Varietal Differences in Stem Diameter and Rooting Number of Phytomers in Conjunction with Root System Development of Field-Grown Rice (*Oryza sativa* L.)

Yoichiro Kato¹, Jun Abe², Akihiko Kamoshita¹* and Junko Yamagishi¹

¹Graduate School of Agricultural and Life Sciences, The University of Tokyo, Nishitokyo, Tokyo 188-0002, Japan; ²Graduate School of Agricultural and Life Sciences, The University of Tokyo, Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan)

**Key words**: Deep root, *Oryza sativa*, Phytomer, Plant architecture, Root diameter, Upland rice.

A vigorous root system is a desirable characteristic in rice (*Oryza sativa* L.) under upland conditions for effective water and nutrient uptake from the soil (Kato et al., 2006a, b, 2007). To date, numerous studies have shown that allometric correlations between root and shoot growth exist in rice (Yoshida et al., 1982; Kondo et al., 2003). These studies indicate that a large rooting zone in traditional varieties is associated with the aboveground characteristic of low tillering (Yoshida et al., 1982). However, we have found that some improved cultivars show profuse tillering with well-developed, deep root systems (Kato et al., 2006b). These cultivars may possess a unique relationship between their above- and below-ground growth, suggesting that it is worthwhile to reconsider the ideotype of rice under upland conditions, based on developmental morphology.

Many higher plants, including rice, are composed of successive stem segments called phytomers (Nemoto et al., 1995). The phytomer concept has long been recognized among grass scientists (Rickman et al., 1995; McMaster, 2005). Each phytomer consists of an internode of the stem with one leaf, one tiller bud and several adventitious (nodal) roots (Kawata et al., 1963; Abe and Morita, 1994). The coordinated development of stem, tiller bud, and adventitious roots in each phytomer corresponds to the phyllochronic time in rice (Fujii, 1961; Abe and Morita, 1994; Nemoto et al., 1995). This indicates that genotypic variation in root-and-shoot growth can be ascribed to the variation of stem and adventitious root development at the phytomer level (Harada and Yamazaki, 1993). However, quantitative comparisons of phytomer ontogeny, including rhizogenesis, among rice genotypes are lacking compared with those of shoot development such as tillering habit (Tivet et al., 2001; Miyamoto et al., 2004). The objective of this study was to show the relationship between root-to-shoot growth for six rice cultivars at the phytomer level.

**Materials and Methods**

1. **Plant materials**  
   Six *japonica* rice cultivars (*Oryza sativa* L.) with various plant architectures were used in this study. ‘Otomemochi’, ‘Akihikari’ and ‘Nipponbare’ are lowland-adapted cultivars developed in Japan that have many thin tillers and shallow root systems (Kato et al., 2006a, b). ‘Lemont’ is also an lowland-adapted cultivar from the United States and has a small number of thick stems. ‘Yumeno-hatamochi’ and ‘IRAT109’ are deep-rooted, upland-adapted cultivars (Kato et al., 2006a, c). Yumeno-hatamochi was recently bred in Japan and often performs better than other cultivars under water-limited upland conditions (Hirasawa et al., 1998). IRAT109 was developed in Ivory Coast and is often used as a drought-resistant donor in the breeding program (Nemoto et al., 1998).

2. **Field management**  
   A field experiment was conducted at the Field Production Science Center of The University of Tokyo, Nishitokyo, Japan (lat. 35°43 N, long. 139°32 E) during the summer of 2005. Rice plants were grown in upland fields where frequent sprinkler irrigations were applied to maintain near-field capacity of soil water (above −0.02 MPa at 20 cm depth). Plot dimensions for each cultivar were 2.4 m x 2.4 m, and planting density was 33.5 hills m⁻² (one plant per hill). Compound chemical fertilizers (high-analysis compound fertilizer A907, COOP Chemical Inc., Tokyo) were applied at sowing at the rate of N=60, P₂O₅=90, and K₂O=80 kg ha⁻¹. Topdressing with ammonium sulfate (N=40 kg...
Plant Production Science Vol. 10, 2007

358

ha⁻¹) was applied 46 days after sowing. The details of field management were previously described (Kato et al., 2006c).

