Jpn. J. Crop Sci. 65(1) : 131—140 (1996)

Root System Structure of Six Food Legume Species : Inter- and Intraspecific Variations

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Received June 16, 1995

Abstract : Root characteristics of 114 genotypes of six food legume species, i.e., chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), grasspea (*Lathyrus sativus* L.), lentil (*Lens culinaris* Medik.), black gram (*Vigna mungo* (L.) Hepper) and mung bean (*Vigna radiata* (L.) Wilczek) were studied to evaluate the inter- and intraspecific variations in root system structure. Eleven root and shoot characteristics of 10-day-old seedlings, raised in growth pouches in a growth chamber, were subjected to principal component analysis. The results indicated that the root system structure is determined mainly by taproot and lateral root lengths and lateral root density, in which the species varied significantly. Chickpea produced long individual lateral roots and cowpea produced a great number of lateral roots, which resulted in relatively large root system formation. Grasspea also developed relatively long lateral roots. In contrast, the formation of smaller-sized root system was due to a smaller number of lateral roots produced for lentil and shorter lateral roots for black gram and mung bean. Large genotypic variations in root characteristics were found within each species, particularly in cowpea and chickpea. The high-yielding, drought-tolerant or deep-rooting genotypes reported earlier tended to produce large root system. Significant correlations of root growth parameters between plants grown in growth pouches and soil indicated that the growth pouch technique can be a useful tool for screening of root characteristics.
Key words : *Cicer arietinum* L., *Lathyrus sativus* L., *Lens culinaris* Medik., Principal component analysis, Root, *Vigna mungo* (L.) Hepper, *Vigna radiata* (L.) Wilczek, *Vigna unguiculata* (L.) Walp.

6種食用マメ科作物の根系構造とその種間および種内変異 : Md. Wahiduzzaman MIA・山内　章・河野恭廣
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要　旨 : 6種のマメ科作物，すなわち，ヒヨコマメ (*Cicer arietinum* L.)，ササゲ (*Vigna unguiculata* (L.) Walp.)，ガラスマメ(*Lathyrus sativus* L.)，レンズマメ(*Lens culinaris* Medik.)，リョクトウ(*Vigna mungo* (L.) Hepper)，ケツルアズキ (*Vigna radiata* (L.) Wilczek)の，合計114品種・系統を対象に，根系構造における種間，種内変異を評価する目的で，グロースポーチ法によって10日間生育させた幼植物の根および地上部の計11形質を主成分分析法によって解析した．その結果，根系構造は基本的に主根・側根長および側根発生密度によって規定されることが明らかとなり，これらの形質において種間で有意な差異が認められた．ヒヨコマメは個々の側根が長いことによって，ササゲは側根の発生数が多いことによって，相対的に大きな根系を形成した．ガラスマメの側根長も比較的長かった．それに対し，レンズマメでは側根発生数が少なく，また，リョクトウとケツルアズキは側根が短く，それぞれ相対的に小さい根系を形成した．各種内における変異も認められ，とくにササゲとヒヨコマメで大きかった．また，これまで高収量性，強耐旱性，あるいは深根性と報告されてきた品種・系統は，各種内で相対的に大きな根系を形成した．さらに，各種より数品種・系統を選び，円筒を用い土壌中で28～44日間生育させた．これによって得た根系諸形質の値と，グロースポーチ法で得られた値との間には高い正の相関関係が認められ，グロースポーチ法は根系形質に注目した選抜によって有効である可能性が示された．
キーワード : ガラスマメ，ケツルアズキ，ササゲ，主成分分析，根，ヒヨコマメ，リョクトウ，レンズマメ．

In many parts of the world in general, and developing countries in particular, food legumes are very important as a source of protein. However, their productivity is usually low, largely because they are grown in stressful soil environments. For example, important food legume species, such as chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), grasspea (*Lathyrus sativus* L.), lentil (*Lens culinaris* Medik.), black gram (*Vigna mungo* (L.) Hepper) and mung bean (*Vigna radiata* (L.) Wilczek) are usually grown in marginal areas under rainfed conditions[3,9,10,23,24] and their yields are fairly low[20,21].

