Comparison of Root System Structures of 13 Species of Cereals*

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Some abilities of plants, for instance, to withstand adverse environments are closely related to the nature of their root systems. NAGAI and HIROTA¹⁴⁾ grouped the root systems of 280 varieties of rice plants into three types based on the color and diameter of roots. They found a close relationship between the root system types and plant growth and between the root system types and resistabilities against soil reduction. UEDA¹⁹⁾ observed that wheat of relatively great cold resistance had such a rooting habit that the roots penetrated rapidly into deeper soil layer in their early stages of growth. SANDERS and BROWN¹⁷⁾ attributed the difference of the yield of soybean varieties between indeterminate and determinate types to the differences in the distribution of their root systems, although the dry weight of root systems were almost the same.

The relationship between the distribution of

root systems or rooting pattern in the soil and the drought resistance of the plant species has been one of main interests of root ecologists and agronomists, and the relationship appears to be evident at least in certain environments^{13,16,18)}.

Therefore, adequate information on the structure, function and their responses to varied environments are one of the most important keys to control and improve crop production through deeper understanding of the growth of crop plants as a whole under different environments. Moreover, the demand of basic information on crop root systems is increasing recently also in the field of plant breeding for screening the varieties with some ecological characters^{13,15)}, but the information are too limited to meet the demand fully as of now.

To study the structure of plant root systems,

Table 1. Species used in this experiment.

Species	Varieties	Weight of seeds (g/1000 grains)
Paddy rice	<i>Oryza sativa</i> L.	Nipponbare 22.0
Upland rice	<i>Oryza sativa</i> L.	Norin No.11 22.8
Finger millet	<i>Eleusine coracana</i> (Gaerth.)	Gifu, local 2.2
Japanese barnyard millet	<i>Echinochloa utilis</i> Ohwi et Yabuno.	Okayama, local 2.7
Common millet	<i>Panicum miliaceum</i> L.	Saitama, local 4.2
Foxtail millet	<i>Setaria italica</i> Beauv.	Saitama, local 1.7
Pearl millet	<i>Pennisetum typhoideum</i> L.	Miyazaki, local 5.0
Sorghum	<i>Sorghum bicolor</i> Moench.	Saitama, local 15.1
Maize	<i>Zea mays</i> L.	Golden cross bantam 216.8
Job's tears	<i>Coix lacryma-jobi</i> L.	Kyoto, local 67.4
Barley	<i>Hordeum vulgare</i> L.	Nakatchadaka 23.5
Wheat	<i>Triticum aestivum</i> L.	Norin No.26 35.0
Oat	<i>Avena sativa</i> L.	Zenshin 33.4
Rye	<i>Secale cereale</i> L.	Haruichiban 28.0

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it is essential to compare them under controlled conditions. In our present study, the revised root box method¹²⁾ was adopted purposely, which enables us to sample the intact root system with minimum disturbance of root arrangement and minimum injury.

By the use of this method, we attempted to investigate and compare the fundamental structures and forms of root systems among 13 species of cereals, with special reference to the spatial arrangement of nodal and lateral roots, and their development.

Materials and Methods

Table 1 shows the species and varieties of crops used in this experiment, which are cereals grown in the world.

Air dried soil (*Kisogawa* sandy loam) was sieved in 2 mm mesh and mixed with compound synthetic fertilizer (N ; 14%, P₂O₅ ; 16%, K₂O ; 14%) at the rate of 0.2 g per 1 kg of the soil. Root boxes (40 cm × 25 cm × 2 cm) were filled with this soil by following the procedures reported elsewhere¹²⁾. They were soaked in water until the water content in the soil reached to its maximum holding capacity. This procedure served as the irrigation and had been done once a week during the experimental period.

After the soil in the root boxes were allowed to drain to the field capacity, two or three pregerminated seeds except for barley, wheat, rye and oat were sown in each root box on June 20, 1980. After the establishment, seedlings were thinned to one plant per root box and allowed to grow in the growth cabinet, where the air temperature was controlled at 30°C during day time (for 12 h) and 24°C at night (for 12 h), with natural light conditions. The experiments were triplicated per crop (species). Thirty days after sowing, the plants with intact root systems were sampled by the revised root box method¹²⁾.

