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Effect of Deep Tillage on Growth and Yield of Rice Cultivars Grown under Water Deficit

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Root systems play an important roles, especially under water stress conditions in rice (*Oryza sativa* L.). However, the contribution of root systems to growth and yield has not been clarified, because of the difficulty of investigating root systems under field conditions. In this study, we grew 12 rice cultivars belonging to different ecotypes in an upland field, to investigate the effect of tillage depth on root development, growth and yield of rice grown under water deficit. Also to identify the genotypic differences in effect. Drought stress significantly reduced plant height, panicle dry weight and total dry weight at the end of the water deficit treatment. Water deficit imposed around the late panicle development to anthesis stage reduced grain filling. However, a sink–source imbalance increased total dry weight and the number of tillers in drought plots at harvest time. Furthermore, drought stress reduced the number of spikelets, percentage of ripened grain and 1000 kernels weight. Consequently, the grain yield was significantly reduced by both drought stress and shallow tillage. The *indica* upland rice cultivars showed the highest drought resistance, and the *japonica* upland and lowland cultivars showed reduced resistance. On the other hand, under well-irrigated conditions, deep tillage improved the growth of *japonica* lowland cultivars and some *indica* upland cultivars, but *japonica* upland cultivars were not affected. This result shows that the *japonica* upland cultivars used may have good root penetration into hard soil.

INTRODUCTION

Water deficit is one of the most serious factors limiting the production of rice (Widawsky and O'Toole, 1990). Water stress is common in uplands and in rain-fed lowlands (Fukai and Cooper, 1995). Under rainfed conditions, rice is generally grown in the monsoon season in Asian countries where a bimodal rainfall pattern is common. The effect of drought varies with its timing and severity in relation to crop phenology. Three types of drought stress are recognized in these regions, *i.e.* early, mild-intermittent and late stress (Chang *et al.*, 1979). Mild-intermittent stress coincides with the period from tillering to flowering in the monsoon season. If the water supply is even slightly less than the demand from the plants, the yield is significantly reduced because of leaf area growth reduction and stomatal closure (Fukai and Cooper, 1995).

Water deficits at any growth stage may reduce the grain yield of rice; the magnitude of the reduction depends on the severity and duration of the drought stress and the crop growth stage (O'Toole and Moya, 1981). Grain yield is more sensitive to water deficit during the reproductive stage than during the vegetative stage (O'Toole and Moya, 1981; Yambao and Igram, 1988), and is drastically reduced when water deficit occurs at the flowering stage (Boonjung and Fukai, 1996a, b). O'Toole and Chang (1979) suggested that

water stress during early panicle development decreases the number of spikelets per panicle, and that stress in the meiosis to anthesis stage increases sterility. Rice is sensitive to water stress owing to its shallow root distribution and limited capacity to extract water from deep soil layers compared with other cereal crops (Angus *et al.*, 1983). However, Yoshida and Hasegawa (1982) reported that upland rice cultivars have extensive root systems and are able to extract water from the middle soil layer after the surface has dried. An extensive and deep root system would allow a rice plant to better use the soil moisture in the deeper layers. Although a deep and thick root system is considered to be an advantage, allowing rice plants to maintain their water status under water stress, the relationship between root system and drought resistance has not been clarified yet, because of the difficulty of measuring root traits under field conditions.

In this study, we grew 12 rice cultivars belonging to different ecotypes in an upland field to investigate the effect of tillage depth on root development, growth, and yield of rice grown under water deficit; and to identify the genotypic difference in effect.

MATERIALS AND METHODS

Plant materials

We grew four *japonica* upland cultivars, six *indica* upland cultivars and two *japonica* lowland cultivars (Table 1).

Culture details

The experiment was conducted in the rainy season of 2005 in a frame-house set up in an upland field on an experimental farm of Kyushu University, Japan (Fig. 1).