Crop performance under such stressful conditions is closely related to root system development. For example, drought tolerance of the food legume species is closely related to the distribution of root system, or rooting pattern in the soil[6,13,19], which is, in general, the consequence of root growth of plants in the early growth stage. In these aspects, knowledge of

interspecific difference in relevant root characteristics is required agronomically to select suitable crop species to be grown in a particular environment. Further, knowledge of genotypic variation within each species is also essential for agronomy as well as genetic improvement of crop species.

A crop root system consists of different types of component roots whose characteristics, such as length and number, determine the structure of root system[27]. However, in many cases, the root system structure in the field is so greatly affected by environmental conditions that identification of the root system structure of a particular species or genotype sometimes seems to be almost impossible. In spite of this fact, several attempts have been made, which found that rooting shape, size and root system structure vary greatly among the species[2,11,27]. In addition, based on the extensive review on various root research, O'Toole and Bland[12] concluded that genetic variation exists among different crop species.

Moreover, for widely-grown legume species such as soybean[8], black bean[25] and pea[1] genotypic differences in rooting characteristics have been reported. Such data for chickpea, cowpea, grasspea, lentil, black gram and mung bean are merely available[7,26], or absent. In addition, interspecific comparison among these species has not been attempted so far.

In this study, we used the seed-pack growth pouch technique, which allows us to handle a great number of root specimens in one experiment[2]. The objectives of our study were to 1) identify the root characteristics that determine the root system structure of the six food legume species, 2) evaluate their inter- and intraspecific differences and variations, and 3) examine the usefulness of the seed-pack growth pouch technique for the characterization of root system structure.

Materials and Methods

One-hundred and-fourteen genotypes of six food legume species were used for this study as shown in Table 1. The term genotype is used to cover cultivar, land race, line and strain in this paper. The genotypes were received from Bangladesh Agricultural Research Institute (BARI) and the International Center for Agricultural Research in the Dry Areas (ICARDA). Actually, they included a number of genotypes that BARI collected from several countries and research institutes (see Table 1 for details). Seeds used in this experiment were harvested at respective stations (i.e., BARI and ICARDA), either in 1990 or 1991 and kept in a cold storage.

Seedlings of each genotype were grown in 16 cm long × 15 cm wide seed-pack growth pouches (Vaughan's Seed Company, USA) as outlined by Brar et al.[2] in November, 1992. Each growth pouch contained an absorbent paper insert that was folded into a 'v'-shaped trough at the top. The absorbent paper was uniformly moist with 15 m*l* of 0.25 strength Hogland's solution[4] (pH 6.8) and suspended upright in a 26 cm × 20 cm × 16 cm box. The bottoms of the growth pouches were pierced to drain out the excess nutrient solution. Seeds were germinated in the dark at 20°C. One germinated seed per genotype was placed into the trough of absorbent paper and aligned with forceps so that the roots would properly elongate downward. Each genotype was grown in triplicates and each growth pouch was assigned randomly to different boxes. The boxes were covered in such a way that the roots would not be exposed to light and placed in a growth chamber (day temperature, 25°C; night temperature, 20°C; photoperiod, 12 hours). To keep the absorbent papers sufficiently moist, 5 m*l* of 0.25 strength Hogland's solution was added to each pouch on a daily basis.

Ten days after seed placement, all plants were sampled and data on leaf number and plant height were taken. The shoots were then dried at 80°C for 48 hours and weighed. The root systems were preserved in FAA (Formalin 1: Acetic acid 1: 70% Ethyl alcohol 18 by volume) solution for further analysis. From the sampled root system, the length of taproot was measured, and then the number and length of lateral roots on the taproot were determined. Then the root systems were dried at 80°C for 48 hours and weighed. For each genotype, the mean values of three replications of eight root and three shoot characteristics (Table 3) were calculated, which were then used to perform principal component (PC) analysis as suggested by Iezzoni and Pritts[5] to detect important characteristics responsible for determining the root system structures and their inter- and intraspecific differ-

Table 1. List of the genotypes of six food legume species used in this study.