Barley, wheat, rye and oat were allowed to grow in green house. Their seeds were sown on November 12, 1980 and the plants were sampled by the same method on March 18, 1981.

The sampled plant was cut into shoot and root system. The root system was preserved in FAA (formalin•acetic acid•alcohol) for further observation after taking its photograph. Numbers of leaves, tillers and nodal roots were counted and leaf blade area was measured by

an automatic leaf area meter. The seminal roots were taken from the root systems of upland rice, maize, rye, common millet and Job's tears and then spread on the nylon mesh so that no 1st order lateral root overlapped with each other. After taking photograph of each seminal root, the length of every 1st order lateral root on the seminal root axis was determined by an image analyzer (Photem IBAS 1, Karl Zeiss).

Results

1. Development of the whole root system

Figure 1 shows typical figure of root system of each crop plant. Figure 2 shows the illustration of nodal roots of upland rice, common millet, maize, rye and Job's tears. Comparing the development of whole root systems, maize, sorghum and four species of winter cereals showed well-developed root systems. However, not only above species but also pearl millet, finger millet and Japanese barnyard millet developed dense root systems even though their seeds were very small (Table 1). It is interesting to note that the development of root systems of these species seem to have nothing to do with their seed sizes.

2. Quantitative indication of the arrangement of nodal roots

In this paper, the seminal root is included in the category of nodal root where there is no specification stated. The angle between the downward extension of plant axis and each nodal root of the root system at the depth of 5 cm from the soil surface (rooting angle) was measured and shown in Fig. 3. Comparing the root systems based on the rooting angles, root systems of the 13 species could be grouped into four types as follows ;

The 1st group ; in this group, most of nodal roots grew vertically into soil profile and, therefore, their rooting angles were relatively small. Paddy rice, upland rice, finger millet and Japanese barnyard millet belonged to this group. More than 65% of nodal roots were below 30° in rooting angles and none of them was above 60° except for Japanese barnyard millet.

The 2nd group ; foxtail millet and common millet belonged to this group. Their seminal roots and some of nodal roots ran vertically into soil, while other nodal roots grew obliquely. The ratios of nodal roots whose rooting

Fig. 1. Root system profiles (Explanations are shown on page 622)

angles were above 20° were apparently higher (50% in foxtail millet and 67% in common millet) than those of the species in the 1st group.

The 3rd group; this group was consisted of pearl millet, sorghum, maize, barley, wheat, rye and oat, whose root systems developed vigorously. In these species, none or few nodal roots ran vertically but most of them ran obliquely in the soil. More than 50% of the nodal roots showed their angles of greater than 30° , and some of the species even showed

relatively high ratios of nodal roots with the rooting angles of above 60° , such as pearl millet (11%), sorghum (11%), rye (64%), barley (17%) and wheat (33%).

In Job's tears, more than 80% of nodal roots were below 30° in rooting angles. However, it can not be classified into the 1st group nor the other two groups because of a unique structure of its early root system among the species examined. The root system of Job's tears consisted of one seminal root and two seminal adventitious roots, which developed

Fig. 1. (continued)

obliquely in the opposite side to embryo in the seed, and nodal roots which ran to the opposite side of the seminal roots *i.e.*, the embryo side of the seed. Therefore, Job's tears was fallen in the 4th group.

3. Number of nodal roots

Table 2 summarizes the number of nodal roots determined in the present study. The data determined in the plant of maturity stage^{11,21)} are also shown in parentheses for comparison. It is obvious that the total number of nodal roots was greater in the species of

the 1st group (rice, finger millet and Japanese barnyard millet) than those of the other groups. This trend was clearer at maturity stage. However, it should be noted that this was partially attributed to relatively great number of tillers in the species of the 1st group.

In number of nodal roots per main stem at maturity stage, the species of the 1st group except for finger millet were greatest, followed by the species of the 2nd group (common millet and foxtail millet), the species of the 3rd

Fig. 1. Root system profiles of 13 species of cereals at 30 days (from paddy rice to Job's tears) and 126 days (from barley to rye) after sowing grown in the root boxes of which inner size were 25 cm in width, 40 cm in depth and 2 cm in thickness, and sampled by pinboard¹²⁾.