3. Sampling and measurements

At 78 days after sowing, the number of stems of per plant was counted for 15 plants of each cultivar, and five plants of medium size were collected. After soil was carefully washed off, the samples with leaves, stems and adventitious roots were conserved in 70% ethanol. The numbers of stems, adventitious roots per plant and leaves on the main stem (which reflects the reciprocal of the phyllochron) were determined. Then, the number and diameter of stems and adventitious roots at the fifth, sixth and seventh phytomers (i.e., the stem segments from which the fifth, sixth and seventh leaves emerged), as well as the leaf blade length at the ninth phytomer on the main stem, were determined after all the tillers were carefully detached from the main stem. It takes about three phyllochrons after leaf emergence before root primordia emergence from the stem (Fujii, 1961). Therefore, we did not examine the phytomers above the seventh phytomer, which might not have emerged roots, although we measured the leaf blade length at the ninth phytomer because the lower leaves had already abscised. The diameter of adventitious roots (root diameter) 10 mm from the base of each plant was measured with a binocular microscope. The stunted roots, which were less than 10 mm in length, were included in the number of adventitious roots (root number), although their diameters were not measured. The diameter of stem segments (stem diameter) was measured at the fifth, sixth and seventh phytomer positions with a digital caliper. Analysis of variance (ANOVA) was conducted using SAS 9.1 software (SAS Institute Inc., Cary, NC, USA), and the least significant difference at \( P=0.05 \) was presented when comparing varietal differences.

Results

The root diameter, stem diameter and root number at the fifth, sixth and seventh phytomers showed significant differences among the six cultivars (Fig. 1). The rankings of cultivars for these traits were similar at all phytomers; thus, we averaged the values among the fifth, sixth and seventh phytomers for further analysis. All the plant characteristics, including root number per phytomer, also significantly differed among the six cultivars (Table 1). Lemont had the thickest stems and roots, followed by IRAT109, whereas Otomemochi, Akihikari and Nipponbare had thin stems and roots. Yumeno-hatamochi had many slender tillers with a small number of thick roots. Correlation analysis indicated that among the aboveground characteristics of the cultivars, only stem diameter had a relatively high correlation with root diameter (Table 2). Root number per phytomer was also associated with root diameter, but not stem diameter. Therefore, we conducted multiregression analysis to predict adventitious root diameter from two variables, stem diameter and root number per phytomer:

\[
Y = 0.081 \times X_1 - 0.038 \times X_2 + 0.804 \quad (r=0.959^*, n=6)
\]

where, \( Y \) = adventitious root diameter, \( X_1 \) = stem diameter, and \( X_2 \) = root number per phytomer. Similar relationships were observed when we analyzed each phytomer (\( r=0.950\text{–}0.963^* \)). The root number per phytomer was also correlated with root number per stem (\( r=0.876^* \)) and root number per plant (\( r=0.895^* \)).

Discussion

Several upland-field observations have revealed thick roots as constitutively well-developed roots in rice (Araki et al., 2002; Kato et al., 2006c). Therefore, we used root thickness as an indicator of vigorous root growth in this study.

The characteristics of thick roots and a small number of thick stems are considered as an ideotype of rice under upland conditions (Yoshida et al., 1982).

---

![Bar graphs showing adventitious root diameter (a), stem diameter (b), and adventitious root number (c) on the main stem at the fifth (white), sixth (gray), and seventh (black) phytomers 78 days after sowing for six rice cultivars grown in upland fields. Bars indicate standard deviation (n=5).](image-url)
because root thickness is associated with stem thickness in rice (Nemoto and Yamazaki, 1986, 1989). This trend was also recognized in this study, and the cultivars that had a small number of thick stems also having thick roots, such as Lemont and IRAT109 (Table 1). However, the multiregression analysis revealed that root number per phytomer as well as stem diameter had a close relationship with root diameter. For example, the upland cultivar, Yumeno-hatamochi, which has a deep root system in upland fields (Kato et al., 2006c), had many thin stems and thick roots with a small number of roots per phytomer. These indicate that root number per phytomer and the size of the phytomer unit—that is, the stem diameter—are phytomer-based units that are closely related to the underground structure of rice. The thicker the stems and the less the rooting number, the thicker the roots.

A previous study indicated that the relationship between root number per phytomer and stem diameter is cultivar-dependent (Nemoto and Yamazaki, 1989). Our study also showed that there is a poor relationship between these two characteristics in upland fields (Table 2). Interestingly, two upland-adapted cultivars (Yumeno-hatamochi and IRAT109) had a much smaller number of adventitious roots per phytomer than typical lowland-adapted cultivars (Otomemochi, Akihikari and Nipponbare). Historical rice breeding strategies for upland environments might have unconsciously selected a series of cultivars that have a small number of sturdy roots, irrespective of their aboveground characteristics. Lemont, which also had a small number of roots per phytomer, is often grown under dry-seeded lowlands where vigorous rooting may be important. Although this study was a preliminary observation of a limited number of cultivars under a single condition, we suggest that deeper insights into root and shoot development at the phytomer level will give us potentially valuable information for the breeding and modeling of an ideotype of rice on the basis of developmental morphology.

