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Genotypic Variation of the Ability of Root to Penetrate Hard Soil Layers among Japanese Wheat Cultivars

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Abstract : The hard soil in the field is a major constraint for the cereal production because it mechanically restricts the root expansion and water absorption. The ability of root to penetrate into the hard soil is an important factor affecting yield stability of wheat (*Triticum aestivum* L.) under hard soil and drought conditions. We investigated the variation in the penetrating ability of roots (PA) among Japanese wheat cultivars and its relationship with other shoot and root characters to acquire basic information to develop the cultivars with a higher PA. The evaluation was conducted by the two experiments using the two groups of cultivars: 1) 43 Hokkaido cultivars in the first experiment, 2) 38 Honsyu, including Shikoku and Kyusyu, cultivars in the second experiment. In each experiment, one seedling of each cultivar was grown in a pot with a disc made of paraffin and Vaseline mixture (PV) as a substitute for the hard soil layer. The number of roots penetrating through the PV disc per plant (NRP), the number of seminal and crown roots reached the PV disc per plant (NRR) and the penetration index (PI = NRP/NRR) of each cultivar were evaluated as the traits related to PA. NRP significantly varied with the cultivar from 4.0 to 29.7 and 3.0 to 22.0 in the first and second experiments, respectively. NRP were significantly correlated with NRR (r=0.644** in the first and r=0.477** in the second experiment) and PI (r=0.863** in the first and r=0.811** in the second experiment), but the relationships between NRR and PI were not significant (r=0.260 in the first and r=0.190 in the second experiment). NRR was significantly correlated with the degree of winter growth habit (requirement of vernalization), root dry weight (DW) above the PV disc, the number of stems and leaf DW in each population. Correlations between PI and other characters were low or not significant. These results indicate that a large genotypic variation exists among Japanese wheat cultivars in NRP, and that PI is a suitable indicator of PA. Cultivars with a high PA detected in this study will be useful genetic resources of wheat to improve the yield stability under drought and hard soil conditions.

Key words : Breeding materials, Genetic variation, Hard soil, Penetrating ability of root, Screening, Soil compaction, *Triticum aestivum* L., Wheat.

The root system plays an important role in resisting water stress. Although water acquisition from deep soil is advantageous for crops to avoid drought (Loomis and Connor, 1992), root elongation into deep soil is sometimes prevented mechanically by the hard soil layer (Unger and Kaspar, 1994). Suppression of root penetration into deep soil results in reduced productivity in wheat (Kirkegaard et al., 1992; Oussible et al., 1992; Gemtos et al., 1999, 2000; Ishaq et al., 2001). Also in Hokkaido district, Japan, wheat yields are reduced because of shallow root systems due to hard soil layers, especially in years with low precipitation (Itoh et al., 2001; Sato et al., 2004). For a stable wheat production on hard soil regions, genetic improvement of the ability of roots to penetrate into hard soil layers is important (Zubaidi et al., 1999; Kubo et al., 2004).

In a previous study (Kubo et al., 2004), we found a large genotypic difference in soil-penetrating ability of root (PA) in durum wheat (*Triticum turgidum* L. var. *durum*) using a pot installed with a disc made of a mixture of paraffin and Vaseline as a substitute for hard soil layer. Ethiopian landraces adapted to hard soil have a markedly higher PA than cultivars bred in the International Maize and Wheat Improvement Center (CIMMYT) in Mexico for a high-yielding potential under suitable conditions.

As represented by Norin 10 that has contributed to the breeding of modern cultivars worldwide, Japanese wheat cultivars are expected to have large genotypic

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Abbreviations : CIMMYT, international maize and wheat improvement center; DW, dry weight; PV disc, a disc made of paraffin and vaseline mixture; NRP, the number of roots penetrating through the PV disc per plant; NRR, the number of seminal and crown roots reaching the PV disc per plant; PA, penetrating ability; PI, penetration index.

variations in shoot and root characters. In fact, it is reported that a large variation in the growth angle of root exists among Japanese wheat cultivars (Oyanagi et al., 1991). In this study, we investigated the PA of 81 old and new cultivars selected from different districts of Japan to acquire basic information on the diversity and distribution pattern of PA throughout Japan. The relationships between root traits related to PA and the other physio-morphological characters were also analyzed.

