ht)★          | 1997         | Panicle number type [n] |
| Fukuil49 (149)              |             | Panicle weight type [w] |
| Ousu339 (339)*              |             | Panicle weight type [w] |
| Menkoina (Me)               | 1999         | Intermediate type [i] |
| Iwanan7 (17t)               |             | Panicle number type [n] |
| Fukuhiiki (Fu)              | 1993         | Panicle weight type [w] |
| Ousu16 (316)                |             | Panicle weight type [w] |
| Iwate43 (43)*               |             | Panicle number type [n] |

Letters and numerals in ( ) indicate abbreviated names of cultivars or lines. ★ : Cultivars widely cultivated in the Tohoku region (WCC), and ★★ : Lines. Letters in [ ] indicate the abbreviated name of the plant type. *: Cultivars were not used in 2002.
short radius (mm) and long radius (mm) of the inside of a measured internode, respectively.

5. Bending stress (g mm\(^{-2}\))=Breaking strength/ Cross section modulus.

Results

1. The length of culms and that of upper and lower internodes on a culm

Because culm length was similar in 2001 and 2002 (the coefficient of correlation between culm length in 2001 with that in 2002 was 0.913, \(P<0.01\)), only the data in 2001 are presented here (Fig. 1). The culm length of NRC, except Okiniiri, was shorter than that of WCC. In comparison with CONT, the culm length in BNo was shorter, and the difference between BNo and CONT in culm length appeared to be larger in the long-culm cultivars (Hananomai, Okiniiri, Akitakomachi and Hitomebore) than in the short-culm cultivars (Ouu316 and Iwate43).

Fig. 2 shows the length of upper internodes (I+II+III) and basal (lower) internodes (IV+V). Both upper and lower internodes were often longer in WCC than in NRC, except Okiniiri. Although the upper internodes in BNo were similar to those in CONT, the lower internodes, especially in the long-culm cultivars, were significantly shorter in BNo than in CONT.

Fig. 3 shows the correlation of the culm lengths with the length of lower internodes (IV+V). The length of the lower internodes relative to culm length was clearly shorter in Iwate43 and Fukei149, but was longer in Fukuhibiki than in other cultivars in both BNo and CONT. It was also shorter in BNo than in CONT. Overall, the length of lower internodes positively and significantly correlated with culm length in both BNo (\(r = 0.550, P<0.05\)) and CONT (\(r = 0.803, P<0.01\)). The slope coefficient, of the regression line of the length of the lower internodes against the culm length, was significantly (\(P<0.05\)) smaller in BNo (0.14) than in CONT (0.23), indicating that as culm length increased, the length of lower internodes increased at a smaller extent in BNo than in CONT.

2. The thickness of culm at the basal internode (IV)

The thickness (the outside diameter) of culms at the
basal internode (IV) was not different between NRC and WCC, and did not vary with the length of culms (Fig. 4). The thickness, however, varied with the plant type of the cultivars and with the cultivation practice. It was larger in the cultivars of the panicle-weight type than in the cultivars of the panicle-number type, and was also larger in BNo than in CONT.

3. Fresh plant weight, bending moment by whole plant, breaking strength and lodging index

Table 2 shows the fresh plant weight, bending moment by whole plant, breaking strength at the basal internode (IV) with leaf sheaths and lodging index. The fresh plant weight was not clearly different between NRC and WCC. The fresh plant weight, however, was larger in the cultivars of the panicle-weight type than in the cultivars of the panicle-number type. It was largest in Okinii (a cultivar with long culms belonging to the intermediate type), and was smallest in Iwate43 (a cultivar with short culms belonging to the panicle-number type). The fresh plant weight was heavier in BNo than in CONT in all cultivars, and the fresh plant weight averaged over cultivars was 12% heavier in BNo than in CONT.