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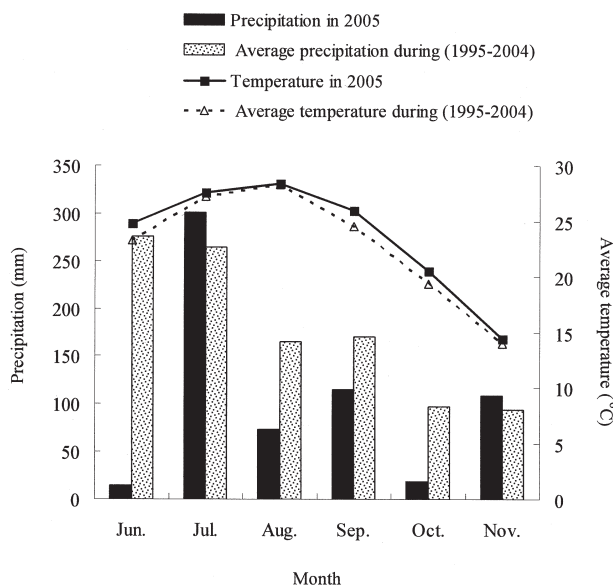
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Table 1. Plant materials

| Cultivar | Origin | Cultural type | Variety type |
|------------------|---------|---------------|-----------------|
| Rikuko Norin 22 | Japan | Upland | <i>japonica</i> |
| Owarihata Mochi | Japan | Upland | <i>japonica</i> |
| Hataminori Mochi | Japan | Upland | <i>japonica</i> |
| Sensho | Japan | Upland | <i>japonica</i> |
| Beo dien | Vietnam | Upland | <i>indica</i> |
| IR57920-AC-25-2 | IRRI* | Upland | <i>indica</i> |
| LC 90-12 | IRRI | Upland | <i>indica</i> |
| IR71525-19-1-1 | IRRI | Upland | <i>indica</i> |
| WAB 96-1-1 | IRRI | Upland | <i>indica</i> |
| UPLRI-7 | IRRI | Upland | <i>indica</i> |
| Nipponbare | Japan | Lowland | <i>japonica</i> |
| Koshihikari | JApan | Lowland | <i>japonica</i> |

*International Rice Research Institute.

**Fig. 1.** The experimental field with irrigation system.**Fig. 2.** Precipitation and average temperature from June to November in 2005 and during 1995–2004 at Fukuoka, Japan.

The soil structure were 21.7% clay, 12.8% silt, and 65.5% sand. Precipitation and average temperature from June to November 2005 and during 1995–2004 are shown in Fig. 2. The average temperature from June to November 2005 was similar to that during 1995–2004 except in July and November.

A split-split-plot design with three replications was used, with two water regimes (good irrigation and drought) as main plots, two tillage depths (shallow and deep) as subplots, and the 12 rice cultivars as sub-subplots (36). The dimensions of each plot were 1.5 m by 1.35 m, with six rows of nine hills. In the irrigated plot, sufficient moisture was applied by drip irrigation and rainfall throughout the experiment. In the drought plot, irrigation was suspended for 20 days from 64 to 84 days after sowing (DAS), during which time the plot was covered with clear vinyl. This period coincided with the panicle development stage for most of the cultivars. The subplots were disk-plowed once to about 10 cm in depth (shallow tillage) or twice to about 25 cm in depth (deep tillage). Four treatment combinations were applied: irrigation + deep tillage (IDt), irrigation + shallow tillage (ISt), drought + deep tillage (DDt), and drought + shallow tillage (DSt).

Chemical fertilizers were applied at 12 g N m⁻², 12 g P m⁻², and 12 g K m⁻². P and K were each applied once as a basal dressing. Nitrogen fertilizer was dressed three times in the growth period. The first (4 g m⁻²) was applied as a basal dressing, and the second (4 g m⁻²) and third (4 g m⁻²) as top dressings at 30 and 84 DAS. Rice seeds were soaked in water at 30 °C for 3 days. Two or three pre-germinated seeds were sown per hill on June 9th. Plant spacing was 25 cm by 15 cm (26.7 hills m⁻²). At 21 DAS, the seedlings were thinned to one plant per hill. Weeds were controlled by chemical herbicides and hand-weeding until the canopy was fully closed.