Note : 1) In the root systems of Japanese barnyard millet, pearl millet, sorghum and maize, which developed vigorously, bottom parts which were not caught by nails on the pinboard upon sampling tailed slightly.
2) U-PR, Paddy rice grown under upland conditions ; UR, Upland rice ; F, Finger millet ; JM, Japanese barnyard millet ; CM, Common millet ; FM, Foxtail millet ; PM, Pearl millet ; S, Sorghum ; M, Maize ; J, Job's tears ; B, Barley ; W, Wheat ; O, Oat ; R, Rye.

Fig. 2. Illustrations of nodal roots of upland rice (UR), common millet (CM), maize (M), rye (R), and Job's tears (J).

Table 2. Comparison of numbers of leaves, tillers and nodal roots among 13 species of cereals.

Species	Leaves	Tillers	No. of		
			Main stem	Tillers	Total
Paddy rice	7.8 (14.0)	2 (16.7)	17 (89.0)	9 (538.3)	28 (627.3)
Upland rice	8.1 (14.0)	4 (9.0)	20 (63.7)	15 (170.3)	35 (234.0)
Finger millet	14.5 (29.7)	2 (3.7)	17 (47.7)	11 (95.0)	28 (142.7)
Japanese barnyard millet	8.2 (19.0)	1 (2.3)	33 (83.3)	0 (97.7)	33 (181.0)
Common millet	7.8 (16.0)	0 (2.0)	15 (50.3)	0 (33.7)	25 (84.0)
Foxtail millet	7.5 (15.7)	0 (0.3)	15 (63.3)	0 (5.7)	26 (69.0)
Pearl millet	12.5 (17.0)	1 (4.0)	20 (43.7)	0 (22.3)	23 (66.0)
Sorghum	8.2 (14.0)	0 (0)	15 (39.3)	0 (0)	15 (39.3)
Maize	9.1 (15.0)	0 (0)	14 (30.7)	0 (0)	17 (30.7)
Job's tears	8.8 (15.0)	0 (3.3)	15 (24.3)	0 (12.7)	20 (37.0)
Barley	7.6 (11.0)	6 (6.7)	12 (-)	8 (-)	20 (65.6)
Wheat	6.8 (10.0)	5 (5.2)	16 (-)	9 (-)	27 (66.5)
Oat	6.8 (14.0)	3 (4.5)	- (-)	- (-)	- (81.4)
Rye	7.7 (13.0)	8 (8.8)	12 (-)	15 (-)	27 (88.7)

Note : Data cited from the studies of KONO et al.¹¹⁾ from paddy rice to Job's tears and YAMAUCHI et al.²¹⁾ for the rest, determined at their maturities by pot experiments are shown in the parenthesis of each species for comparison. Variety of each species used was the same with the present study except for foxtail millet (Gifu, local and barley (Nakatehadaka).)

group (pearl millet, sorghum and maize), and Job's tears (the 4th group).

4. The feature of development of lateral roots

The development of lateral roots also differed distinctively among the groups (Fig. 1).

Species in the 1st group bore nodal roots which mostly distributed just below their shoot bases with profusely branching fine and relatively short laterals of the 1st order. It was observed that the development of the 1st order lateral roots which branched the higher order laterals was poor. However, lateral root devel-

opment of finger millet and Japanese barnyard millet should be subject to more detailed study since they also produced some distinctively longer 1st order laterals in deeper soil layer. In contrast, the 3rd group species had well-developed 1st order lateral roots that were relatively long, thick and branched the second and even higher order laterals more densely than those in the 1st group species. Many of the 1st order lateral roots ran horizontally, some of which reached from one side to the other side (25 cm apart) of the root box. The space just below the shoot base

Fig. 3. Comparison of rooting angles among 13 species of cereals. Rooting angles indicate the one between the downward extension from plant axis and each nodal root.

where nodal roots scarcely distributed were filled with these 1st order lateral roots with higher order ones.

5. Quantitative analysis of lateral root development on the seminal root

Fig. 4 shows the seminal root of upland rice (1st group), common millet (2nd group), maize (3rd group), rye (3rd group) and Job's tears (4th group). Number, length and density of the 1st order lateral roots on their seminal root axes are given in Table 3.