The bending moment by whole plant (product of plant length and fresh plant weight) was also not clearly different between NRC and WCC. It was, however, smallest in Iwate43 (a cultivar with short culms belonging to the panicle-number type), and largest in Okinii (a cultivar with long culms belonging to the intermediate type). The bending moment by whole plant was also significantly larger in BNo than in CONT in most cultivars, except for Fukuhibiki. The average bending moment of 12

![Fig. 4. The thickness (the outside diameter) of culms at internode IV of different rice cultivars in CONT and BNo in 2001. Letters in ( ) indicate the plant type of the cultivars as shown in Table 1. ★: the widely-cultivated cultivars (WCC). Error bars indicate standard errors.](image-url)

Table 2. Fresh plant weight, bending moment by whole plant, breaking strength at basal internode (IV) with leaf sheaths and lodging index of different rice cultivars grown under CONT and BNo in 2001.

| Cultivars | Fresh plant weight (g) | Bending moment by whole plant (g cm) | Breaking strength (g cm) | Lodging index |
|-----------|------------------------|--------------------------------------|--------------------------|--------------|
|           | CONT       | BNo       | R         | CONT        | BNo        | R         | CONT        | BNo        | R         |
| Ha (w)★   | 11.1       | 12.6 (12) | d         | 1181        | 1322 (12)  | b         | 970         | 1491 (24)  | d         | 1.22   | 0.89 (27)  | a         |
| Ak (n)★   | 9.8        | 11.0 (12) | f         | 935         | 1035 (11)  | f         | 1032        | 1413 (37)  | d         | 0.91   | 0.73 (20)  | c         |
| Hi (n)★   | 9.4        | 10.8 (15) | g         | 880         | 996 (13)   | g         | 993         | 1532 (54)  | d         | 0.88   | 0.65 (26)  | cd        |
| Ok (i)    | 12.4       | 14.9 (20) | a         | 1207        | 1438 (19)  | a         | 1156        | 1622 (40)  | c         | 1.06   | 0.89 (16)  | b         |
| Hat (n)   | 10.6       | 11.5 (9)  | e         | 1004        | 1089 (8)   | e         | 1189        | 1598 (34)  | bc        | 0.85   | 0.68 (20)  | cd        |
| 339 (w)   | 10.4       | 11.2 (8)  | c         | 955         | 1034 (8)   | f         | 1187        | 1538 (30)  | c         | 0.80   | 0.67 (17)  | e         |
| Me (i)    | 11.2       | 12.7 (14) | d         | 1025        | 1164 (14)  | ed        | 1172        | 1595 (36)  | c         | 0.88   | 0.73 (17)  | cd        |
| 149 (w)   | 11.1       | 12.3 (11) | d         | 1023        | 1087 (6)   | de        | 1218        | 1727 (42)  | ab        | 0.84   | 0.63 (25)  | e         |
| 17 (n)    | 9.6        | 10.4 (9)  | g         | 871         | 913 (5)    | h         | 1038        | 1428 (38)  | d         | 0.84   | 0.64 (24)  | de        |
| Fu (w)    | 13.2       | 13.5 (3)  | b         | 1110        | 1116 (1)   | c         | 1332        | 1703 (28)  | a         | 0.84   | 0.65 (22)  | de        |
| 316 (w)   | 11.7       | 13.2 (13) | c         | 966         | 1080 (12)  | cf        | 1350        | 1714 (27)  | a         | 0.72   | 0.63 (12)  | f         |
| 43 (n)    | 8.4        | 9.7 (15)  | h         | 706         | 785 (11)   | i         | 1060        | 1424 (34)  | d         | 0.67   | 0.56 (17)  | f         |