Measurements

Plant height (PH) and the number of tillers (NT) per square meter were measured at 63 DAS (before the start of the water deficit treatment) and at 85 DAS (after the end of the water deficit treatment). At the end of the water deficit treatment, five plants were sampled in each sub-subplot, and then divided into stem, leaf, and panicle. The dry weights of stem (SDW), leaf (LDW), and panicle (PDW) were measured after drying at 70 °C for 3 days, and summed as total dry weight (TDW). At maturity, the above-ground parts of four plants per sub-subplot were harvested to investigate grain yield and yield components. TDW measured at harvest was termed TDWH. The drought resistance index (DRI) was determined as the ratio of yield in the DSt plot to that in the IDt plot.

RESULTS

Plant growth

Figures 3 and 4 show root system profiles of representative rice cultivars grown under irrigated conditions. Roots in the shallow tillage plots were distributed mostly

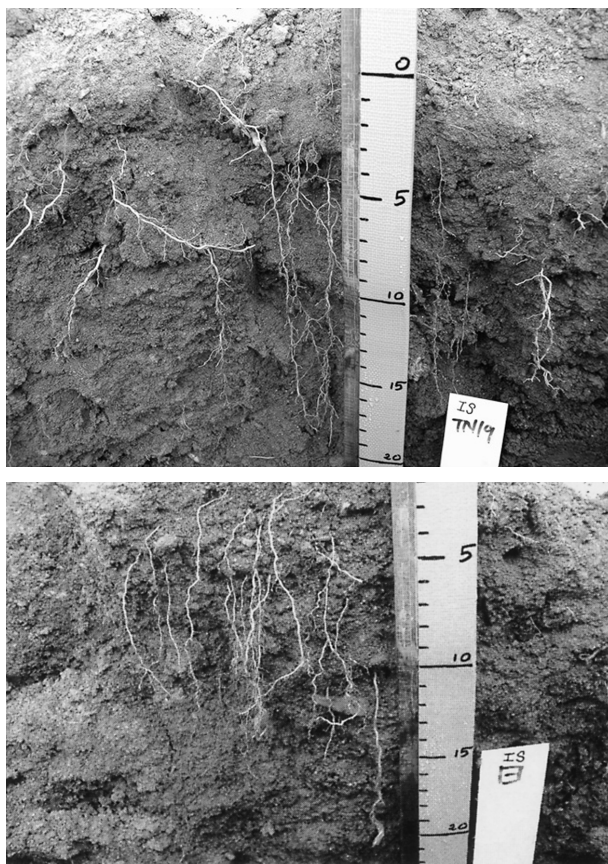


Fig. 3. Root systems at 115 DAS in the irrigation + shallow tillage plot. Cultivars LC 90-12 (Upper) and Nipponbare (Lower).

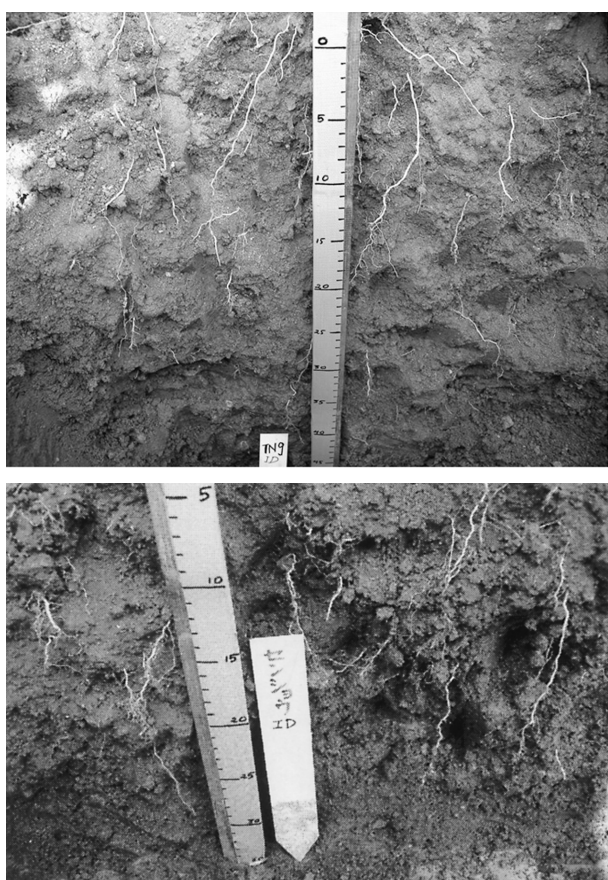


Fig. 4. Root systems at 115 DAS in the irrigation + deep tillage plot. Cultivars UPLRi-7 (Upper) and Sensho (Lower).

at 0–15 cm depth. On the other hand, most roots in the deep tillage plots reached 25 to 30 cm.