Several workers^{1,3,6)} recognized heterorhizy in lateral roots of rice plants. KONO et al.⁹⁾ found that there are two types of lateral roots, i.e., L-type and S-type, according to their length and diameter and inner histological structure. The L-type lateral roots branch higher order laterals on their axes, while the S-type ones do not. They correspond to thick and thin lateral roots reported by KAWATA and SHIBAYAMA⁶⁾, respectively. And the heterorhizy

was also recognized in other cereal species (unpublished). In the present determination, the 1st order laterals with and without higher order laterals were regarded as L-type and S-type, respectively. However, some of newly emerging L-type laterals which had not yet developed higher ones were possibly mistaken to be S-type, though most of L-type ones were clearly detected.

In all species examined, more than 91.5% was accounted for by laterals in total length. Sums of the numbers of laterals in upland rice and Job's tears were more than two times as large as those of the rest species. The percentages of the number of S-type laterals in the whole seminal root were highest in those two species (77.5%~67.7%), followed by common millet and maize, and smallest in rye (19.2%). Upland rice and Job's tears also showed higher lateral root densities than the rest species. In contrast, the difference in the densities of L-type laterals was small among

the species, except for Job's tears which showed apparently higher density than the others.

Mean length of laterals was largest in rye, followed by maize, common millet and Job's tears. Upland rice showed the smallest mean length of lateral roots. In L-type laterals, considerable variation in the mean length was found among the species, while in S-type laterals, the variation was small. Total length of the seminal root axis and laterals on it showed the similarity between maize, rye and Job's tears, and between upland rice and common millet, respectively. The large total length of maize and rye was mainly due to the large length of L-type laterals, while that of Job's tears was additionally attributed to S-type laterals whose contribution was remarkably greater than any other species. Composition of L- and S-type of laterals in the total length of seminal axis and lateral roots of

Fig. 4. Comparison of lateral root development on a seminal root axis. (Explanations are shown on page 626).

upland rice and Job's tears, and maize and rye, respectively, were similar to each other although that of common millet was different from them.

Comparing the mean length of single lateral root among the 5 species (Fig. 5), maize and rye had greater number of longer L-type lateral roots as compared with the others. In maize and rye, 54 and 50% of L-type laterals, respectively, were found in the range longer

than 100 mm. Especially around 10 laterals were longer than 200 mm in these species. In contrast, only 5 lateral roots in upland rice and Job's tears, and 9 in common millet were longer than 100 mm. However, no distinctive difference was found in the length of S-type laterals among the species.

Discussion

The root systems of cereals investigated in

Fig. 4. Comparison of lateral root development on a seminal root axis of upland rice (UR, 1st group), common millet (CM, 2nd group), maize (M, 3rd group), rye (R, 3rd group) and Job's tears (J, 4th group). The length of each bar is 10 cm.

the present study were grouped into 4 types based on their nodal root arrangement (Figs. 1, 2 and 3) and lateral root development (Figs. 1, 4 and 5, and Table 3).

Among the 4 types, especially the root systems of the species which belonged to the 1st group, paddy rice, upland rice, finger millet and Japanese barnyard millet and the root systems which belonged to the 3rd group, pearl millet, sorghum, maize, barley, wheat, rye and oat showed contrastive feature in their structures.

Each type of root system is to be characterized as follows; the root system of the 1st group species was the one with relatively many nodal roots, whose rooting angles were relatively small, *i.e.*, most of them distributed just below their shoot bases closely to each other, bearing relatively short, slender, fibrous, but numerous lateral roots. The root system of the 3rd group species was the one which consisted of relatively small number of nodal roots, most of which ran obliquely into soil profile and scarcely distributed just below the main stem.

(In some species like maize, those spaces were free from any nodal roots as often observed in pot experiments). Vigorously developed lateral roots which were relatively long, thick and well-branched often distributed densely in the spaces where nodal roots were absent or far apart from each other.

KOBAYASHI and SUZUKI⁸⁾ made a morphological comparison of root systems of early stage of Italian ryegrass, upland rice, rye and wheat. They also observed more vigorous lateral root development in root systems of rye and wheat than in those of Italian ryegrass and upland rice.

