Effect of Field Drainage on Root Lodging Tolerance in Direct-Sown Rice in Flooded Paddy Field

Kazuo Terashima, Takeshi Taniguchi*, Hitoshi Ogiwara** and Takayuki Umehoto***

(Agriculture, Forestry and Fisheries Research Council Secretariat, 1-2-1 Kanumigasaki, Chiyoda-ku, Tokyo, 100-8950, Japan; *Nagano Agricultural Experiment Station, 492 Ogawara, Suzaka, Nagano 382-0072, Japan; **National Agriculture Research Center for Tohoku Region, 4 Akahira, Shimosakuyagawa, Morioka, Iwate, 020-0198, Japan; ***National Institute of Crop Science, 2-1-18, Kannondai, Tsukuba, Ibaraki 305-8518, Japan)

Abstract: To elucidate the effect of drainage of paddy fields on root lodging tolerance in direct-sown rice, we measured the pushing resistance (R), diameter of hill at the base (Dm), shoot dry weight (Ws) and root dry weight (Wr), in rice varieties grown using several irrigation management schemes that differed in the frequency and length of field drainage during the growing season. Soil hardness was also monitored to investigate the relationship between the variance of soil physical properties caused by different irrigation treatments and root lodging tolerance. Pushing resistance moment (Rh), i.e., product of pushing resistance (R) and height of pushed part of hill (h), showed higher values in rice grown in fields drained more frequently or for longer periods. A similar pattern was found in rice grown in field plots where root penetration to the subsoil layers was prevented by laying an unwoven cloth between the topsoil and subsoil layers. Higher values for pushing resistance efficiency based on root dry weight (Kr: Rh/Wr/Dm) were also found in plots subjected to more frequent or prolonged drainage, irrespective of rice variety. Soil hardness was progressively increased by each field drainage during the growing season, and showed a highly significant relationship with Kr. The above results suggest that field drainage increases the root lodging tolerance in direct-sown rice through improvement of anchoring ability caused by increased soil hardness.

Key words: Direct-sown rice cultivation, Field drainage, Irrigation management, Pushing resistance, Rice, Root, Root-lodging tolerance.

In direct-sown cultivation of rice (Oryza sativa L.) in flooded paddy fields, root lodging is frequently observed, since seeds that are sown on the surface or just below the soil surface grow into plants with less physical support provided by the soil, and is considered to be a serious problem. Improvements in root lodging tolerance through plant breeding and advances in cultivation techniques are needed to guarantee the productivity of direct-sown crops (Akita, 1996; Rutger and Brandon, 1981; McKenzie et al., 1994; Wahio, 1989; Yamamoto, 1990).

Irrigation management is believed to be a key determinant of lodging tolerance in transplanting rice cultivation. Seko (1982) reported that midsummer drainage improved culm morphology and reduced lodging degree. Miyasaka (1970) also pointed out that the effect of field drainage on lodging tolerance is related to the amount of nitrogen absorbed during the elongation of No. 3 internode (counted from the uppermost). In direct-sown rice, several researchers have examined the effect of field drainage on lodging tolerance. Nishio et al. (1966) reported that field drainage did not improve lodging degree in direct-sown rice. On the other hand, Uemura et al. (1985) pointed out that field drainage increased the anchoring ability of direct-sown rice as measured by pushing resistance, i.e., the maximum resistance of the plant stem to being pushed to 45° away from the vertical (Uemura et al., 1985), except for rice that had germinated on the soil surface. Yasuhara et al. (1992) and Taniguchi et al. (1996) also observed a reduction of lodging angle in direct-sown rice varieties as a result of field drainage. The results of recent studies indicate that field drainage is effective in reducing lodging degree in direct-sown rice. However, the physiological cause of root lodging tolerance caused by field drainage is still unclear, since insufficient data is available to permit the quantitative analysis of its effects.