The values of PH and NT measured before the start of the water deficit treatment are shown in Table 2. Shallow tillage significantly reduced both parameters in both irrigation treatments. Fig. 5 shows the irrigated and drought plots at the end of the water deficit treatment. In the drought plot, the soil moisture contents of the deep and shallow tillage subplots were almost the same at the end of the water deficit period, although that of the deepest soil layer in the deep tillage subplot was slightly (but not significantly) higher than that in the shallow tillage subplot (Fig. 6). The values of PH and NT measured after the end of the water deficit treatment are shown in Table 3. Shallow tillage again significantly reduced both parameters. IDt gave the

Table 2. PH and NT before the start of the water deficit treatment

| Treatment | Plant height (cm) | Number of tillers (m^{-2}) |
|-----------|-------------------|--------------------------------|
| IDt | 75.2 ± 2.2 | 220.8 ± 21.4 |
| ISt | 68.3 ± 1.2 | 184.6 ± 09.3 |
| DDt | 75.9 ± 1.1 | 218.5 ± 10.2 |
| DSt | 70.8 ± 3.6 | 196.1 ± 10.2 |
| LSD 05 | 2.14 | 21.8 |

Data are shown as means \pm SD. PH, plant height (cm); NT, number of tillers; IDt, irrigation + deep tillage; ISt, irrigation + shallow tillage; DDt, drought + deep tillage; DSt, drought + shallow tillage; LSD 05, least significant difference at $P = 0.05$.



Fig. 5. Irrigated (Upper) and drought plots (Lower) at the end of the water deficit treatment.

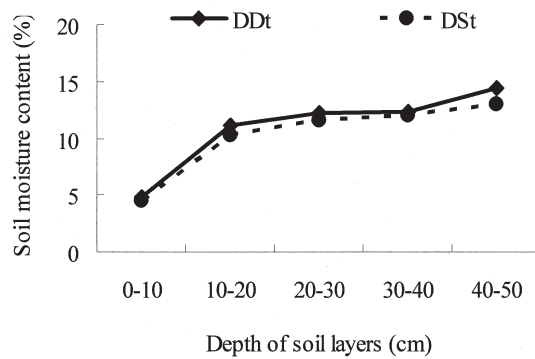


Fig. 6. Soil moisture content in the drought plots at the end of the water deficit period. DDt, drought + deep tillage; DSt, drought + shallow tillage.

Table 3. PH and NT at the end of the water deficit treatment

| Treatment | Plant height (cm) | Number of tillers (m^{-2}) |
|-----------|-------------------|--------------------------------|
| IDt | 108.3 \pm 4.3 | 199.8 \pm 12.6 |
| ISt | 94.0 \pm 2.7 | 166.8 \pm 10.2 |
| DDt | 84.3 \pm 2.7 | 192.0 \pm 9.1 |
| DSt | 80.6 \pm 4.2 | 181.0 \pm 10.4 |
| LSD 05 | 3.69 | 18.6 |

Data are shown as means \pm SD. PH, plant height (cm); NT, number of tillers; IDt, irrigation + deep tillage; ISt, irrigation + shallow tillage; DDt, drought + deep tillage; DSt, drought + shallow tillage; LSD 05, least significant difference at $P = 0.05$.