As for the 2nd group species, their root systems exhibited transitional forms between the 1st and the 3rd group, judging on the basis of nodal root arrangement (Figs. 1 and 3) and lateral root development (Table 3). It should be determined whether each species belongs to either 1st or 3rd group, or forms an independent group by the observation of root system in the later growth stage.

As for Job's tears, as shown in Figs. 1 and 2, the arrangement of nodal roots was unique among the species examined. However, its feature of lateral root development on the seminal axis was similar to that of upland rice which belonged to the 1st group (Table 3 and Figs. 4 and 5).

In addition to their root figures and the difference in the feature of development of nodal and lateral roots, the manners of contribution of the two types of lateral roots (L and S) to the construction of the whole root system were also different between the root systems of the 1st and 3rd group species in the following two points. The first difference was found in the long, thick and vigorously branched L-type lateral roots in the root system of the 3rd group species. It was observed that they played more significant role by compensating for scarcely distributing area of nodal roots than in the root system of the 1st group species where L-type lateral roots were less developed (Fig. 1).

The second difference was that in the seminal root of upland rice (1st group), not only L-type but also S-type lateral roots were significant constituent. The same trend was also found in the seminal root of Job's tears (4th group). In these two species, almost one third of the total length of laterals on the

Table 3. Comparison of the numbers and length of laterals on a seminal root axis among upland rice (1st group), maize (3rd group), rye (3rd group), common millet (2nd group) and Job's tears (4th group).

Species	Root categories ¹⁾	Total number	Length		Density of laterals (No./cm seminal root axis)
			Mean $\pm$ S. D.	Total	
(mm)					
Upland rice	SR	1 (0.2) ²⁾		423 (6.0)	
	Laterals	635(99.8)	10.4 $\pm$ 16.4	6,604(94.0)	15.0
	L	142(22.3)	29.9 $\pm$ 25.8	4,246(60.4)	3.3
	S	493(77.5)	4.7 $\pm$ 3.7	2,317(33.0)	11.7
	Whole root system	636		7,027	
Maize	SR	1 (0.3)		716 (5.0)	
	Laterals	303(99.7)	45.9 $\pm$ 70.1	13,908(95.0)	4.2
	L	175(57.6)	74.0 $\pm$ 81.5	12,950(88.6)	2.4
	S	128(42.1)	7.6 $\pm$ 6.1	973 (6.4)	1.8
	Whole root system	304		14,624	
Rye	SR	1 (0.5)		494 (3.4)	
	Laterals	212(99.5)	66.3 $\pm$ 70.6	14,056(96.6)	4.3
	L	171(80.3)	80.7 $\pm$ 71.5	13,780(94.7)	3.5
	S	41(19.2)	6.6 $\pm$ 6.3	271 (1.9)	0.8
	Whole root system	213		14,550	
Common millet	SR	1 (0.3)		594 (8.5)	
	Laterals	316(99.7)	20.2 $\pm$ 27.1	6,383(91.5)	5.3
	L	148(46.7)	35.3 $\pm$ 32.9	5,224(74.9)	2.5
	S	168(53.0)	6.9 $\pm$ 7.0	1,159(16.6)	2.8
	Whole root system	317		6,977	
Job's tears	SR	1 (0.1)		558 (3.8)	
	Laterals	928(99.9)	15.3 $\pm$ 19.2	14,198(96.2)	16.6
	L	299(32.2)	30.6 $\pm$ 26.8	9,149(62.1)	5.4
	S	629(67.7)	8.0 $\pm$ 6.4	5,032(34.1)	11.3
	Whole root system	929		14,756	

Note : 1) SR ; seminal root axis. Laterals ; all 1st order lateral roots on a seminal root axis. L : the 1st order L-type lateral roots. S ; the 1st order S-type lateral roots. Whole root system ; a seminal root axis and all 1st order laterals on it.

2) ( ) ; percentage to the whole root system.

seminal axis was accounted for by S-type laterals. In common millet (2nd group), the contribution of S-type laterals was almost one sixth, while they were almost negligible in maize and rye (3rd group). However, their mean length were similar in all species (Table 3). As pointed out earlier, short laterals were observed to be dominant in the root systems of

the 1st group, while long laterals were dominant in those of the 3rd group. However, quantitative determination needs to be conducted on other species of respective group.