A. Chickpea (*Cicer arietinum* L.)

1. A-121, 2. E-153*, 3. E-155, 4. E-193, 5. E-196, 6. E-199, 7. Faridpur local(B), 8. FLIP-87-59C(IC), 9. ICC-4958*(IC), 10. ICCL-4320*(ICR), 11. ICCL-11329(ICR), 12. ICCL-84215(ICR), 13. ICCL-85109(ICR), 14. ICCL-86102(ICR), 15. ICCL-89851(ICR), 16. ICCV-3274(ICR), 17. ILC-6104(IC), 18. Nabin*(ICR), 19. PAO 2990R(3601)(ICR), 20. PAO 2990R(3602) (ICR), 21. RBH-228a(B), 22. Sabur-4*(B).

B. Cowpea [*Vigna unguiculata*(L.) Walp.]

23. All Season(IR), 24. HAF-26, 25. HAF-43*(B), 26. IT82E-60(AU), 27. IT85F-2020(IT), 28. SSD-90*(AU), 29. SSD-284(AU), 30. SSD-625(AU), 31. SSD-693*(AU), 32. TV×1948-012 F(AU), 33. TV×289-4G*(IR), 34. TV×2939-09D(IR), 35. TV×4654-44E, 36. TV×4659-02E(AU), 37. V-51 (AU), 38. VITA-4(IR).

C. Grasspea (*Lathyrus sativus* L.)

39. 3968(B), 40. 8603*(B), 41. 8604(B), 42. 8605(B), 43. 8607(B), 44. 8608(B), 45. 8609(B), 46. 8610 (B), 47. 8612(B), 48. Charbadna*(B), 49. Jamalpur(B), 50. P-24, 51. RU-7*(B), 52. RU-15(B), 53. RU -21*(B), 54. RU-36(B), 55. RU-37(B), 56. RU-42(B), 57. RU-69(B), 58. RU-89(B).

D. Lentil (*Lens culinaris* Medik.)

59. 111-77, 60. 113-55, 61. B-77*, 62. BLL-81144, 63. BL-84142, 64. BLL-84143*, 65. BLL-84144, 66. BLL-84212, 67. BLL-84228, 68. BLL-84248*, 69. BLL-85017, 70. BLL-85049, 71. ILL-4400*(IC), 72. ILL-4401(IC), 73. ILL-5582*(IC), 74. ILL-5715(IC), 75. ILL-6004(IC), 76. ILL-6024(IC), 77. ILL-6035*(IC), 78. L-4076, 79. Utfala*(B).

E. Black gram [*Vigna mungo*(L.) Hepper]

80. 2055(B), 81. 2140, 82. 80194, 83. 86001, 84. 86047, 85. 9001, 86. 9005, 87. B-23*(B), 88. JES-4(B), 89. MAK-1(B), 90. MAK-2*(B), 91. MAK-3(B), 92. PANT-4-26(I), 93. RU-12(B), 94. RU-69(B), 95. RU-97(B), 96. RU-158*(B).

F. Mung bean [*Vigna radiata* (L) Wilczek]

97. A-88, 98. A-127, 99. B-1(B), 100. BM-7704, 101. BM-7706, 102. BM-7715*, 103. BM S84-1-62-1 (B), 104. BM S84-2-7-1*(B), 105. BM-880147, 106. Chittagong local*(B), 107. CUMB-13(B), 108. Faridpur local(B), 109. Kanti, 110. MK-19, 111. MK-72, 112. MK-73, 113. MOSK-1*, 114. PAGASA -2.

Note : All seeds were collected from Bangladesh Agricultural Research Institute (BARI) except those from International Center for Agricultural Research in the Dry Areas (ICARDA). Letter(s) within parenthesis indicate the actual seed sources from where BARI collected. AU stands for Australia ; B for Bangladesh ; I for India, IC for ICARDA ; ICR for International Crop Research Institute for the Semi-Arid Tropics ; IR for Intenational Rice Research Institute and IT for Internationl Institue of Tropical Agriculture. The actual seed sources of the genotypes without letter are unknown.

* indicates the genotypes used in tube experiment (see text for details).

ences. Principal component analysis was done by using SAS (ver. 6). Analysis of variances (ANOVA) was carried out for root characteristics following a standard procedure of completely randomized design.