In relation to the above point, Miyasaka (1970) reported that field drainage induced root extension into deeper soil layers. Kawata and Soejima (1977) also observed that the density of formation of thick secondary roots was higher in the fields that had been subjected to midsummer drainage than in constantly submerged fields. Since Terashima et al. (1994) pointed out that, in comparison with susceptible varieties, root lodging tolerant varieties allocated more dry matter to the roots, showing greater root development in the subsoil layer, the promotion of root development by field drainage is considered to enhance the plant anchoring ability via the roots. Changes in the soil physical properties caused by field drainage may be another possible cause of better plant anchoring. Terashima et al. (1995) pointed out that soil physical properties like soil hardness and bulk density significantly affect plant anchoring by roots.

Received 10 February 2003. Accepted 3 July 2003. Corresponding author: K. Terashima (kazuo@affrc.go.jp, fax +81-3-3507-8794).
Pushing resistance per unit root dry weight was higher in rice grown in soil with higher bulk density and higher soil hardness than in soil with lower bulk density and lower soil hardness (Terashima et al., 1995). Differentiation of soil physical properties between topsoil and subsoil due to cultivation and puddling (Nakatsuka and Ishii, 1989), was considered to be related to the higher contribution of roots in the subsoil to anchoring, and in turn, to the superior anchoring ability of the varieties that extend more roots into the subsoil layer (Terashima et al., 1995). Since field drainage affects the soil hardness of the topsoil layer (Tada et al., 1967a, 1967b; Kohno, 1979), it is inferred that pushing resistance may be increased by field drainage through changes in soil physical properties like soil hardness. However, not enough data has been published to allow a quantitative analysis or verification of the above presumptions based on a quantitative analysis.

The objective of this paper is to identify the physiological causes of the effects of field drainage on root lodging tolerance. For this purpose, soil hardness, root development and pushing resistance were compared among direct-sown rice varieties grown under several irrigation management schemes that differed in the frequency and length of field drainage during the growing season, with or without laying an unwoven cloth between the topsoil and subsoil layers. The unwoven cloth was laid to prevent root penetration into the subsoil layer, and thence to elucidate the influence of root penetration into the subsoil layer on pushing resistance under well-drained conditions.

Materials and Methods

Experiments were conducted in the experimental paddy fields of the Agricultural Research Center for the Tohoku Region, located near Omagari City, Akita Prefecture, Japan in 1997 and 1998.

In 1997, the root lodging susceptible Japanese variety Domannaka and the root lodging tolerant USA variety S-201 were used as experimental material. Seeds of both varieties were coated with coating materials including calcium peroxide to perform better germination and seedling establishment, and sown on the soil surface of field plots with unwoven cloth laid on May 12 and 13 in 30 cm-wide rows and with 7.5 cm intrarow spacing at the rate of 6 coated seeds per hill. The unwoven cloth was used for both varieties using the method described in a previous report (Terashima et al., 1995): briefly, after rotary cultivation, the topsoil layer (from the soil surface to around 15 cm depth) was removed and a piece of unwoven cloth was laid on the exposed subsoil. The topsoil was then returned to the same position on the unwoven cloth and puddled after irrigation. Control plots without unwoven cloth were provided for Domannaka only, and planted in the same way as the plots with unwoven cloth. All plots were fertilized at the rate of 5 g m⁻² as N, P₂O₅, K₂O for the basal fertilizer. A top-dressing of fertilizer was also applied at 2 g m⁻² as N, P₂O₅, K₂O at the tillering stage and 5 g m⁻² as N, P₂O₅, K₂O at the young panicle formation stage. Four irrigation treatments were conducted as indicated in Table 1: plots were continuously submerged (D0), drained once (D1), twice (D2) or three times (D3). In the D1 plot, irrigation water was drained for 9 days during the vegetative stage. The D2 plot was drained for 6 days during the reproductive stage with 9-day drainage before the young panicle formation stage in the same way as in the D1 plot. The D3 plot was drained for 8 days during the early ripening stage and 11 days during the reproductive stage in addition to the 9-day drainage during the vegetative stage.