Table 4. PDW and TDW at the end of the water deficit treatment

| Treatment | PDW ($g\ m^{-2}$) | TDW ($g\ m^{-2}$) |
|-----------|---------------------|---------------------|
| IDt | 84.1 \pm 7.9 | 444.9 \pm 46.2 |
| ISt | 51.2 \pm 6.9 | 309.8 \pm 30.4 |
| DDt | 31.5 \pm 2.3 | 321.7 \pm 20.1 |
| DSt | 31.2 \pm 4.2 | 286.5 \pm 33.4 |
| LSD 05 | 7.74 | 43.0 |

Data are shown as means \pm SD. PDW, panicle dry weight; TDW, total dry weight; IDt, irrigation + deep tillage; ISt, irrigation + shallow tillage; DDt, drought + deep tillage; DSt, drought + shallow tillage; LSD 05, least significant difference at $P = 0.05$.

highest values of PH and NT, DSt gave the lowest value of PH, and ISt gave the lowest value of NT.

Table 4 shows PDW and TDW after the end of the water deficit treatment. PDW in the irrigated plots was significantly higher than that in the drought plots. PDW was also higher in IDt than in ISt, but there was no significant difference between the drought plots. TDW in IDt was significantly higher than in the other three treatment combinations. On the other hand, TDWH values in the drought plots were significantly higher than those in the irrigated plots. IDt gave a significantly higher TDWH than ISt, but there was no significant difference between DDt and DSt (Table 5).

Yield and yield components

We measured yield, number of panicles per square meter (NP), number of spikelets per panicle (NS), percentage of ripened grains (PRG), and weight of 1000 kernels (WK).

The results of ANOVA are shown in Table 6. Water regime had significant effects on yield and WK ($P = 0.05$), and on NP, NS, and PRG ($P = 0.01$). Tillage depth had significant effects on yield and PRG ($P = 0.01$), and on NS ($P = 0.05$). Cultivars had significant effects on all traits except WK ($P = 0.01$). There was no interaction of water and tillage in any parameters except WK. However, the interaction of water and cultivar was significant in all traits ($P = 0.01$) except WK. The interaction of tillage and cultivar was significant in yield and PRG ($P = 0.01$), and in NS ($P = 0.05$).

Table 5. Total dry weight at the harvest time

| Treatment | TDWH ($g\ m^{-2}$) |
|-----------|----------------------|
| IDt | 533.2 \pm 47.0 |
| ISt | 408.5 \pm 13.2 |
| DDt | 623.7 \pm 24.6 |
| DSt | 653.3 \pm 39.8 |
| LSD 05 | 61.9 |

Data are shown as means \pm SD. TDWH, total dry weight at the harvest time; IDt, irrigation + deep tillage; ISt, irrigation + shallow tillage; DDt, drought + deep tillage; DSt, drought + shallow tillage; LSD 05, least significant difference at $P = 0.05$.

Table 6. Three-way ANOVA of yield and yield components

| | Yield ($g\ m^{-2}$) | Number of panicles (m^{-2}) | Number of spikelets (panicle $^{-1}$) | Percentage of ripened grains (%) | Weight of 1000 kernels (g) |
|--|-----------------------|---------------------------------|--|----------------------------------|----------------------------|
| Water | * | * | ** | ** | * |
| Tillage | ** | ns | * | ** | ns |
| Cultivar | ** | ** | ** | ** | ns |
| Water \times Tillage | ns | ns | ns | ns | ** |
| Water \times Cultivar | ** | ** | ** | ** | ns |
| Tillage \times Cultivar | ** | ns | * | ** | ns |
| Water \times Cultivar \times Tillage | ns | ns | * | ns | ns |

* and **, significantly different at $P = 0.05$ and $P = 0.01$, respectively; ns, not significant.

Table 7. Yield and yield components among the treatment combinations

| Treatment | Yield (g m^{-2}) | Number of panicles (m^{-2}) | Number of spikelets (panicle^{-1}) | Percentage of ripened grains (%) | Weight of 1000 kernels (g) |
|-----------|-----------------------------|--|---|----------------------------------|----------------------------|
| IDt | 333.6 ± 23.5 | 167.0 ± 11.1 | 97.1 ± 1.2 | 81.6 ± 0.3 | 25.8 ± 0.2 |
| ISt | 252.7 ± 22.6 | 141.3 ± 03.5 | 103.8 ± 5.5 | 70.0 ± 0.7 | 25.5 ± 0.1 |
| DDt | 160.9 ± 07.5 | 284.1 ± 07.1 | 74.2 ± 1.1 | 40.3 ± 1.7 | 23.5 ± 0.2 |
| DSt | 116.9 ± 17.0 | 282.0 ± 08.2 | 78.9 ± 1.1 | 24.8 ± 4.5 | 24.0 ± 0.2 |
| LSD 05 | 32.3 | 28.2 | 6.34 | 5.04 | 0.43 |

Data are shown as means \pm SD. IDt, irrigation + deep tillage; ISt, irrigation + shallow tillage; DDt, drought + deep tillage; DSt, drought + shallow tillage; LSD 05, least significant difference at $P = 0.05$.