**MEAN** | **10.7** | **12.0 (12)** | **989** | **1088 (10)** | **1141** | **1571 (37)** | **0.88** | **0.70 (-20)** |

ANOVA

Cultivar (C) ★★
Cultivation practice (CP) ★★
C × CP ★★

Letters in ( ) indicate the plant type of the cultivars as shown in Table 1. ★: the widely-cultivated cultivars (WCC). 1) R indicates the ranking of cultivars, and cultivars with the same letter are not significantly different from each others. 2) Numerals in ( ) indicate the relative increase or decrease (%) in the value in BNo as compared with that in CONT. 3) the mean value of 12 cultivars in CONT or BNo. ANOVA: analysis of variance. ★★, ★: significant at 0.01 and 0.05 probability levels, respectively.
cultivars was about 10% larger in BNo than in CONT. The breaking strength at the basal internode (IV) with leaf sheaths, especially in CONT, was often smaller in WCC than in NRC, and was also smaller in the cultivars of the panicle-number type than in the cultivars of the panicle-weight type. It was largest in Fukei149, Fukuhibiki and Ouu316 (three cultivars of the panicle-weight type), and smallest in all WCC (Hanonomai, Akitakomachi, Hitomebore) as well as in Iwanan7 and Iwate43 (two cultivars of the panicle-number type). The breaking strength in BNo was larger than that in CONT, and the average breaking strength of 12 cultivars was 1571 g cm$^{-1}$ in BNo and 1141 g cm$^{-1}$ in CONT (the ratio of value in BNo to that in CONT, B/C, is 137%). The difference between BNo and CONT in breaking strength varied with the cultivar. It was very large in two WCC, Hanonomai and Hitomebore (B/C=154%), but was small in some NRC with short culms such as Fukuhibiki (B/C=128%), Ouu316 (B/C=127%) and Iwate43 (B/C=134%).

Lodging index (the result of bending moment divided by breaking strength) was smaller in the short-culm cultivars than in the long-culm ones, and was also often smaller in NRC, except in Okiniiri, than in WCC. Lodging index was significantly lower in BNo in all cultivars, especially in two WCC, Hanonomai and Hitomebore (B/C=73%). Lodging index averaged over 12 cultivars was 20% smaller in BNo than in CONT.

4. Relationship between lodging index and culm length

Fig. 5 shows the relationship between lodging index and culm length. Among the plants with the same

![Fig. 5. Relationship between culm length and lodging index in 2001. Letters or numerals beside symbols indicate the abbreviating cultivar names. ⋆: the widely-cultivated cultivars (WCC). **: significant at 0.01 probability level.](image)

### Table 3. Some physical characteristics of internode IV without leaf sheaths in different rice cultivars grown in CONT and BNo in 2001.

| Cultivars | Dry weight (mg cm$^{-1}$) | Dry matter density (mg mm$^{-1}$) | Breaking strength (g cm)$^{-1}$ | Section modulus (mm$^3$)$^{-1}$ | Bending stress (g mm$^{-2}$)$^{-1}$ |
|-----------|---------------------------|-----------------------------------|-------------------------------|---------------------------------|----------------------------------|
|           | CONT | BNo | R$^0$ | CONT | BNo | R | CONT | BNo | R | CONT | BNo | R | CONT | BNo | R | CONT | BNo | R |
| Ha (w)⋆⋆  | 12.6 | 18.7 (48) | cd | 0.15 | 0.18 (17) | de | 741 | 1126 (52) | f | 5.9 | 8.4 (43) | bc | 1263 | 1343 (6) | h | *** | ** |
| Ak (a)⋆    | 12.6 | 18.7 (48) | cd | 0.15 | 0.20 (31) | ab | 831 | 1177 (42) | de | f | 5.4 | 6.3 (17) | ef | 1552 | 1882 (21) | b |
| Hi (n)⋆    | 11.2 | 17.4 (56) | f | 0.16 | 0.20 (27) | a | 719 | 1185 (65) | f | 4.4 | 5.5 (25) | g | 1645 | 2172 (32) | a |
| Ok (i)     | 13.1 | 18.6 (42) | bcd | 0.15 | 0.18 (18) | ef | 865 | 1256 (45) | d | 6.5 | 8.4 (30) | b | 1335 | 1487 (11) | g |
| Hat (n)    | 12.6 | 18.9 (50) | cd | 0.15 | 0.19 (26) | bc | 888 | 1248 (41) | cd | 5.7 | 7.0 (23) | d | 1550 | 1774 (14) | b |
| 149 (w)    | 13.9 | 20.3 (46) | a | 0.14 | 0.17 (22) | f | 904 | 1399 (55) | a | 7.1 | 8.9 (26) | a | 1277 | 1573 (23) | f |
| 339 (w)    | 12.7 | 17.9 (41) | d | 0.16 | 0.18 (13) | bc | 848 | 1202 (42) | de | 5.5 | 6.4 (16) | de | 1540 | 1874 (22) | b |
| Me (i)     | 12.3 | 17.3 (41) | ef | 0.16 | 0.18 (16) | ed | 845 | 1222 (45) | d | 5.2 | 6.7 (27) | c | 1619 | 1838 (14) | b |
| 17 (n)     | 11.5 | 17.0 (48) | f | 0.15 | 0.19 (29) | cd | 835 | 1226 (47) | d | 4.9 | 5.9 (20) | fg | 1702 | 2078 (22) | a |
| Fu (w)     | 13.6 | 19.5 (44) | ab | 0.15 | 0.20 (31) | abc | 962 | 1314 (37) | ab | 6.6 | 7.4 (12) | c | 1460 | 1780 (22) | cd |
| 316 (w)    | 14.1 | 18.1 (28) | bc | 0.15 | 0.18 (13) | def | 985 | 1276 (30) | bc | 6.8 | 8.1 (20) | b | 1458 | 1571 (8) | ef |
| 43 (n)     | 12.5 | 16.3 (30) | f | 0.14 | 0.17 (20) | f | 818 | 1107 (35) | ef | 5.4 | 6.5 (21) | de | 1514 | 1700 (12) | de |