In 1998, coated seeds of Domannaka were sown in the paddy field with or without the unwoven cloth on May 11 and 12 in the same manner as in 1997. Irrigation treatments were similar to the 1997 experiment except for the date and duration of each drainage period (Table 1). The same amount of fertilizer as in 1997 was applied to each plot. The experiments in both years were split-plot designs in which irrigation treatment corresponded to the primary plots. Three replications (10 rows by 1.5 m for each) were provided for each variety and treatment.

Pushing resistance, which was defined as the maximum resistance of plant hill to being pushed at 10 cm height to 45° away from the vertical, was measured for 10 hills in each plot using a prostrate tester (Daiki Rika Co.) at full heading stage in 1997, and 12 days after heading in 1998 under submerged condition with 2–5 cm water depth. After measuring pushing resistance, the shoots of all measured hills were sampled, and the diameter of the hill at the uppermost culm base from which nodal root grow (Dm) was recorded. In the unwoven cloth plots, the underground parts of 2 hills were sampled at once using a root sampler (Inada, 1960) (30 cm × 15 cm × 15 cm), and the underground parts of 4 hills in total were taken from each plot. After the soil was washed off, the sampled shoots and roots were

| Drainage treatment | Duration of field drainage | 1997          | 1998          |
|--------------------|----------------------------|---------------|---------------|
| D0                 |                            |               |               |
| D1                 | 7/11–7/17(37,21.9)         | 7/11–7/17(2,20.9) |
| D2                 | 7/11–7/17(37,21.9)         | 7/11–7/17(2,20.9) |
|                    | 8/3–8/8(31,24.4)           | 8/3–8/11(147,22.7) |
| D3                 | 7/11–7/17(37,21.9)         | 7/11–7/17(2,20.9) |
|                    | 7/29–8/8(33,25.0)          | 8/3–8/11(147,22.7) |
|                    | 8/20–8/27(19,23.4)         | 8/13–8/20(88,23.4) |

Numbers in parentheses are precipitation (mm) and average temperature (°C) during each drainage period.

Heading date: Domannaka: 8/10 (1997), 8/8 (1998).
8-201: 8/10 (1997).
Table 2. Effects of field drainage and unwoven cloth treatment on shoot dry weight (Ws), diameter of hill at the base (Dm), and pushing resistance moment (Rh) in rice variety Domannaka (1997).

| Unwoven cloth treatment | Drainage (a) | Ws (g hill⁻¹) | Dm (cm) | Rh (g cm hill⁻¹) |
|-------------------------|-------------|---------------|---------|------------------|
| Control                 | D0          | 21.1±1.1      | 3.43±0.05 | 1300±187        |
|                         | D1          | 19.6±0.8      | 3.28±0.13 | 4667±274        |
|                         | D2          | 20.3±1.5      | 3.17±0.13 | 7800±567        |
|                         | D3          | 21.6±0.7      | 3.30±0.10 | 6550±628        |
| Treatment               | D0          | 22.4±0.1      | 3.63±0.06 | 1580±40         |
|                         | D1          | 19.8±0.5      | 3.19±0.10 | 4500±64         |
|                         | D2          | 22.4±0.3      | 3.41±0.04 | 7045±68         |
|                         | D3          | 24.5±0.6      | 3.42±0.07 | 8932±342        |

F

| Drainage (a) | Treatment (b) | a X b |
|--------------|---------------|-------|
|              |               |       |

Average±s.e. (n=3)
* : Significant at the 0.05 level. ** : Significant at the 0.01 level.

Rh, Dm: Refer to Table 2.