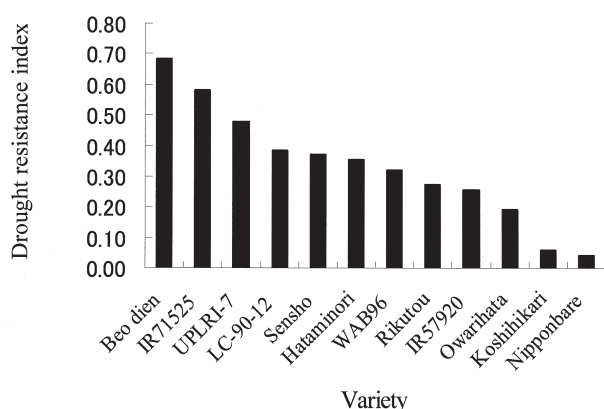
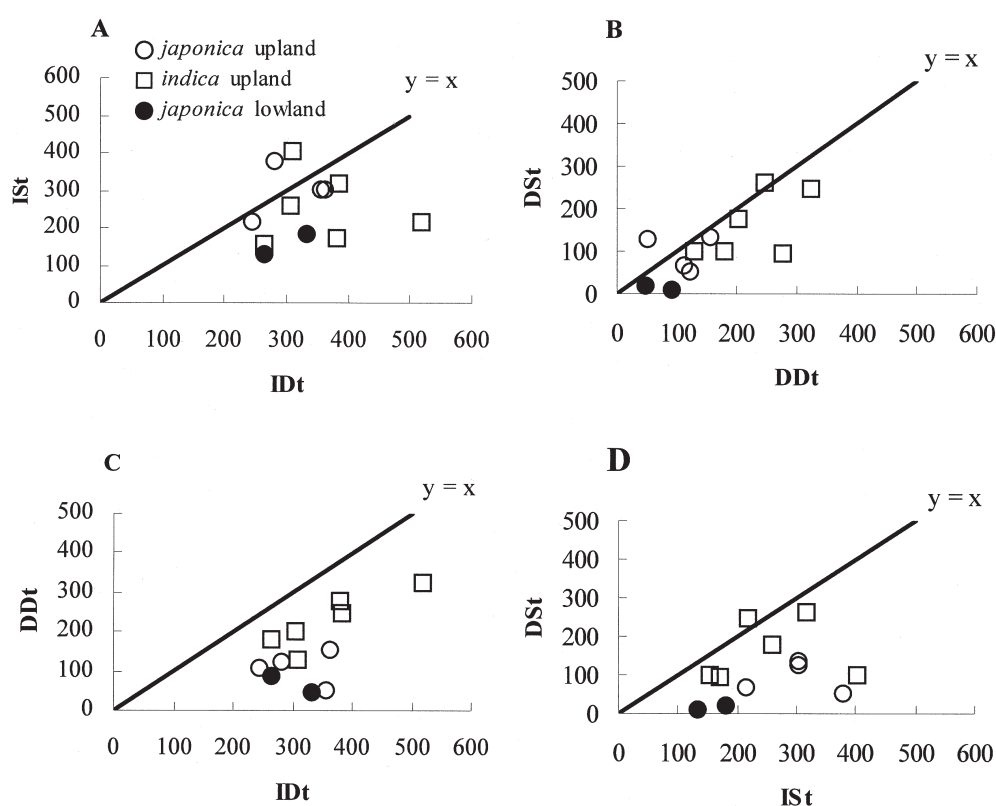
**Fig. 7.** Drought resistance index: yield ratio of the drought + shallow tillage plot (DSt) to the irrigation + deep tillage plot (IDt).