Materials and Methods

The soil-penetrating ability of roots (PA) of 81 cultivars was examined in two experiments, at different times because of labor shortage. The first experiment with Hokkaido cultivars was conducted from May 19 to July 14, 2003, in a polyhouse at the Field Science Center for the Northern Biosphere, Hokkaido University (Sapporo, Japan, 43°N, 141°E). The second experiment with Honsyu cultivars was conducted from October 7 to December 2, 2003, in a greenhouse adjacent to the polyhouse. In the first experiment with Hokkaido cultivars, 27 winter wheat and 16 spring wheat cultivars bred in Hokkaido district were used (Table 1). In the second experiment with Honsyu cultivars, 27 cultivars bred in Tohoku, Kanto, Chubu and Chugoku districts, and 11 cultivars bred in Kyusyu district were used (Table 2). In each experiment, two Ethiopian landraces with high PA (ET-31 A-1-113 and ET-47 B-3-115), two CIMMYT cultivars with low PA (Plover 'S' and Bittern 'S') identified in the previous study (Kubo et al., 2004), and Norin 61, the Japanese leading cultivar, were investigated in both experiments as check cultivars.

The pot used to evaluate PA consisted of a 10 cm-tall polyvinylchloride cylinder and 5 cm-tall cylinder, with a disc (0.3 cm thick, 6 cm diameter) made of a mixture (w/w) of 40% paraffin and 60% Vaseline (PV) fixed between them (Fig. 1). The PV disc was used as a substitute for the hard soil layer. The cylinders (pots) were filled with non-compacted vermiculite, and placed on a tray (135L×55W×15H cm), being covered with a silver sheet made of polyethylene, to stabilize the temperature. Three seeds were sown 1 cm deep in a pot, and the seedlings were thinned to one plant per pot at 10 days after sowing. The vermiculite below the PV disc in the pot was kept saturated with water by keeping the water level in the trays 1 cm deep during the experiment. The water content of the vermiculite above the PV disc in each pot was measured by using an FDR soil moisture meter (DIK-311A, Daiki Rica Kogyo Co., Ltd., Tokyo, Japan), and was adjusted to 50% in volume by irrigation. The experimental design was a randomized complete block design with three replications in the first experiment with Hokkaido cultivars, and a completely randomized design with two replications in the second experiment with Honsyu cultivars.

Because the hardness of the PV disc varies with the temperature, the hardness was estimated by using a regression formula of the relationship between the temperature and the hardness of the PV mixtures,

$$Y = -0.360\mathrm{Log}_e(X) + 1.533,$$

where, Y (MPa) is the hardness of the PV disc, and X (°C) is the temperature of the PV disc (Kubo et al., 2004). This formula was obtained by measuring the hardness with Yamanaka's hardness tester at five temperature levels (3, 8, 20, 30 and 40°C). The temperature of the PV disc was measured with thermocouples (copper-constantan, 0.6 mm diameter) inserted into the PV disc in three pots in each experiment, and was recorded with a data collector (DC100, Yokogawa Ltd., Tokyo, Japan) every 30 minutes during the whole experimental period.

At eight weeks after sowing, the shoot length, the numbers of stems and leaves on the main stem were recorded. Aboveground parts were divided into leaf and shoot to measure their dry weight (DW). After washing away the vermiculite from the roots, the number of roots penetrating through the PV disc per plant (NRP) and the number of seminal and crown roots reaching the PV disc per plant (NRR) were counted. The penetration index (PI) was calculated as the proportion of NRP to NRR (Yu et al., 1995). The DW of the roots above the PV disc was measured after oven-drying at 80°C for 48 hrs. The degree of winter-growth habit (vernalization requirement) defined by Kakizaki and Suzuki (1937), released year and pedigree information of the cultivars were obtained from breeding data of each cultivar and the database of Hon and Faberova (2002). Statistical analyses were done by using the software SPSS (Ver.7.5.1J, SPSS Japan, Tokyo, Japan).

Results and Discussion

1. Experimental conditions

The mean day length during the first and second experiments was 15.2 and 10.2 hrs, respectively (National Astronomical Observatory, 2002). The mean daily solar radiation was 20.1 and 7.5 MJ/m^2/day in the first and the second experiments, respectively (Japan Meteorological Agency, 2005). The mean temperature in the experimental site was 20.0°C in the first experiment and 18.7°C in the second experiment. The temperature of the PV disc was 7.1-24.7°C and 16.8-25.7°C in the first and second experiments, respectively, and the hardness of the PV disc was 0.38-0.83 MPa and 0.43-0.58 MPa, respectively (Fig. 2). The average hardness of the PV disc during the experiments showed little difference (0.46 MPa and 0.48 MPa in the first and second experiments, respectively), and were within the 0.43-0.50 MPa in our previous experiments, in which PA of durum wheat genotypes was examined (Kubo et al., 2004, 2005).

Table 1. NRP, NRR and PI in the first experiment with Hokkaido cultivars.