Based on the results of this experiment, four to seven genotypes were chosen from each species so that great variations in root lengths were obtained (Table 1) for another experiment that examined the root growth in the later stage of soil-grown plants. The genotypes were grown in slightly slanted half-split PVC tubes (7.5 cm diameter×100 cm long) that contained loamy sand soil. A clear acrylic plate was fixed on the cut face of the tubes which enabled visualization and marking of the taproot and lateral root tips every day. The plants were grown under glass-house conditions from April 25, 1993 to June 8, 1993 with five replications. Mean air temperature during the experimental period was 19.8°C. They were irrigated weekly starting 16 days

after planting. In every other irrigation, water was replaced by 0.25 strength Hogland's solution[4]. The root systems were harvested when the taproot tips reached the bottom of the tubes. Thus, the growth period was different from one genotype to another, ranging 28 to 44 days. For data analysis, first, the taproot length at 10 days after planting (DAP) was read on the acrylic plates. Further, as the plants were harvested in different dates, daily taproot elongation, daily total root (taproot + 1st order lateral root) elongation and daily lateral root production were calculated from the final length and lateral root number of the whole root system at harvest. Based on these data, correlations of root growth parameters were determined between the plants grown in the growth pouches and in the PVC tubes.

Results and Discussion

1. Identification of important characteristics that determine the root system structure with principal component analysis

Principal component (PC) analysis was used to identify the important characteristics that determine the root system structure of 114 genotypes of six food legume species. The eigen values from PC analysis are shown in Table 2. The first three PCs accounted for 88% of total variance observed and were considered for further analysis in detail.

The eigen vectors (Table 3) indicated that all characteristics had positive weight for PC1, which accounted for 48% of the total variation among the genotypes (Table 2). Important characteristics integrated by PC1 were length factors, such as total root length, total lateral root length, single lateral root length, taproot length, and root dry weight. These results suggest that the PC1 provided a measure of root system size. Among the characteristics examined, PC1 had the highest weight for total root length. The total root length consisted of taproot length and 1st order lateral root length at this growth stage. Since lateral roots contributed the major portion of the total root length in all the species (Table 4) and strongly correlated with each other ($r=0.998$, significant at 1% level), it is understood that PC1 measured mainly the total lateral root length.

PC2 accounted for 27% of the total variation observed (Table 2) and had positive weight for lateral root density (number of lateral roots produced on a unit length of taproot), number of lateral roots and shoot dry weight (Table 3). Among these characteristics, lateral root density was the most important character for PC2. Therefore, from the

Table 2. Eigen values and proportions of total variation among 114 genotypes of six food legume species as explained by the first three principal components (PC).

PC	Eigen value	Proportion	Cumulative
1	5.2987	0.4817	0.4817
2	2.9766	0.2706	0.7523
3	1.3554	0.1232	0.8755

Table 3. Characteristics of 114 genotypes of six food legume species used in the principal component analysis and the eigen vectors of each character on the first three principal components (PC).

Characteristics	PC1	PC2	PC3
Shoot dry weight (mg)	0.301	0.338	0.212
Plant height (cm)	0.167	−0.308	0.427
Number of leaves	0.229	−0.443	0.086
Root dry weight (mg)	0.360	0.073	−0.431
Root to shoot ratio	0.195	−0.090	−0.710
Total root length (cm)	0.423	0.036	0.056
Tap root length (cm)	0.333	−0.189	0.208
Total lateral root length (cm)	0.420	0.054	0.043
Single lateral root length (cm)	0.334	−0.291	−0.052
Number of lateral roots	0.271	0.407	0.146
Lateral root density	0.101	0.539	0.049

Table 4. Root characteristics of six food legume species grown in growth pouches for 10 days.