Table 3. Effects of field drainage and unwoven cloth treatment on shoot dry weight (Ws), diameter of hill at the base (Dm), pushing resistance moment (Rh) in rice variety Domannaka (1998).

| Unwoven cloth treatment | Drainage (a) | Ws (g hill⁻¹) | Dm (cm) | Rh (g cm hill⁻¹) |
|-------------------------|-------------|---------------|---------|------------------|
| Control                 | D0          | 23.3±0.8      | 3.01±0.11 | 1750±126        |
|                         | D1          | 24.1±0.5      | 3.22±0.04 | 4250±702        |
|                         | D2          | 28.7±1.6      | 3.52±0.07 | 7067±303        |
|                         | D3          | 28.0±1.8      | 3.43±0.08 | 8017±322        |
| Treatment               | D0          | 25.8±0.3      | 3.15±0.10 | 2367±268        |
|                         | D1          | 23.7±2.2      | 3.06±0.12 | 4000±609        |
|                         | D2          | 29.3±0.8      | 3.71±0.01 | 6717±145        |
|                         | D3          | 28.1±1.3      | 3.40±0.05 | 8233±337        |

F

| Drainage (a) | Treatment (b) | a X b |
|--------------|---------------|-------|
|              |               |       |

Average±s.e. (n=3)
* : Significant at the 0.05 level. ** : Significant at the 0.01 level.

Rh, Dm: Refer to Table 2.

Terashima et al. — Drainage and Root Lodging Tolerance

desiccated in a dry oven maintained at 70°C for three days, and then weighed as dry matter. The ratio of the root dry weight to the shoot dry weight of 4 hills was multiplied by the average shoot dry weight of each plot to estimate the root dry weight of corresponding plot. Pushing resistance moment (Rh: Pushing resistance (R) \times height of plant part pushed by the prostrate tester (h: 10 cm)), and pushing resistance efficiency based on root dry weight (Kr: Rh/Dm/root dry weight) were calculated according to the relationship between the biomass of an individual hill and plant anchoring ability (Terashima et al., 2002). The hardness of the soil surface (from the soil surface to around 4 cm depth at the mid-point between rows) in each plot was monitored during the growing season using a plate-type penetrometer (Fujiwara Scientific Company Co., Ltd.)
Table 4. Effect of field drainage on root dry weight (Wr), pushing resistance moment (Rh), and pushing resistance efficiency based on root dry weight (Kr) in rice variety Domannaka and S-201 grown in the plots with unwoven cloth (1997).

| Drainage | Wr (g hill⁻¹) | Rh (g cm hill⁻¹) | Kr |
|----------|--------------|-----------------|----|
| Domannaka |              |                 |    |
| D0       | 2.44±0.16    | 1580±40         | 179.2±8.3 |
| D1       | 2.14±0.09    | 4600±64         | 663.5±34.4 |
| D2       | 2.55±0.09    | 7045±68         | 813.7±31.1 |
| D3       | 2.23±0.10    | 8932±342        | 1182.6±110.3 |
| S-201    |              |                 |    |
| D0       | 3.26±0.18    | 5215±343        | 455.4±64.0 |
| D1       | 2.81±0.12    | 6347±578        | 698.0±65.9 |
| D2       | 3.41±0.11    | 11306±824       | 885.0±60.9 |
| D3       | 2.99±0.21    | 11292±347       | 1081.6±64.4 |

F

| Variety | 78.40** | 79.98** | 4.51 |
|---------|---------|---------|------|
| Drainage | 4.85*  | 151.8***| 44.44**|
| a × b   | 0.22    | 2.71    | 5.57*|

Average ± s.e. (n=3)

*: Significant at the 0.05 level.
**: Significant at the 0.01 level.

Rh, Dm: Refer to Table 2. Kr: Rh/Dm/Wr.