Name of cultivar	Growth Habit[1)]	Rereased Year[2)]	NRP[3)]	NRR[4)]	PI[5)]	Name of cultivar	Growth Habit	Rereased Year	NRP	NRR	PI
Kitami 18	W	–	29.7	24.3	1.22	Kairyoudatewase	W	–	8.3	18.7	0.44
Et-31 A-1-113[6)]	S	–	21.6	19.6	1.14	Bittern 'S'[8)]	S	1987	8.3	14.7	0.57
Norin 62	W	1943	18.7	22.7	0.79	Kitakei 8	W	–	8.0	20.7	0.38
Norin 61	S	1943	17.7	21.0	0.91	Kitami 19	W	–	8.0	19.3	0.45
Norin 8	W	1933	17.7	30.0	0.57	Plover 'S'[9)]	S	1978	8.0	19.0	0.42
Et-47 B-3-115[7)]	S	–	17.7	19.7	0.90	Haruhikari	S	1965	7.7	12.7	0.61
Taisetsukomugi	W	1974	16.7	26.3	0.64	Hokuiku 1	S	–	7.7	17.7	0.47
Ounakayama	W	–	16.3	23.3	0.73	Horoshirikomugi	W	1974	7.7	29.0	0.28
Kachiminori	W	1962	15.3	32.3	0.50	Kitami 17	W	–	7.7	19.7	0.40
Hokkai 178	S	1942	15.3	21.0	0.69	Kitami 22	W	–	7.7	26.0	0.32
Kitami 51	W	–	15.0	28.0	0.55	Haruyutaka	S	1985	7.0	13.7	0.47
Kitakeiharu 533	S	–	13.0	17.7	0.77	Norin 75	S	1948	6.7	15.7	0.43
Chihokukomugi	W	1981	12.3	23.3	0.57	Akasabishirazu 1	W	1927	6.3	17.7	0.36
Norin 3	W	1930	12.3	20.7	0.68	Kitamiharukomugi	S	1958	5.7	16.7	0.34
Hokuei	W	1954	11.3	18.0	0.64	Kitami 16	W	–	5.7	20.0	0.29
Hokushin	W	1995	11.3	22.7	0.58	Sapporoharukomugi	S	–	5.3	16.7	0.33
Hokkai 6	S	–	10.7	17.7	0.61	Kitamiharu 30	S	–	4.7	14.0	0.36
Takunekomugi	W	1974	10.7	20.3	0.53	Mukakomugi	W	1968	4.7	16.7	0.28
Kitakei 1354	W	–	10.7	21.0	0.53	Norin 29	S	1938	4.3	9.7	0.48
Kitami 35	W	–	10.7	20.7	0.51	Harunoakebono	S	1994	4.3	12.0	0.33
Martin 8	W	1919	9.0	17.0	0.56	Norin 35	S	1938	4.0	13.3	0.30
Kitamiharu 31	S	–	8.7	15.3	0.54	Haruhinode	S	2001	4.0	13.0	0.28
Akagawaaka 1	W	–	8.7	19.7	0.45	Kitamiharu 34	S	–	4.0	15.7	0.23
Dawson 1	W	1923	8.7	19.3	0.45	ANOVA			**[10)]	**	*
Hokkai 240	W	–	8.7	23.0	0.38	LSD[11)] (P<0.05)			8.1	9.9	0.39

1) Degree of winter growth habit (vernalization requirement) difined by Kakizaki and Suzuki (1937) was 6-7 in winter wheat cultivars (W) and 1-2 in spring wheat cultivars (S).
2) –; Not released.
3) Number of roots penetrating through the PV disc per plant (cultivars in the table are listed in order of NRP).
4) Number of seminal and crown root reaching PV disc per plant.
5) NRP/NRR.
6),7) Ethiopian landraces.
8),9) CIMMYT cultivars.
10) ** and * show significant levels at P<0.01 and 0.01 ≦ P<0.05, respectively.
11) Least significant difference.

Table 2. NRP, NRR and PI in the second experiment with Honsyu cultivars.