**MEAN**$^0$ | 12.7 | 18.2 (43) | 0.15 | 0.19 (22) | 853 | 1226 (44) | 6 | 7.1 (23) | 1493 | 1756 (18) |  

ANOVA

| Cultivar (C) | Cultivation practice (CP) | C×CP |
|--------------|--------------------------|------|
| * *** | ** | ** |
| ** | ** | ** |
| ** | ** | ** |

Letters in ( ) indicate the plant type of the cultivars as shown in Table 1. ⋆: the widely-cultivated cultivars (WCC). 1) R indicates the ranking of the cultivars, and cultivars with the same letter are not significantly different from each others. 2) Numerals in ( ) indicate the relative increase (%) in the value in BNo as compared with that in CONT. 3) the mean value of 12 cultivars in CONT or BNo. ANOVA: analysis of variance. ***, *: significant at 0.01 and 0.05 probability levels, respectively.
length of culms, the lodging index was smaller in BNo than in CONT. Overall, lodging index positively and significantly correlated with culm length, and the correlation coefficient (r) was 0.815 (P<0.01) in BNo, and 0.909 (P<0.01) in CONT. The slope coefficient, of the regression line of the lodging index against culm length, was significantly (P<0.05) smaller in BNo (0.011) than in CONT (0.017), indicating that as culm length increased, lodging index increased at a smaller extent in BNo than in CONT.

5. Physical characteristics relating to lodging resistances of the basal internode (IV) without leaf sheaths

Table 3 shows the dry weight per unit length, dry-matter density (specific weight), breaking strength, cross section modulus and bending stress of the basal internode (IV) without leaf sheaths. The dry weight per unit length was lighter in the cultivars of the panicle-number type than in the cultivars of the panicle-weight type, and was also lighter in CONT than in BNo. It was heaviest in Fukei149 and Fukuhibiki, the cultivars of the panicle-weight type, and lightest in Hananomai, Iwanan7 and Iwate43, the cultivars of the panicle-number type. The difference between BNo and CONT in dry weight per unit length was large in WCC (B/C is 148, 148 and 156% in Hananomai, Akitakomachi and Hitomebore, respectively), but was small in NRC with short culms such as Fukuhibiki (B/C=137%), Ouu316 (B/C=130%) and Iwate43 (B/C=135%).

The dry-matter density (specific weight) of the basal internode (IV) did not vary with the plant type of the cultivar, but was often higher in Akitakomachi and Hitomebore than in Fukei149 and Iwate43 in both BNo and CONT. The dry-matter density was higher in BNo than in CONT, and the average dry-matter density of 12 cultivars was 22% higher in BNo than in CONT.

The breaking strength was often smaller in WCC than in NRC, and was also smaller in the cultivars of the panicle-number type than in those of the panicle-weight type. The breaking strength was largest in Fukei149 and Fukuhibiki, of the panicle-weight type, and smallest in Hananomai and Akitakomachi, of WCC. The breaking strength in BNo was larger than that in CONT, and the average breaking strength of 12 cultivars was 1226 g cm\(^{-1}\) in BNo and 853 g cm\(^{-1}\) in CONT (B/C=144%). The difference between BNo and CONT in breaking strength varied with the cultivar. The difference was large in Hananomai (B/C=152%) and Hitomebore (B/C=165%), but was small in some NRC with short culms such as Fukuhibiki (B/C=137%), Ouu316 (B/C=130%) and Iwate43 (B/C=135%).