Table 5. Effect of field drainage on root dry weight (Wr), pushing resistance moment (Rh) and pushing resistance efficiency based on root dry weight (Kr) in rice variety Domannaka grown in the plots with unwoven cloth (1998).

| Drainage | Wr (g hill⁻¹) | Rh (g cm hill⁻¹) | Kr |
|----------|--------------|-----------------|----|
| D0       | 2.08±0.04    | 2367±263        | 360.4±34.3 |
| D1       | 2.38±0.22    | 4000±469        | 551.7±36.3 |
| D2       | 2.46±0.12    | 6717±145        | 736.8±29.8 |
| D3       | 2.52±0.13    | 8233±837        | 959.8±58.7 |

F

| Root dry weight (g sample⁻¹) | 0 | 1 | 1.5 | 2 |
|------------------------------|---|---|-----|---|
| 0-5cm                        | a | b |     |   |
| 5-10cm                       | a | b |     |   |
| 10-15cm                      | a | a |     |   |
| 15-20cm                      | a | a |     |   |
| 20-25cm                      | a | a |     |   |

Means within layers followed by the same letter are not significantly different according to Tukey's Studentized Range Test (p<0.05).

Results

1. Effect of field drainage on pushing resistance in rice grown with or without unwoven cloth laid

Pushing resistance moment (Rh) was increased by field drainage, irrespective of whether unwoven cloth had been used (Tables 2 and 3). No significant effects of the unwoven cloth on Rh were found in either experimental year. Higher Rh values were found when drainage treatment was more frequent and prolonged, except for that the highest Rh in 1997 was obtained in D2 among control plots. For example, in the case of the 1998 control plots, the lowest value of Rh was 1750 g cm, recorded in the D0 plot. The Rh values of the drained plots were 4250 g cm in D1 plot, 7067 g cm in D2 plot, and the highest value of 8017 g cm was found in D3 plot.

2. Effect of field drainage on root development

Total root dry weight obtained from the field plots with unwoven cloth was compared among irrigation treatments. Although root dry weight at the full heading stage was heavier in the root lodging tolerant USA rice variety S-201 than in the root lodging-susceptible Japanese variety Domannaka, root dry weight in the 1997 experiment was not correlated with the frequency and length of drainage (Table 4). In 1998, root dry weight in early ripening stage tended to show a larger value in more frequently drained plots. However, the differences among treatments were not significant (Table 5). Fig.1 shows the root penetration to each soil layer in the control plots of Domannaka in 1997 experiment. Although a larger root mass was found in the 0-5 cm depth layer (the shallowest layer) in the D2 and D3 plots, no significant effect of drainage on root distribution was found in the monolith samples taken from the control plot of Domannaka in 1997. Pushing resistance efficiency based on root dry weight (Kr) differed signifi-
3. Effect of field drainage on soil hardness

Figures 2 and 3 show the seasonal change of soil hardness, measured at the soil surface of each plot during the growing season, in 1997 and 1998. The effect of field drainage on soil hardness was similar in both experimental years. The soil hardness in the continuously submerged (D0) plot was less than 0.5 kg cm\(^{-2}\) and lower than other plots throughout the growing season. Field drainage significantly raised soil hardness during field drainage periods, irrespective of the date of drainage. Although soil hardness was decreased by re-irrigating the field, a higher value of soil hardness than that before drainage was recorded even after re-irrigation. Thus, soil hardness during the ripening stage was highest in the D3 plot followed by D2 and D1 plots, corresponding to the frequency or length of drainage treatment. To elucidate the relationship between soil hardness and pushing resistance, we plotted all data for Kr obtained from the field plots laid with unwoven cloth in 1997 and 1998 against soil hardness of the corresponding field plot and date (Fig. 4). Higher values of Kr were recorded in the field plots with higher soil hardness. However, the increase in Kr relative to soil hardness declined gradually as the value of soil hardness was raised by frequent drainage of the field. A nonlinear equation was fitted to the relationship between soil hardness and Kr, which indicated a significantly high correlation coefficient ($r = 0.93$ in Domannaka, $r = 0.95$ in S-201).