Name of cultivars	Region	Growth habit[1)]	Released year[2)]	NRP[3)]	NRR[4)]	PI[5)]	Name of cultivars	Region	Growth habit	Released year	NRP	NRR	PI
Fukuhokomugi	Kanto	2	1979	22.0	21.0	1.20	Shiroganekomugi	Kyusyu	2	1974	6.5	13.0	0.50
Norin 27	Tohoku	4	1937	17.0	23.5	0.75	Toyohokomugi	Kanto	2-3	1975	6.5	13.0	0.52
Ayahikari	Kanto	2	1999	15.5	17.5	0.89	Asakazekomugi	Kyusyu	2	1979	6.0	13.5	0.45
Haruibuki	Tohoku	5	2001	14.5	15.5	0.94	Shiranekomugi	Chubu	4	1986	6.0	15.0	0.40
Syunyo	Chubu	4	1995	14.0	20.0	0.70	Bittern 'S'[8)]		1?	1987	6.0	12.5	0.49
Et-31 A-1-113[6)]		1?	–	13.5	25.0	0.55	Nishikazekomugi	Kyusyu	2	1984	5.5	11.0	0.50
Kinuhime	Chubu	4	1999	12.5	17.5	0.70	Abukumawase	Kyusyu	2	1992	5.0	9.5	0.53
Nishihonami	Kyusyu	2	1995	11.5	16.0	0.72	Akitakko	Tohoku	5	1992	5.0	28.5	0.19
Norin 61	Kyusyu	2	1943	11.0	16.0	0.69	Fujimikomugi	Kanto	1	1960	5.0	10.0	0.49
Kitakamikomugi	Tohoku	4-5	1959	10.5	14.5	0.72	Aobakomugi	Tohoku	4	1951	4.5	12.0	0.38
Daichinominori	Kyusyu	2	1989	10.0	12.0	0.82	Chugoku 143	Chugoku	1	2002	4.5	9.5	0.48
Tsurupikari	Kanto	2	1992	10.0	18.5	0.56	Nanbukomugi	Tohoku	4	1951	4.5	15.5	0.29
Et-47 B-3-115[7)]		1?	–	10.0	22.0	0.46	Airakomugi	Kanto	3	1988	3.5	14.0	0.24
Yumeseiki	Chubu	4	2001	9.5	14.0	0.71	Daburu 8	Kanto	1	1999	3.5	6.5	0.54
Nebarigoshi	Tohoku	5	2000	9.0	16.0	0.60	Fukusayaka	Chugoku	2	2002	3.5	15.0	0.36
Yukichikara	Tohoku	5	2003	9.0	16.0	0.57	Nishinokaori	Kyusyu	2	1999	3.5	10.0	0.35
Bandowase	Kanto	1	1990	8.5	16.0	0.53	Setokomugi	Kyusyu	1-2	1975	3.5	11.5	0.31
Chikugoizumi	Kyusyu	2	1993	8.5	11.0	0.78	Plover 'S'[9)]		1?	1978	3.5	12.0	0.28
Iwainodaichi	Kyusyu	4	1999	8.0	14.5	0.55	Kinuiroha	Kyusyu	2	1993	3.0	11.0	0.27
Kinunonami	Kanto	2	1996	8.0	16.5	0.52	Shirasagikomugi	Chugoku	2-3	1956	3.0	12.0	0.25
Kinuazuma	Kanto	2	2000	7.5	12.0	0.64							
Koyukikomugi	Tohoku	5	1988	6.5	18.0	0.36	ANOVA				**[10)]	**	**
Mikunikomugi	Kanto	4	1962	6.5	11.0	0.59	LSD[11)] ($P<0.05$)				3.6	7.7	0.44

1) Degree of winter-growth habit.
2)-11) As shown in Table 1.

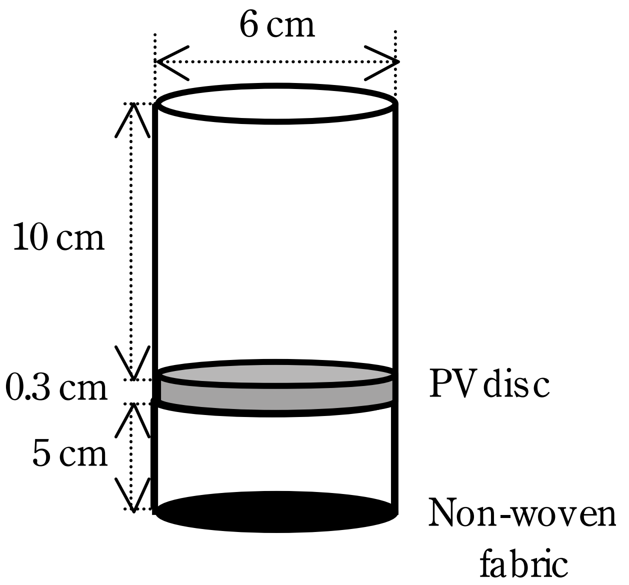

Fig. 1. Diagram of the pot used in the experiments.
Each pot was made of polyvinylchloride cylinders, and had inside a PV disc (mixture of 40% paraffin and 60% Vaseline in weight).