On the basis of these characteristics in the structure of the root systems, a proposal of designation is presented here, "concentrated" type for the root systems of crop species in the

Fig. 5. Comparison of numbers of the 1st order L-type and S type lateral roots on a seminal root axis among upland rice (1st group), maize (3rd group), rye (3rd group), common millet (2nd group) and Job's tears (4th group). Note: Numerals in the parentheses indicate the numbers of lateral roots which were longer than 200 mm in L type and 30 mm in S-type laterals.

1st group and "scattered" type for the ones in the 3rd group.

A correspondence was found between cereal species grouped on the basis of the structures of the root systems presently shown, and their waterlogging and drought tolerance capacities (WTC and DTC)^{10,21)}. The species which belonged to the 1st group, paddy rice, upland rice, finger millet and Japanese barnyard millet, with "concentrated" type root systems had relatively large WTC compared with their DTC, while species in the 3rd group, pearl millet, sorghum, maize, barley (naked), wheat, rye and oat whose root systems were "scattered" type showed larger DTC than WTC.

Although this correspondence is interesting, further study is needed on the root system structure in more mature stage as well as on the response of the root system structure to different soil moisture conditions in order to relate these two different characters.

It is possible that almost two-dimensional and limited spaces of the root box used in the present study brought some effects on the development and consequently the structure of the root systems studied. To interpret the present result, it is, therefore, significant to compare the data obtained presently with those obtained under field conditions where there is no limit in space for root development.

Under field conditions, it has been reported that most of nodal roots of maize grow obliquely into the soil and few roots vertically^{4,20,22)}. In rice plant, KAWATA and KATANO⁵⁾ observed that a seminal root and many of nodal roots emerging from lower nodes of main stem and from prophyll "shoot unit" (the lowest node) of tillers grew vertically and obliquely downward. These data is in good agreement with our data. This indicates that the direction of nodal root extension is scarcely affected by the existence of walls of the root box, at least in the case of maize and rice.

As for the number of nodal roots, the data of YAMAZAKI and NAKAMOTO²⁴⁾ is available for comparison. In their study, the same trend was observed with our study that the species of the 1st group such as rice and Japanese barnyard millet had more nodal roots per main stem than those of the other group such as foxtail millet, common millet, pearl millet and sorghum. The relatively small number of nodal roots in foxtail millet, which belonged to the 1st group in the present study was also shown in their study. However, the nodal root number of maize in the present study was rather small as compared with their data.

As for lateral root development, data on their length which are comparable with ours are scarcely available. On the other hand, data on the density of lateral roots of the 1st order in rice were obtained by KAWATA and SHIBAYAMA⁷⁾, and FUJII²⁾, which shows similar trend to the results shown in Table 3. The density in wheat also shows good agreement between ours and FUJII's²⁾. In contrast, the density of the 1st order laterals in maize on a

seminal axis (Table 3) was different from the results of other investigators. FUJII's data²⁾ was 1.8 times as great as our data and that by YAMAZAKI and KAERIYAMA²³⁾ was much greater.

The discordancy of data found in nodal root number and lateral root density of maize may suggest that some root parameters of large root system in size would be affected by the small size of rooting volume in the root box. Nevertheless, above results strongly support the possibility that in spite of the limited soil space in the root box, plants examined in the present experiment show the fundamentally same trend of root system structure with those grown under field conditions. We, therefore, considered that the differences in root system structure among the cereal species exhibited under our experimental conditions reflected their interspecific differences which should be demonstrated under optimum field conditions.

More intensive study to describe detailed and precise structure of root systems needs to be undertaken including other species of cereals. The comparison of data obtained by our revised root box method with those by field experiment, and the further examination on the degrees of modification in root system structure by the small size of root box, which seem to vary with plant species and root parameters, will be also important.