Species	Total root length (cm)	Taproot length (cm)	Lateral root length (cm)	Number of lateral roots/plant	Average length/lateral root (cm)	Lateral root density (roots/cm taproot)
Chickpea	149.0 **a	23.0 *a	126.0 **a	44.7 **b	2.9 **a	2.7 c
Cowpea	12.3 **b	18.3 **bc	94.0 **ab	71.9 **a	1.2 c	5.5 **a
Grasspea	91.1 *b	21.2 **a	69.9 *bc	33.7 c	2.1 b	2.1 d
Lentil	51.8 **c	17.3 b	34.3 **cd	17.7 **d	1.8 **b	1.3 **e
Black gram	46.7 **c	13.7 **cd	33.1 **cd	31.8 **c	1.0 d	3.4 b
Mung bean	42.4 **c	16.0 *bc	26.6 **d	32.8 **d	0.9 d	2.9 c

Note : a) Data are shown in the mean value of the genotypes in each species.

b) ** and * indicates significant difference at 1% and 5% levels, respectively, among the genotypes within species.

c) Means within a column followed by the same letter are not significantly different among the species according to Duncan's multiple range test ($P \leq 0.01$).

examination of PC1 and PC2, we found that the root system structure of these plants was primarily determined by lateral root development.

It is also worth noting here that leaf number had considerably high negative weight for PC2 (Table 3), indicating that a genotype that produces lateral root densely tends to have a smaller number of leaves. In fact, lateral root density and leaf number were found to be negatively correlated ($r = -0.558$, significant at 1% level).

PC3 explained 12% of the variation among the genotypes (Table 2). Characteristics that appeared important to this component were root-to-shoot ratio and root dry weight (Table 3). A significant correlation was observed between root-to-shoot ratio and total root length ($r = 0.334$, significant at 1% level), while root-to-shoot ratio was not correlated with lateral root density ($r = -0.057$, ns) or lateral root number ($r = 0.071$, ns). In other words, more allocation of dry matter to roots was associated with a greater length of lateral roots but not with a greater number of lateral roots. This means that the impact of root-to-shoot ratio on root system structure is not consistent among different genotypes. In fact, when PC3 scores of all genotypes were plotted against those of PC1 or PC2, the species overlapped and scatter diagrams did not give any clear indication of root system structure characteristics for each species (data are not shown). In addition, considering the fact that the contribution of this component to total variation was relatively small, we excluded PC3 in the following characterization of root system structure.

From these analyses, it is concluded that the root system structure of these species was primarily determined by the lengths of lateral root and taproots, and lateral root number, especially density. Thus, these characteristics were considered for the following evaluation of inter- and intraspecific differences in root system structure.

2. Interspecific differences

By plotting PC scores of the species mean with respect to PC1 and PC2 axes, clear differences were recognized among the species in seedling root system structure (Fig. 1 ; open circle). Proceeding from negative to positive values of PC1, total root length and total lateral root length increase, while from negative to positive values of PC2 lateral root density and number of lateral roots increase. Chickpea, cowpea and grasspea had positive values of PC1, while lentil, black gram and mung bean registered negative values (Fig. 1). Table 4 shows that, chickpea produced significantly the largest total root length followed by cowpea and grasspea, although the latter two were statistically similar in total root length. In contrast, mung bean had the smallest total root length and was closely proximate to black gram, whereas lentil produced slightly larger total root length than those two species. There were no significant differences among these