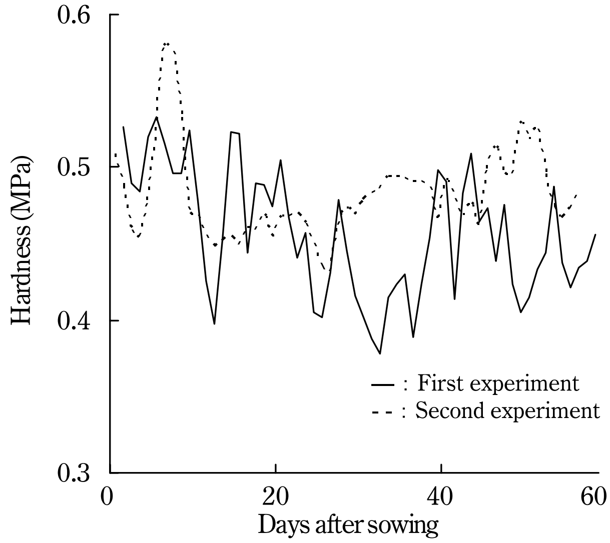

Fig. 2. Changes in hardness of PV disc during the experiments.
Hardness was estimated from the equation of Kubo et al. (2004) using the daily average temperature of the PV disc measured every 30 min during the experiment in the pot.

Table 3. Differences in plant characters between winter and spring wheat cultivars in the first experiment.

	Winter Wheat	Spring Wheat	Significance[1)]
NRP (plant^{-1})[2)]	11.3 ± 1.0[3)]	7.4 ± 0.9	**
NRR (plant^{-1})[4)]	22.0 ± 0.8	15.5 ± 0.7	**
PI[5)]	0.53 ± 0.04	0.46 ± 0.04	ns
Stem number (plant^{-1})	5.0 ± 0.2	3.0 ± 0.1	**
Leaf number on main stem (plant^{-1})	7.7 ± 0.1	6.6 ± 0.2	**
Plant height (cm)	34.2 ± 0.9	69.2 ± 2.3	**
Leaf DW (mg plant^{-1})	623 ± 28	239 ± 17	**
Stem DW (mg plant^{-1})	488 ± 21	1083 ± 71	**
Root DW above PV disc (mg plant^{-1})	577 ± 14	248 ± 12	**

1) Significance of the difference between winter and spring wheat cultivars according to a t-test.
2) Number of roots penetrating through the PV disc per plant.
3) mean±standard error (winter cultivars; n=25, spring cultivars; n=19).
4) Number of seminal and crown root reaching PV disc per plant.
5) NRP/NRR.

The maximum PA in bread wheat, measured in a pot with artificially compacted soil cakes, was 0.30-0.40 MPa (Tanakamaru et al., 1998). It was considered that the hardness of the PV disc in these experiments was suitable for screening the PA of wheat.

In both experiments, although the vermiculite below the PV disc was water-saturated throughout the experiments, water injury of the roots was not observed, i.e., the roots below the PV disc had healthy colour and lateral roots. In addition, there is a report that the rank of PA in wheat cultivars did not vary with the water condition in the pot (Uchino et al., 2003). From these results, it was considered that the water conditions of the vermiculite below the PV disc did not affect the rank of cultivars in PA.

2. Number of roots penetrating through PV disc (NRP)

The mean NRPs of the check cultivars, two Ethiopian landraces, two CIMMYT cultivars and Norin 61, were 19.7, 8.2 and 17.7, respectively, in the first experiment (Table 1), and 11.8, 4.8