Cross section modulus, which is almost determined by the cross sectional area of culm at a measured internode, was not clearly different between NRC and WCC. It was, however, larger in the cultivars of the panicle-weight type than in those of the panicle-number type, and was also significantly larger in BNo than in CONT. The difference between BNo and CONT in cross section modulus varied with the cultivar. The difference was large in Hananomai (B/C=143%) and Okiniiri (B/C=130%), but was small in Akitakomachi (B/C=117%), Ouu339 (B/C=116%) and Fukuhibiki (B/C=112%).

The bending stress (breaking strength divided by cross section modulus), which indicates the strength of a unit plant tissue, was also not clearly different between NRC and WCC, but varied with the plant type of the cultivars and with the cultivation practice. The bending stress was often larger in the cultivars of the panicle-number type (Akitakomachi, Hitomebore, Iwanan7 and Iwate43) than in those of the panicle-weight type (Hananomai, Fukei149, Fukuhibiki and Ouu316). The bending stress was also significantly larger in BNo than in CONT, and the average bending stress of 12 cultivars was 18% larger in BNo than in CONT. The difference between BNo and CONT in bending stress varied with the cultivar. It was small in Hananomai (B/C=106%), Okiniiri (B/C=111%) and Ouu316 (B/C=118%), but was very large in Hitomebore (B/C=132%).

Table 4 shows the correlations among the dry weight per unit length, dry-matter density, breaking strength, cross section modulus and bending stress of the basal internode (IV). Except for the correlation of cross section modulus with dry-matter density, and

|                | Breaking strength (g cm\(^{-1}\)) | Dry weight (mg cm\(^{-1}\)) | Dry density (mg mm\(^{-3}\)) | Cross section modulus (mm\(^{2}\)) | Bending stress (g mm\(^{-2}\)) |
|----------------|-----------------------------------|-----------------------------|-------------------------------|-----------------------------------|-------------------------------|
| Breaking strength (g cm\(^{-1}\)) | 0.942**                          | 0.966**                     | 0.792**                       | 0.723**                          | 0.494**                       |
| Dry weight (mg cm\(^{-1}\))      | 0.727**                          | 0.868**                     | 0.817**                       | 0.759**                          | 0.404**                       |
| Dry density (mg mm\(^{-3}\))     | 0.678**                          | 0.625**                     | 0.177ns                       | 0.283ns                          | -0.238ns                      |
| Cross section modulus (mm\(^{2}\))| 0.535*                           | 0.533*                      | 0.771**                       |                                  |                                |

**. * and ns: significant at 0.01 and 0.05 probability levels, and not significant, respectively.
that of cross section modulus with bending stress, all correlation coefficients were significant. The factor showing the highest correlation with breaking strength was dry weight per unit length, whose correlation coefficient ($r$) was 0.966 ($P<0.01$) in 2001 and 0.942 ($P<0.01$) in 2002. Breaking strength also positively and significantly correlated with its two components: cross section modulus ($r$ was 0.723, $P<0.01$ in 2001 and 0.678, $P<0.01$ in 2002) and bending stress ($r$ was 0.494, $P<0.05$ in 2001 and 0.535, $P<0.05$ in 2002).

Fig. 6 shows the relationships among breaking strength, cross section modulus and bending stress. Generally, the bending stress in both BNo and CONT was small in the cultivars with large cross section modulus (Hananomai, Okiniiri, Fukei149 and Ouu316), but was large in the cultivars with small cross section modulus (Hitomebore, Iwanan7 and Menkoina). The lower breaking strength in WCC (Hananomai and Hitomebore), as compared with that in NRC, was due to either the small cross section modulus (in Hitomebore) or the small bending stress (in Hananomai). Breaking strength was larger in BNo than in CONT in all cultivars. The increase in breaking strength in BNo compared with CONT was mainly attributed to either the enlargement of cross section modulus (in Hananomai, Okiniiri, Menkoina and Ouu316), the increase in bending stress (in Ouu339, Akitakomachi, Fukuhibiki and Hitomebore), or the increase in both cross section modulus and bending stress (in Fukei149 and Iwanan7).