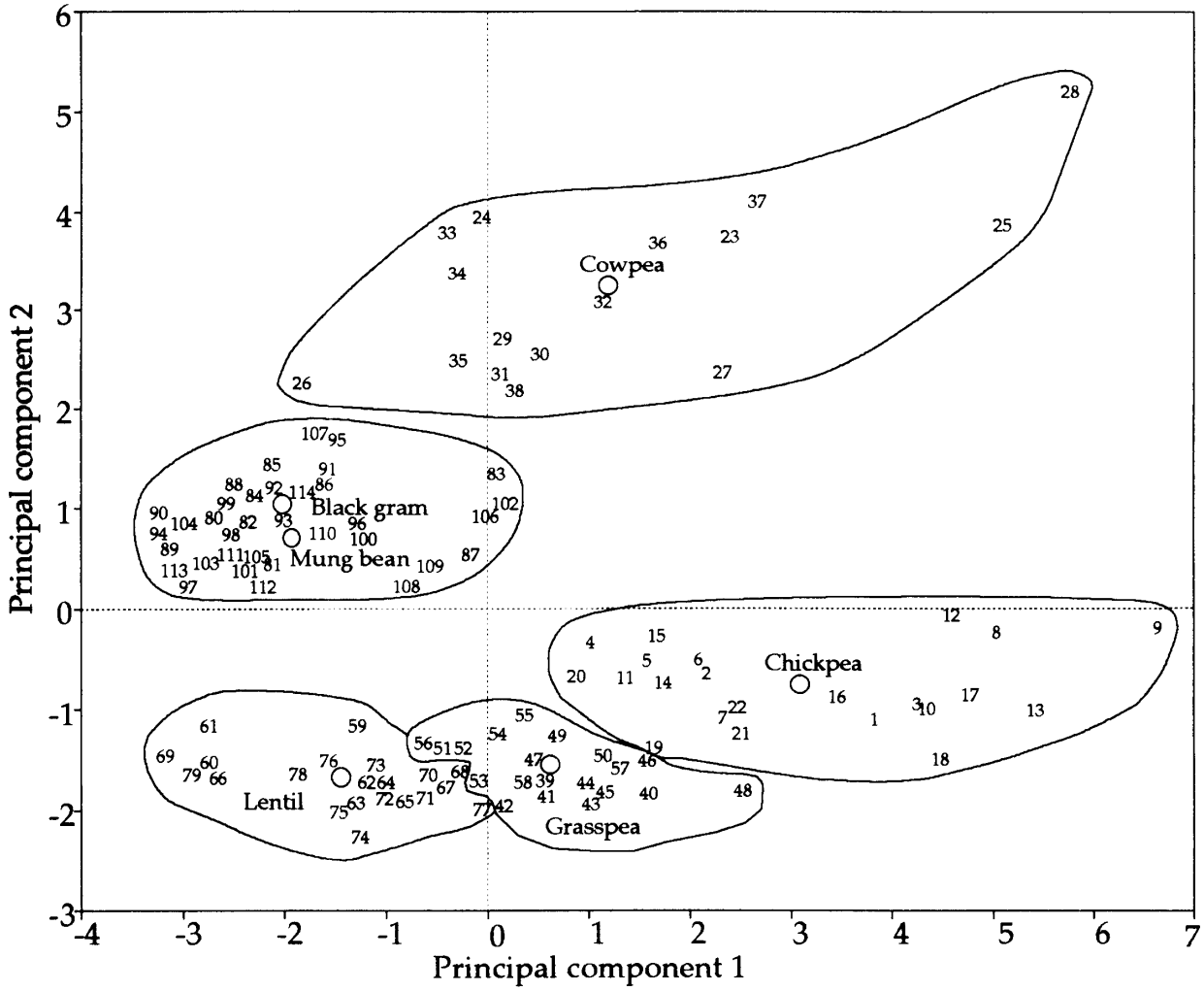

Fig. 1. Inter- and intraspecific differences in seedling root and shoot characteristics of six food legume species as given by the first two principal components. Numbers in the figure indicate the serial number of the genotypes as shown in Table 1. Open circle (○) indicates the mean PC1 and PC2 values of respective species.

three species in total root length, but their total root lengths were significantly shorter compared to those of the former three species. Therefore, we temporarily assigned chickpea, cowpea, and grasspea as the species that formed a large root system, and lentil, black gram and mung bean as those with small root system.

Analysis of PC2 explains more in detail the differences in root system structure in each group. In the species with large root system, cowpea showed positive value, while chickpea and grasspea showed negative values for PC2 (Fig. 1). This indicates that the constituents of total root length were different. As shown in Table 4, chickpea had the longest lateral root (average length of single lateral root) among the six species followed by grasspea. That of cowpea was only 41% that of chickpea. On the other hand, cowpea produced significantly more lateral roots per plant than the other two species, and lateral root density was more than double that of chickpea and grasspea.

In the species with small root system, lentil showed negative value, while mung bean and black gram showed positive values for PC2 (Fig. 1). As shown in Table 4, lentil showed the lowest lateral root density among the three species, but the single lateral root length was relatively large. Lateral root densities of mung bean and black gram were even greater than those of grasspea, but their significantly short lateral roots resulted in relatively small total root length.