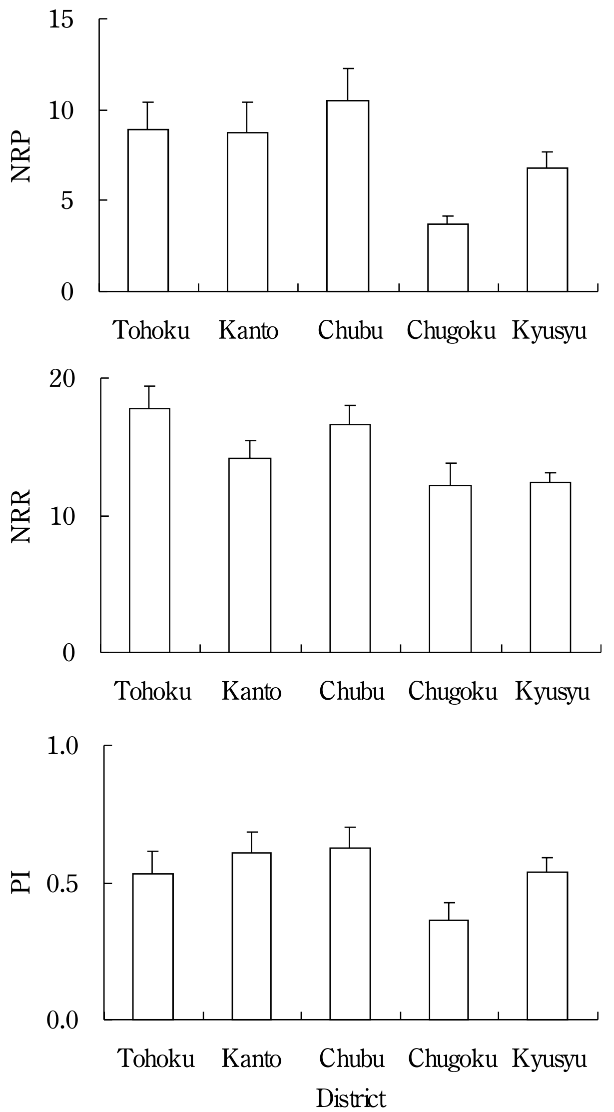

Fig. 3. Comparison of NRP, NRR and PI among breeding districts in the second experiment.
Bars in the figures show standard errors (Tohoku cultivars; n=9, Kanto cultivars; n=11, Chubu cultivars; n=4, Chugoku cultivars; n=3, Kyusyu cultivars including Norin 61; n=12).

and 11.0, respectively, in the second experiment (Table 2). Although the NRP of the check cultivars differed between the two experiments, it might be due to differences in climatic conditions during the experiment; the day length was shorter and solar radiation was lower in the second experiment than in the first experiment.

The NRP varied with the cultivar from 4.0 to 29.7 in the first experiment with Hokkaido cultivars (Table 1) and from 3.0 to 22.0 in the second experiment with Honsyu cultivars (Table 2). In each experiment, the NRP varied significantly with the cultivar, and some cultivars had a higher NRP than Ethiopian landraces and a lower NRP than CIMMYT cultivars. In both experiments, Norin 61 had a NRP as high as that in the Ethiopian landraces. There was no difference in NRP between old and new cultivars in both experiments. In the first experiment with Hokkaido cultivars, the NRP of winter wheat cultivars was higher than that of the spring wheat cultivars (Table 3). In the second experiment with Honsyu cultivars, the average NRP tended to be higher in the cultivars from Tohoku, Kanto and Chubu districts and lower in the Chugoku district (Fig. 3). These results suggest that the NRP greatly varies among cultivars and districts in Japan. The lower NRP in Hokkaido cultivars than in Ethiopian landraces and Norin 61 may be one of the reasons why wheat production in Hokkaido district is greatly affected by the hard soil layer.

3. NRR and PI (penetration index)

NRR was 9.7 to 32.3 in the first experiment with Hokkaido cultivars (Table 1) and 6.5 to 28.5 in the second experiment with Honsyu cultivars (Table 2). The penetration index (PI) was 0.23 to 1.22 in the first experiment and 0.19 to 1.20 in the second experiment. NRR and PI did not differ between old and new cultivars. In the first experiment, NRR was about 1.4 times higher in winter wheat cultivars than in spring wheat cultivars on the average, but the PI differed little between the two groups (Table 3). In the second experiment, NRR tended to be higher in cultivars of Tohoku, Kanto and Chubu districts than in Chugoku and Kyusyu districts (Fig. 3). The PI tended to be higher for cultivars of Kanto and Chubu districts than for Chugoku district. The results indicate that Japanese wheat cultivars have a large variation in both NRR and PI.

NRP had significant positive correlations with NRR and PI in both experiments, but the correlations between NRR and PI were not significant (Fig. 4). This result agrees well with our previous study using recombinant inbred lines of durum wheat (Kubo et al., 2005). These results suggest that although both NRR and the PI contribute to an increase in NRP in wheat, the two traits may be controlled by different genetic factors.

4. Correlations of NRP, NRR and PI with other physio-morphological characters

Table 4 shows the coefficients of correlation of NRP, NRR and PI with other characters in the first and second experiments. NRR was significantly correlated with the degree of winter-growth habit, number of stems, leaf DW and root DW above the PV disc in the first and second experiments. The degree of winter-growth habit is related to the length of vegetative growth period in wheat (Limin and Fowler, 2002). Root size of wheat is controlled by major genes for vegetative growth duration and other minor genes (Monyo and Whittington, 1970). NRR has significant positive correlations with the number of stems and root DW in *Triticeae* species (Kara et al., 1999). These