Summary

The structures of root systems of 13 species of cereals (Table 1) at 30 days (126 days in barley, wheat, rye and oat) after sowing were investigated by using the revised root box method¹²⁾. On the basis of the rooting angles of nodal roots and the degree of development of nodal and lateral roots in their root systems, they were divided into four groups as follows;

The 1st group. Most of nodal roots grew vertically into the soil profile. Crop species in this group bore more nodal roots than the others. The 1st order lateral roots were numerous, but relatively short, slender and poorly branched. Paddy rice, upland rice, finger millet and Japanese barnyard millet belonged to this group. *The 2nd group.* Some of nodal roots grew obliquely into the soil, while the others did vertically. Their root systems appeared to be transitional form between the 1st and 3rd group based on the nodal root

arrangement and lateral root development. Common millet and foxtail millet were the members. *The 3rd group.* Root systems in this group were well developed. Almost all nodal roots ran obliquely in the soil profile. Relatively small numbers of nodal roots compared to those of the 1st group crops had the 1st order lateral roots which were long, thick, and branched higher order laterals. This group consisted of pearl millet, sorghum, maize, barley, wheat, rye and oat. *The 4th group.* Job's tears did not belong to any of these groups, but formed a unique root system.

Based on these characteristics, a proposal of designation of the root systems was presented; "concentrated type of root system" for the root systems of the 1st group species and "scattered type of root system" for those of the species in the 3rd group. Furthermore, good correspondence between the cereals species grouped based on the types of their root systems, and the cereals grouped based on the waterlogging and drought tolerance capacities^{10,21)} was pointed out.

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References

1. DEHAAN, J. van B. 1911. De Rijstplant. I. Eene anatomische beschrijving der rijstplant. Government office of the Dutch East Indies. Bulletin of Department of Agriculture. No.15.
2. FUJII, Y. 1961. Studies on the regular growth of the roots in the rice plants and wheats. Agr. Bull. Saga Univ. **12**: 1—117*.
3. JULIANO, J.B. and M.J. ALDAMA. 1938. Morphology of *Oryza sativa* Linnaeus. The philippine Agriculturist. **25**: 1—76.
4. KAERIYAMA, N. and K. YAMAZAKI. 1983. The development of rooting zone in soil in relation to the growth direction and the elongation rate of the primary roots in corn plants. Japan. Jour. Crop Sci. **52**: 508—514*.
5. KAWATA, S. and M. KATANO. 1976. On the direction of the crown root growth of rice plants. Proc. Crop Sci. Soc. Japan. **45**: 471—483*.
6. ——— and H. SHIBAYAMA. 1965. On the lat-

- eral root primordia formation in the crown roots of rice plants. *Proc. Crop Sci. Soc. Japan.* **33** : 423—431*.
7. ——— and ———. 1966. Types of branching in lateral roots of rice plants. *Proc. Crop Sci. Soc. Japan.* **35** : 59—70*.
  8. KOBAYASHI, H. and N. SUZUKI. 1979. Studies on polysaccharide-exudates with the advance of forage root growth. I. Growth of root-system and polysaccharide-exudate on several crops. *J. Japan. Grassl. Sci.* **25** : 222—226*.
  9. KONO, Y., M. IGETA and N. YAMADA. 1972. Studies on the developmental physiology of the lateral roots in the rice seminal roots. *Proc. Crop Sci. Soc. Japan.* **41** : 192—204*.
  10. ———, A. YAMAUCHI, N. KAWAMURA, J. TATSUMI, T. NONOYAMA and N. INAGAKI. 1987. Interspecific differences of the capacities of water-logging and drought tolerances among summer cereals. *Japan. Jour. Crop Sci.* **56** : 115—129.
  11. ———, ———, T. NONOYAMA and J. TATSUMI. Comparison of growth responses to water-logging of summer cereals with reference to rooting ability. *Japan. Jour. Crop Sci.* (submitted).
  12. ———, ———, ———, ——— and N. KAWAMURA. A revised experimental system of root-soil interaction for laboratory work. *Environ. Control. in Biol.* (in press).
  13. MILLER, D.E. 1986. Root systems in relation to stress tolerance. *HortScience.* **24** : 963—970.
  14. NAGAI, T. and H. HIROTA. 1958. Cultivated rice varieties viewed from root characters. (I) Some ecological characters of rice plants continuously grown in nursery. (II) Root diameter, rooting and others. *Proc. Crop Sci. Soc. Japan* **27** : 217—220.
  15. O'TOOLE, J.C. and T.T. CHANG. 1979. Drought resistance in cereals - rice : a case study. In *Stress Physiology in Crop Plants* (Eds) H. Mussell and R.C. Staples, John Wiley & Sons, New York. 373—406.
  16. PASSIOURA, J.B. 1981. Water collection by roots. In *The Physiology and Biochemistry of Drought Resistance in Plants* (Eds) L.G. Paleg and D. Aspinall, Academic Press, Sydney. 39—53.
  17. SANDERS, J.L. and D.A. BROWN. 1978. A new fiber-optic technique for measuring root growth of soybean under field conditions. *Agron. J.* **70** : 1073—1076.
  18. TROUGHTON, A. and W.J. WHITTINGTON. 1969. The significance of genetic variation in root system. In *Root Growth* (Ed) W.J. Whittington, Butterworths, London. 296—313.
  19. UEDA, S. 1936. On the development of root system of wheat and barley in sandy soil. *Proc. Crop Sci. Soc. Japan.* **8** : 140—143**.
  20. WEAVER, J.E. 1926. *Root Development of Field Crops.* McGraw-Hill, New York. 180—191.
  21. YAMAUCHI, A., Y. KONO, J. TATSUMI and N. INAGAKI. Comparison of the capacities of water-logging and drought tolerances among winter cereals. *Japan. Jour. Crop Sci.* (in press).
  22. YAMAZAKI, K. and N. KAERIYAMA. 1982. The morphological character and the growing directions of primary roots of corn plants. *Japan Jour. Crop Sci.* **51** : 584—590*.
  23. ——— and ———. 1983. The diameter of primary roots and the lateral root formation in corn plants. *Japan. Jour. Crop Sci.* **52** : 59—64*.
  24. ——— and T. NAKAMOTO. 1983. Primary root formation in the growing shoots of several cereal crops. *Japan. Jour. Crop Sci.* **52** : 342—348*.