Table 7 lists the mean values of yield parameters in each treatment combination. The irrigated plots had significantly higher yields than the drought plots in both deep and shallow tillage, and the deep tillage plots had significantly higher yields than the shallow tillage plots. The highest yield (333.6 g m^{-2}) came from IDt, and the lowest (116.9 g m^{-2}) from DSt.

NS, PRG, and WK in the drought plots were significantly lower than those in the irrigated plots. PRG also differed significantly between IDt and ISt and between DDt and DSt. However, NP values in the drought plots were significantly higher than those in the irrigated plots. NP values did not differ significantly between IDt and ISt or between DDt and DSt.

A Vietnamese traditional upland rice cultivar, 'Beo dien', showed the highest DRI. The upland cultivars had

**Fig. 8.** Relationship of grain yield in each cultivar between treatments

A: Irrigation + deep tillage (IDt) vs. irrigation + shallow tillage (ISt). B: Drought + deep tillage (DDt) vs. drought + shallow tillage (DSt). C: Irrigation + deep tillage (IDt) vs. drought + deep tillage (DDt). D: Irrigation + shallow tillage (ISt) vs. drought + shallow tillage (DSt).

higher DRIs than the lowland cultivars. Among the upland cultivars, many of the *indica* cultivars had higher DRIs than *japonica* cultivars (Fig. 7). Fig. 8 shows the relationship of grain yield of each cultivar between the four treatment combinations. Under irrigation, the effect of deep tillage on yield was greater in the *japonica* lowland and some *indica* upland cultivars than in the others (Fig. 8A). However, under drought conditions, most cultivars were not affected by tillage depth, but the *japonica* upland and lowland cultivars showed lower yields than the *indica* upland cultivars (Fig. 8B). Under both deep and shallow tillage, irrigation had an effect on all cultivars, more noticeably on the *japonica* cultivars than on most of the *indica* upland cultivars (Figs. 8C, D).

DISCUSSION

Before the water deficit treatment, crop growth was affected by tillage depth (Table 2). We suggest that deep tillage allowed plants to develop deeper root systems and so use water and nutrients in deeper soil. After the water deficit treatment, drought had significantly decreased PH, but not NT (Table 3), and had also significantly decreased PDW and TDW (Table 4). On the other hand, drought significantly increased TDWH (Table 5). We can consider that the growth of plants in the irrigated plots shifted smoothly from vegetative to reproductive phase, and the photoassimilates in the culms were translocated to the panicles. The growth of panicles in the drought plots was likely damaged, so the panicles did not function well as sink organs. This may have caused the photoassimilates to be used to develop new tillers during the recovery period, when plants again received adequate water, explaining the large increase in TDWH. In the irrigated plots, yield parameters except NS in the deep-tilled subplots were higher than those in the shallow-tilled subplots (Table 7). Water regime had significant effects on yield and WK. NP values of the drought plots were higher than those of the irrigated plots, because of the growth of new tillers and panicles during the recovery period, as mentioned above. However, most of the panicles which appeared during the recovery period could not fill grains, because the air temperature had become too low. NS values in the drought plots were significantly lower than those in the irrigated plots (Table 7). Boonjung and Fukai (1996b) reported that water deficit around the flowering stage reduced NS by 40%. In addition, they showed that

water deficit during the mid-panicle development and anthesis stages decreased the ripening ratio of grains. In our experiment, PRG was drastically decreased by the water deficit treatment and increased by deep tillage in both water treatments. Consequently, deep tillage ameliorated yield reduction caused by drought stress. Thus, deep-rooting rice plants will be favored under both drought and irrigated conditions.

Among the cultivars used here, the *indica* upland cultivars showed the highest drought resistance, and *japonica* lowland rice the lowest regardless of tillage depth (Figs. 7, 8B–D). On the other hand, under irrigation, deep tillage improved the yield of the *japonica* lowland rice cultivars and some *indica* upland rice cultivars, but not the *japonica* upland rice cultivars (Fig. 8A). This result suggests that *japonica* upland rice cultivars may have good root penetration through hard soil.

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