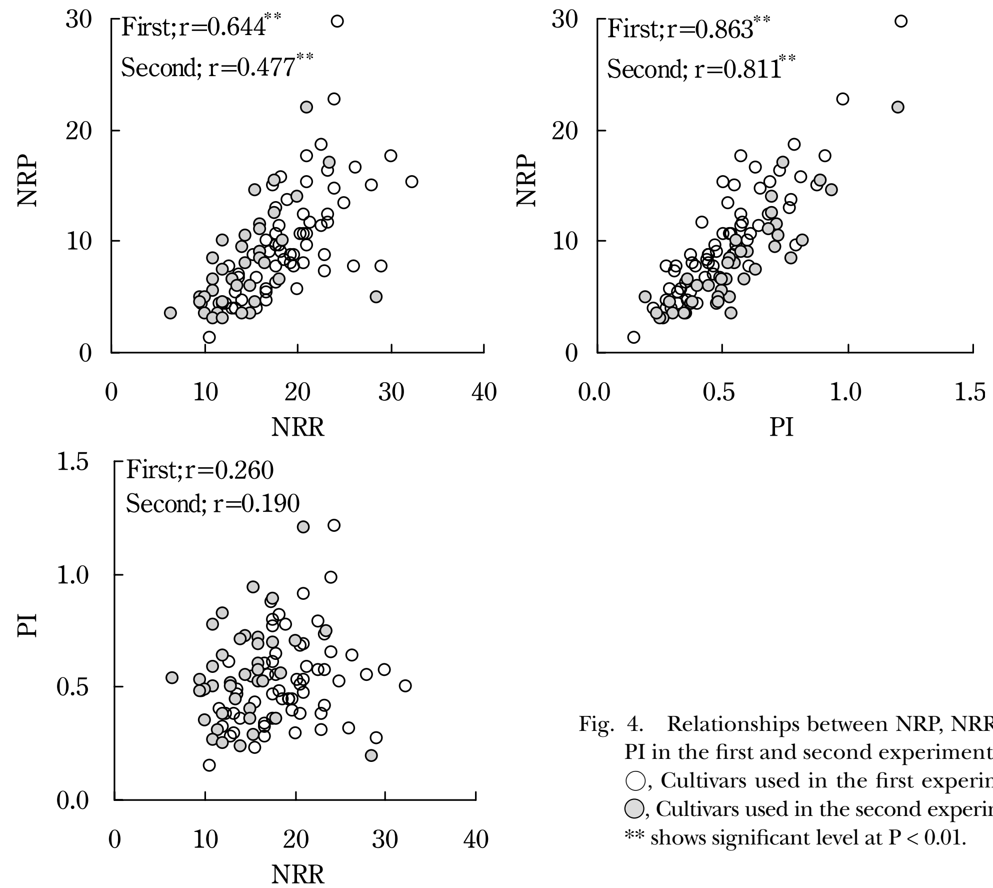

Fig. 4. Relationships between NRP, NRR and PI in the first and second experiments.
○, Cultivars used in the first experiment;
●, Cultivars used in the second experiment.
** shows significant level at P < 0.01.

Table 4. Simple correlation coefficients of NRP, NRR and PI with other physio-morphological characters in the first and second experiments.

	NRP[1]		NRR[2]		PI[3]	
	First exp.	Second exp.	First exp.	Second exp.	First exp.	Second exp.
Degree of winter-growth habit	−0.384 **[4]	0.109 ns	0.648 **	0.422 **	−0.163 ns	−0.066 ns
Number of stems	0.330 **	0.281 ns	0.692 **	0.716 **	0.093 ns	0.045 ns
Leaf number on main stem	0.465 **	−0.078 ns	0.557 **	−0.001 ns	0.322 *	−0.111 ns
Plant height	−0.347 **	0.061 ns	−0.620 **	−0.092 ns	−0.117 ns	0.160 ns
Leaf DW	0.625 **	0.422 **	0.850 **	0.867 **	0.342 *	0.145 ns
Stem DW	−0.182 ns	0.111 ns	−0.389 **	0.240 ns	−0.025 ns	0.103 ns
Root DW above PV disc	0.435 **	−0.253 ns	0.712 **	0.532 **	0.221 ns	0.048 ns

1) Number of roots penetrating through the PV disc per plant.
2) Number of seminal and crown root reaching PV disc per plant.
3) NRP/NRR.
4) ** and * show significant levels at $P < 0.01$ and $0.01 \leqq P<0.05$, respectively, and ns shows not significant.

results suggest that NRR is partly related to length of vegetative growth period and vigor of shoot growth, especially the ability to produce tillers. In the first experiment of the present study, leaf numbers on the main stem, plant height and shoot DW were also significantly correlated with NRR, which may be related to the growth habit of winter and spring cultivars (Fig. 5).