Discussion

Our results clearly indicate that field drainage improves the anchoring ability of direct-sown rice. Uemura et al. (1985) observed that the pushing resistance of direct-sown rice was enhanced by midsummer drainage except when the rice plants were sown on the soil surface. In our experiments, conducted using rice...
plants sown on the soil surface, the effect of field drainage on the resistance to pushing was still significant, irrespective of the variety or the experimental year. Especially, the tendency of Rh toward a higher value in more frequent and prolonged drainage treatments, suggests the importance of field drainage during the growing season for increasing the root lodging tolerance in direct-sown rice in a flooded paddy field.

In this study, the physiological causes of the effects of field drainage on anchoring ability were investigated based on two factors: root development and soil hardness. Several researchers (Miyasaka, 1970; Kawata and Soejima, 1977) pointed out that field drainage stimulated the root growth in rice plant when compared with the root in continuously submerged fields. However, in our experiment, the difference in root dry weight among different irrigation management schemes was significant only in the 1997 experiment, and the relationship between root dry weight and drainage treatment remained unclear. Root dry weight in the drained field plots (D1, D3) was not larger than that in continuously submerged field plots (D0) in the 1997 experiment. To eliminate the effects of difference in root growth induced by drainage, we calculated pushing resistance efficiency (Kr) based on root dry weight. However, the significant effect of drainage was preserved even when Kr was compared among different irrigation management schemes. The above results indicate that a factor other than root dry weight may contribute to the improvement of plant anchoring ability. Moreover, investigation of root penetration to deeper soil layers using the monolith sampling method in 1997 showed no significant difference in penetration to subsoil layers deeper than 15 cm from the surface. Since higher Rh values were observed in well drained field plots even when compared among rice plants grown in the field plots with unwoven cloth to prevent the roots from penetrating to the subsoil layer, root penetration to deeper soil layers is not thought to be an important factor. These results suggest that more extensive or deeper root growth is not necessarily the primary cause of the improvement of pushing resistance induced by field drainage. The physiological activity of the root was not investigated in our experiment. However, Sakai et al. (1994) reported that the physiological activity of the root was not necessarily higher in a root lodging-tolerant USA variety than in a root lodging-susceptible Japanese variety based on the comparison of nutrient absorption and root respiration. Although further experiments will be needed, the physiological activity of root does not seem to be a primary factor affecting plant anchoring ability.

On the other hand, comparison of seasonal change of soil hardness, another possible factor, among different drainage treatments, indicated that field drainage significantly increased soil hardness even after re-irrigation. The hardest value was obtained in the repeatedly drained D3 plot, followed by the D2 and D1 plots at late ripening stage. Tada et al. (1967a, 1967b) and Iwata (1982) observed that midsummer drainage contributes to increased soil hardness, as does drainage in preparation for harvesting. Our observation of seasonal changes in soil hardness under different irrigation treatment regimes supports their findings. The investigation of a relationship between the resistance to pushing per unit root dry weight (Kr) and soil hardness strongly indicates that increased soil hardness caused by drainage significantly contributes to the anchoring ability of the plants, as shown in the highly significant correlation.

The above results suggest that soil hardness is the primary cause of the improvement of root lodging tolerance in repeatedly drained, direct-sown rice, and that monitoring and control of soil hardness during the growing season is needed to protect direct-sown rice from serious root lodging.

References

Akita, S. 1990. Technology and research on rice cultivation in US. (3) Impact on rice research of Japan. Agric. Tech. 45 : 337-341**.

Inada, K. 1960. Sampling method for rice root. Agric. and Hort. 35 : 877-878**.

Iwata, S. 1982. Soil physics of paddy field. In Yamane, I. ed., Soil Science of Paddy Field. Nosoangyou-bunka yokokai, Tokyo. 94-131**.

Kawata, S. and Soejima, M. 1977. Effect of water management of paddy fields on the formation of superficial root of rice. Jpn. J. Crop Sci. 46 : 24-36**.