* In Japanese with English summary.

** In Japanese.

〔和 文 摘 要〕

イネ科作物の根系構造の比較

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改良根箱法を用いて、13種のイネ科作物について(第1表)、根系構造を比較した(第1図・第2図)、節根(種子根を含む、以下同じ)の走向角と(第3図)、側根の発達程度にもとづいて、それらの根系を次の4つのグループに大別した。第1グループ:節根の走向角は比較的小さく、その多くは土壌を縦走した。節根数は4つのグループの中で最も多い傾向があった。第1次側根は細く、短く、分枝に乏しかった。水稻、陸稻、シコクビエ、ヒエが含まれた。第2グループ:数本の節根は株直下へ縦走するが、他の多くの節根は、走向角が大きく土壌中を斜走した。アワ、キビが含まれた。第3グループ:節根の走向角は大きく、土壌中を斜走した。第1次側根は長く、太く、分枝が盛んであった。トウジンビエ、モロコシ、トウモロコシ、オオムギ、コムギ、ライムギ、エンバクが含まれた。第4グループ:節根が斜走し、それらの発達は偏在して進んだ。側根の発達は旺盛であった。ハトムギが含まれた。

これらの作物の根系構造上の特徴より、第1グループおよび第3グループに属する作物の根系をそれぞれ“集中型”、“分散型”と呼んだ。また、第2グループの根系はそれらの中間型、ハトムギの根系は独自の型を形成すると考えた。

この2つの型の根系間の重要な差異は、“集中型”では、節根が、比較的狭い土壌空間に高い密度で分布したのに対し、“分散型”では、節根は比較的広い土壌空間に疎に分布したことであった。また、種子根上の側根で比較した場合(第3表、第4図、第5図)、前者ではS型(短く、比較的根径が小さく、高次の側根を分枝しない)1次側根の発生数および単位種子根長当りの密度が高く、根系構成要素に占める割合が比較的高かった。それに対し、後者においてはS型1次側根は発生密度も低く、根系要素中に占める割合が極めて小さかったが、L型(長く、比較的根径が大きく、高次の側根を分枝する)1次側根の割合が高く、長さでみると根系のほとんどを占めていた。また、ハトムギの根系の側根発達の様相は、“集中型”根系のものに類似していた。

この根系によるイネ科作物の分類と、耐湿性・耐旱性程度による分類^{10,21)}とは比較的良好に一致した。