On the other hand, correlations of the PI with other morpho-physiological characters were low or not significant both in the first and second experiments (Table 4). Although the PI is a complex trait and the further analysis is needed to clarify the characters which are related to PI, it may be suitable indicator to improve PA without changing other physio-morphological characters.

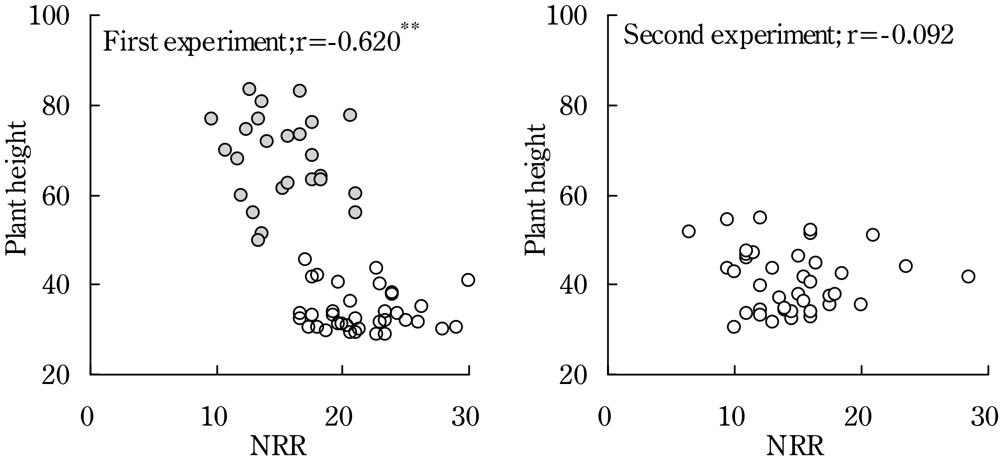

Fig. 5. Relationships between NRR and plant height in the first and second experiments. ○, winter cultivars; ◎, spring cultivars. ** shows significant level at P < 0.01.

The NRP significantly correlated with the degree of winter-growth habit, the number of stems, leaf number on the main stem, plant height, leaf DW and root DW above the PV disc in the first experiment, and with number of stems for the second experiment. However, these correlation coefficients with NRP were low compared with those with NRR. The results indicate that significant correlations of NRP with these characters are mainly due to close relationships between NRR and these characters.

5. Pedigree analysis for PI

Because the PI was independent of other physio-morphological characters, the relationship between pedigree of each cultivar and the PI was further analysed in details. The PI tended to be high in the cultivars that have Kanto 107 as their parent, whereas it was low in the cultivars that have Shirasagikomugi as their parent or grandparent in the second experiment (Fig. 6). Although we did not investigate the PA of Kanto 107, these results suggest that the genotypic difference in PI among Japanese wheat cultivars may be partly due to the difference in PI between breeding materials. The cultivars with high PI, such as Kitami 18 and Fukuhokomugi, may contribute to improve the penetrating ability of roots in wheat.

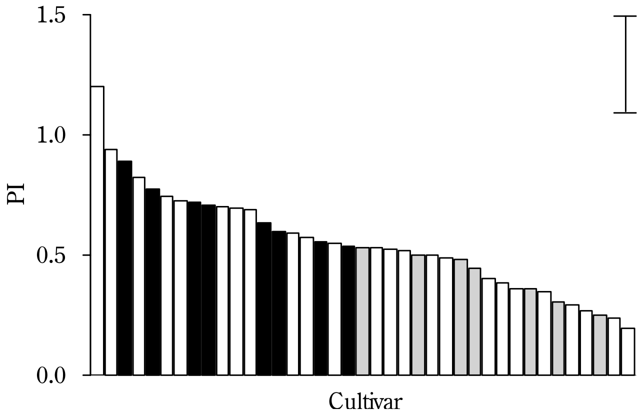

Fig. 6. PI for cultivars descended from Kanto 107 and Shirasagikomugi.
■, Cultivars that have Kanto 107 as a parent (Nebarigoshi, Yumeseiki, Ayahikari, Kinuazuma, Kinunonami, Tsurupikari, Chikugoizumi and Nishihonami); ▨, Cultivars that have Shirasagikomugi as a parent or grandparent (Shirasagikomugi, Fukusayaka, Chugoku 143, Abukumawase, Shiroganekomugi, Nishikazekomugi and Asakazekomugi); □, other cultivars (not including Ethiopian landraces and CIMMYT cultivars). The bar shows least significant difference among all cultivars (P<0.05).

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