Kohno, E. 1979. Studies on the engineering properties of soil in view of the shrinkage behavior on the surface soil of paddy field. Trans. JSIDRE. 81 : 1-8**.

McKenzie, K.S., Johnson, C.W., Tseng, S.T., Oster, J.J. and Brandon, D.M. 1994. Breeding improved rice cultivars for temperate regions: a case study. Aust. J. of Exp. Agric. 34 : 987-903**.

Miyasaka, A. 1970. Effects of drainage on the growth of rice plant in ill-drained paddy field. Bull. Hokuriku Agric. Exp. Stn. 12 : 1-80*.

Nakatuka, K. and Ishii, K. 1989. Effect of traffic sole on paddy rice root growth.Agri. Tech. 44 : 8-12**.

Nishio, T., Ishiwaki, I. and Yanazawa, T. 1966. Some consideration on prevention of lodging in direct-sowing rice culture on submerged fields. Bull. Tositoki Agric. Exp. Stn. 7 : 1-8*.

Rutger, J.N. and Brandon, D.M. 1981. California rice culture. Sci. Am. 244 : 38-47.

Sakai, K., Terasima, K. and Kabuki, N. 1994. Characteristics of root growth and nutrient absorption in US rice cultivar. Jpn. J. Crop Sci. 63 (Extra issue1) : 26-27**.

Seko, H. 1962. Studies on lodging in rice plants. Bull. Kyushu Agric. Exp. Stn. 7 : 419-499*.

Tada, A., Yasutomi, R. and Tsutsushi, S. 1967a. The studies on the bearing capability of paddy fields with heavy clay soil. (I) - The annual variation of bearing capacity-. Trans. ASCEJ. 21 : 24-28**.

Tada, A., Yasutomi, R., Tsutsushi, S. and Tabuchi, T. 1967b. The studies on the bearing capacity of paddy fields with heavy clay soil. (II) -The relation between bearing capacity and...
surface drainage-. Trans. ASEJ. 21: 29-35**.
Taniguchi, T., Nakamura, K., Ogiwara, H. and Terashima, K. 1998. Effects of irrigation management on lodging tolerance and growth of direct seeded rice plant in paddy field. Jpn. J. Crop Sci. 67 (Extra issue!) : 254-255***
Terashima, K., Ogata, T. and Akita, S. 1994. Eco-physiological characteristics related with lodging tolerance of rice in direct sowing cultivation. II. Root growth characteristics of tolerant cultivars to root lodging. Jpn. J. Crop Sci. 63 : 34-41**.
Terashima, K., Akita, S. and Sakai, N. 1995. Eco-physiological characteristics related with lodging tolerance of rice in direct sowing cultivation. III. Relationship between the characteristics of root distribution in the soil and lodging tolerance. Jpn. J. Crop Sci. 64 : 243-250**.
Terashima, K., Sakai, K. and Kabaki, N. 2002. Relationship between biomass of an individual hill and root lodging tolerance in direct seeded rice. Jpn. J. Crop Sci. 71 : 161-168**.
Uemura, K., Matsuo, K. and Komatsu, Y. 1985. Lodging tolerance in directly seeded rice to submerged field. Rep. Shikoku Br. Crop Sci. Soc. Japan. 22 : 25-31***.
Washio, O. 1989. Recent trend of direct sowing cultivation of rice plant in flooded paddy field. (1) Progress of development and present status of cultivation technique. Agric. Tech. 44 : 150-153***.
Yamamoto, R. 1990. The milestone for rice cultivar development for direct seeding. Agric. Tech. 45 : 385-391***.
Yasuhara, H., Kanda, M., Sumi, H., Ito, J., Yamane, T., Nakashima, K., Nagase, K., Fujihara, T. and Degawa, M. 1992. Application of direct underground sowing of rice to submerged paddy field in Sanin Region. Bull. Shimane Agric. Exp. Sta. 26 : 1-24***.

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