Table 1. Root diameter, root number per phytomer, root number per plant, root number per stem, stem diameter, stem number per plant, leaf blade length at ninth phytomer and leaf number on the main stem at 78 days after sowing for six rice cultivars grown in upland fields.

|                  | Root diameter† (mm) | Root number† (phytomer⁻¹) | Root number (plant⁻¹) | Root number (stem⁻¹) | Stem diameter† (mm) | Stem number (plant⁻¹) | Leaf length‡ (cm) | Leaf number§ |
|------------------|--------------------|----------------------------|-----------------------|----------------------|---------------------|-----------------------|------------------|-------------|
| Lemont           | 1.13               | 6.9                        | 109                   | 15.2                 | 6.73                | 7.4                   | 38.8             | 10.7        |
| IRAT109          | 0.97               | 7.7                        | 116                   | 13.2                 | 6.18                | 8.8                   | 40.7             | 11.0        |
| Yumeno-hatamochi | 0.94               | 7.7                        | 153                   | 12.3                 | 4.68                | 12.8                  | 26.4             | 12.3        |
| Otomemochi       | 0.72               | 15.3                       | 276                   | 22.3                 | 5.25                | 12.4                  | 29.2             | 12.6        |
| Akihikari        | 0.72               | 12.5                       | 154                   | 24.6                 | 5.11                | 6.4                   | 31.3             | 11.2        |
| Nipponbare       | 0.66               | 13.1                       | 232                   | 19.9                 | 5.00                | 11.6                  | 31.5             | 12.1        |
| LSD at 0.05      | 0.05               | 2.1                        | 59                    | 4.1                  | 0.55                | 2.8                   | 3.8              | 0.4         |

† Stem diameter, adventitious root diameter and adventitious root number per stem were measured at the fifth, sixth and seventh phytomers on the main stem, and the averaged values were shown. ‡ Length of leaf blade of ninth leaf on the main stem. § Number of leaves on the main stem as an indicator of plant age.

Table 2. Correlation coefficients among plant characteristics for six cultivars grown in upland fields.

|                  | Root diameter† | Root number per phytomer† | Stem diameter† | Stem number per plant | Leaf blade length | Leaf number   |
|------------------|---------------|---------------------------|----------------|-----------------------|------------------|--------------|
| Root diameter     | 1.000         | -0.910*                   | 0.728          | -0.304                | 0.573            | -0.610       |
| Root number per phytomer | 1.000       | -0.518                    | 0.272          | -0.498                | 0.604            |
| Stem diameter     | 1.000         | -0.587                    | 0.913*         | -0.789                | 0.899*           |
| Stem number per plant | 1.000     | -0.632                    | 0.899*         | -0.848*               |                  |
| Leaf blade length | 1.000         |                           |                |                       | -0.848*          |
| Leaf number       | 1.000         |                           |                |                       |                  |

† Stem diameter, adventitious root diameter and adventitious root number per stem were measured at the fifth, sixth and seventh phytomers on the main stem, and the averaged values were shown. * indicates significance at 0.05 level.
Acknowledgments

We thank Mr. Noboru Washizu, Mr. Ken-ichiro Ichikawa, Ms Shizue Chikazawa, Mr. Hiroshi Kimura and Mr. Ryuichi Soga (Field Production Science Center, The University of Tokyo, Japan) for their technical assistance in carrying out the experiment.

References

Abe, J. and Morita, S. 1994. Plant Soil. 165 : 333-337.
Araki, H. et al. 2002. Plant Prod. Sci. 5 : 286-293.
Fujii, Y. 1961. Bull. Fac. Agric. Saga Univ. 12 : 1-117**.
Harada, J. and Yamazaki, K. 1993. In T. Matsuo and K. Hoshikawa eds., Science of the rice plant Volume 1. Morphology. Food and Agriculture Policy Research Center, Tokyo. 133-186.
Hirasawa, H. et al. 1998. Breed. Sci. 48 : 415-419**.
Kato, Y. et al. 2006a. Plant Prod. Sci. 9 : 422-434.

Kato, Y. et al. 2006b. Plant Prod. Sci. 9 : 435-445.
Kato, Y. et al. 2006c. Plant Soil 287 : 117-129.
Kato, Y. et al. 2007. Plant Prod. Sci. 10 : 3-13.
Kawata, S. et al. 1963. Proc. Crop Sci. Soc. Jpn. 32 : 163-180*.
Kondo, M. et al. 2003. Plant Soil 255 : 189-200.
McMaster, G.S. 2005. J. Agric. Sci. 143 : 1-14.
Miyamoto, N. et al. 2004. Theor. Appl. Genet. 109 : 700-706.
Nemoto, H. et al. 1998. Breed. Sci. 48 : 321-324.
Nemoto, K. and Yamazaki, K. 1986. Jpn. J. Crop Sci. 55 : 352-359*.

Nemoto, K. and Yamazaki, K. 1989. Jpn. J. Crop Sci. 58 : 440-441**.
Nemoto, K. et al. 1995. Crop Sci. 35 : 24-29.
Rickman, R.W. et al. 1995. Agron. J. 87 : 1182-1186.
Tivet, F. et al. 2001. Ann. Bot. 88 : 507-511.
Yoshida, S. et al. 1982. Soil Sci. Plant Nutr. 28 : 473-482.

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