Discussion

1. Factors affecting the length of lower internodes on culms

In the present study, cultivars with long culms possessed long lower internodes (Fig. 1 and 2), and the length of lower internodes (IV+V) positively correlated with culm length in both BNo ($r$ was 0.550, $P<0.05$) and CONT ($r$ was 0.803, $P<0.01$) (Fig. 3). These indicated that the length of culms and that of lower internodes are genetically related. The lower internodes, however, were shorter in BNo than in CONT, suggesting that these internodes were also largely affected by the cultivation practice.

The elongation of lower internodes in rice plants starts at about the end of vegetative stage (Hoshikawa, 1989), and is largely influenced by environmental factors, especially planting density and nitrogen fertilization (Yoshida, 1981; Nishiyama, 1986; Kono, 1995). Matsushima (1995) stated that a limited supply of nitrogen fertilizer in the mid-growth stage (around the neck-node initiation stage) shortened lower internodes and culms, and then increased the lodging resistance in rice plants. Matsuba (2000), however, showed that the elongation of lower internodes was not affected by limiting the supply of nitrogen fertilizer in the mid-growth stage, but by nitrogen applied in the early growth period. He further suggested that the limitation of nitrogen fertilizer in the mid-growth stage shortened upper internodes and lamina (the akiochi type). Kamiji et al. (1993), on the other hand, elucidated that the elongation of lower internodes was not influenced by nitrogen fertilizer, but by solar radiation reaching the stem base, which largely depends on the leaf area index at the panicle initiation stage. In the present study, nitrogen fertilizer was applied in BNo but not in CONT at the neck-node initiation stage; the lower internodes (IV+V), however, were longer in CONT than in BNo (Fig. 2). These findings suggested that the limited supply of nitrogen or the application of nitrogen fertilizer at the neck-node initiation stage is not the main factor affecting the elongation of lower internodes in rice plants. The smaller leaf area index at the panicle initiation stage (Pham et al., 2004b) and the better light intercepting characteristics of rice plants in BNo compared with CONT (Hirano et al., 1997) might have resulted in the shortened lower internodes in BNo.

The difference in the length of lower internodes (IV+V) between BNo and CONT varied with the cultivar, and was often larger in the long-culm cultivars than in the short-culm ones (Fig. 2 and 3). These findings suggested that under the basal application of a large amount of nitrogen and the high planting density in CONT, the long-culm cultivars overgrow, and the resulting excessive elongation of lower internodes is restricted by the sparse planting density.
and small amount of nitrogen fertilizer applied in the early growth stage.

2. Small lodging index in NRC, and in BNo

The lodging index is used as a primary parameter for estimating lodging resistance in rice, and rice plants with small lodging indices are more tolerant to lodging than those with large lodging indices (Seko, 1962). Since the lodging index is the bending moment by the whole plant divided by breaking strength, it is reduced by a decreased bending moment or an increased breaking strength. In the present study, the lodging index was often smaller in NRC than in WCC due to a larger breaking strength at the basal internode (IV) with leaf sheaths in NRC (Table 2). On the other hand, although the bending moment by the whole plant was larger in BNo than in CONT, the lodging index was much smaller in BNo than in CONT because of the significantly larger breaking strength in BNo. The larger difference in breaking strength at the basal internode (IV), and the larger difference in lodging index between BNo and CONT in the long-culm cultivars compared with the short-culm cultivars (Table 2 and Fig. 5) indicated that the lodging resistance of the long-culm cultivars was more improved under BNo condition. This also suggested that BNo practice might be more effective for the cultivation of the long-culm cultivars.

3. Large breaking strength at the basal internode (IV) without leaf sheaths in NRC, and in BNo

Breaking strength of the basal internode (IV) without leaf sheaths and its two components, cross section modulus and bending stress, are the main parameters used for measuring lodging resistance in rice plants. Previously, Ookawa and Ishihara (1992) showed a negative correlation between cross section modulus and bending stress. In the present study, cross section modulus also negatively correlated with the bending stress (in both BNo and CONT), but the breaking strength in most NRC was larger than that in WCC due to the larger bending stress or cross section modulus in the former cultivars (Fig. 6). This indicated that rice breeders had successfully combined the two opposite traits (cross section modulus and bending stress) to create new cultivars with higher breaking strength and higher lodging resistance.

The cross section modulus and bending stress were larger in BNo than in CONT (Table 3 and Fig. 6). The large cross section modulus in BNo was possibly due to sparse planting density and top dressing of nitrogen fertilizer at the neck-node initiation stage (Hoshikawa, 1989). On the other hand, the higher dry matter production after heading in BNo compared with CONT (Pham et al., 2004b) might have resulted in a higher dry-matter density (Table 3) and therefore a higher bending stress in BNo (dry-matter density positively and significantly correlated with bending stress; $r = 0.763$, $P < 0.01$ in 2001 and 0.771, $P < 0.01$ in 2002, (Table 4)). Ookawa et al. (1993) also showed that the bending stress was increased by increasing dry-matter density, and it positively and significantly correlated with the content of glucose, xylose and lignin in rice plants. The larger cross section modulus and bending stress in BNo brought about a significantly larger breaking strength in BNo than in CONT (Table 3 and Fig. 6). Such a large cross section modulus, bending stress and breaking strength in BNo, especially in the long-culm cultivars (Hananomai, Okiniiiri and Hitomebore), indicated that besides plant breeding, cultivation practices play an important role in improving lodging resistance of rice plants.

The above results clearly showed that all morphological and physical characteristics relating to lodging (the length, breaking strength, section modulus and bending stress of lower internodes, and lodging index) were improved in NRC, as compared with those in WCC. However, most NRC, except for Okiniiiri, belong to the short-culm genotype. The improvement of lodging resistance by shortening the culms, nevertheless, may lead to a reduced biomass production, which hinders the further increase in rice yield (Yoshida, 1981; Kuroda et al., 1989; Gent, 1995). At present, breeding and selecting cultivars with good eating quality and high resistance to diseases and insect pests are important, but breeding cultivars that collectively possess these characters and high lodging resistance is not easy (Watanabe, 1997). In the present study, Fukei149 possessed high lodging resistance Characteristics (short, thick, heavy and strong lower internodes) compared with the other cultivars with the same culm length suggesting the possibility of creating new lodging-resistant cultivars with long culms. All the present long-culm cultivars (Hananomai, Okiniiiri, Akitakomachi and Hitomebore) easily lodged under CONT, although they have good eating quality, and have been widely cultivated in the Tohoku region.

Lodging resistance characteristics, especially in the long-culm cultivars, were improved by using BNo practice. In the paddy field, we also observed that at the full ripening stage, lodging did not occur in BNo in all cultivars, but it occurred in CONT, particularly in WCC (Hananomai, Akitakomachi and Hitomebore). The lodging degree in the field was then measured and categorized into 6 levels, from level 0 (not lodged) to level 5 (totally lodged), (Ookawa and Ishihara, 1992). We found that in CONT, the lodging degree of all WCC, which had a small breaking strength and large lodging index (Table 2), was about 3–4, and that of some NRC (Ouu316, Fukuhibiki and Fukei149),

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1: Manual of Study on Rice Cultivars and Lines in the Tohoku Region in 2002. National Agricultural Research Center for Tohoku Region.
which possessed a large breaking strength and small lodging index (Table 2), was 0–1. The lodging degree of all cultivars in BNo, however, was about 0–1 (data not shown). In a previous study (Pham et al., 2004a), we showed that although BNo practice might cause a lower grain yield in favorable weather years, it could bring about the same or higher grain yield compared with CONT in unfavorable weather years. Kuroda et al. (2003) also demonstrated that some characteristics relating to palatability were better in BNo than in CONT. The present study, furthermore, elucidated that rice plants in BNo could tolerate better to lodging than those in CONT. These results suggested that BNo practice is effective to achieve the high quality, stable and high yield of rice plants, especially in the long-culm and lodging-susceptible cultivars.

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*In Japanese with English abstract or summary.

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