As expected, such trends found in total root length reflected the trend in lateral root

length, but not necessarily in taproot length (Table 4). Among the species with large root system, cowpea produced significantly short taproot compared with the other two species, and its length was also as short as those of the species with a small root system. In the group with a small root system, black gram markedly developed a short taproot.

3. Intraspecific differences

As stated earlier, information on the genotypic variation in root system structure is rarely available, and thus we also attempted to evaluate the intraspecific variation within each species. In this respect, the PC scores of genotypes were plotted with respect to PC1 and PC2 to visualize the genotypic differences (Fig. 1).

Overall, we found that considerably large genotypic variations exist within each species and that the variation was even larger than interspecific variation in some cases. In general, the variation in PC1 (root system size) was larger than PC2 (number and density of lateral roots).

ANOVA indicated that genotypes within the species were significantly varied in total root length, taproot length (except lentil), lateral root length, single lateral root length (in chickpea and lentil), lateral root number (except grasspea), and lateral root density (in cowpea and lentil) (Table 4).

Now, mainly based on PC analysis (Fig. 1), we discuss the genotypic variation in each species and point out some genotypes that showed noticeable root characteristics, together with available information on their field performance reported previously. Note that the field performances of the genotypes mentioned hereafter all refer to their performances under rainfed conditions.

The largest genotypic variation was observed in cowpea. The genotypes were fairly well spread along the PC1 axis. Genotypes HAF-43 (#25 ; henceforth, the number within the parenthesis indicates the corresponding number in Table 1 and Fig. 1) and SSD-90 (#28) had far larger PC1 values and total root lengths than the other genotypes. In contrast, genotype IT82E-60 (#26) produced the smallest total root length. The large rooting genotype HAF-43 is one of the most widely grown local cultivar due to its high yield in Bangladesh. In fact, yield trials over several years in Bangladesh showed that this cultivar produced the highest yield as compared to the rest of cowpea genotypes used in this experiment (unpublished data). It is also interesting that although both SSD-90 and IT82E-60 were collected from Australia, their characteristics of root system size expressed in PC1 were contrasting. However, we do not have any information on these two genotypes to further discuss the difference.

Large variations almost equal to those in cowpea were observed in chickpea. The genotypes were also well spread along the PC1 axis. A genotype ICC 4958 (#9) was found to have the highest positive value of PC1 and produced the largest total root length in the species. It is reported that this genotype is drought tolerant, and its drought tolerance is closely related to its large, deep root system[18,19]. Here we have a good example to compare locally grown cultivar and improved cultivar. The genotypes Faridpur local (#7) and Sabur-4 (#22) are the former and Nabin (#18)[14] is the latter, which are the main chickpea cultivars grown in Bangladesh. Fig. 1 indicates that Nabin was superior in root size to the two local cultivars. Nabin has been reported to yield more than some other improved and local cultivars[14]. Thus, it is speculated that the high yielding capacity of this cultivar may be related to its root growth.

The extent of genotypic variation for PC1 in grasspea was almost the same as the species with small root system (lentil, mung bean and black gram). Fig. 1 shows that genotype Charbadna (#48), a local cultivar, had high PC1 value and, in fact, it produced large root length. It is again interesting to note that this cultivar is one of the high yielding cultivar in Bangladesh[15]. However, the genotype Jamalpur (#49), a local cultivar, having relatively low PC1 value, is also a high yielding cultivar. Such root growth of this cultivar may be related to earliness and relatively short plant height[15].

The species with small root system (lentil, mung bean and black gram) showed rather small genotypic variations. The genotypic variations in extent and score values for PC1 were almost similar to each other, but different for PC2.

Lentil genotypes were scattered in lower positions of the coordinates due to the smaller

number of lateral roots produced (negative scores of PC2). Genotype ILL 6035 (#77) was found to produce large root length. This genotype was reported to be deep rooting[22]. In contrast, Utfala (#79), an early and high yielding cultivar[16], produced small root length. Such small root size may also be related to its earliness and short plant height[17].

Black gram and mung bean were integrated in almost the same clusters, reflecting a similar genetic origin, i.e., they belong to the genus *Vigna*. In black gram, a well-known high yielding local cultivar, B-23 (#87) was found to have high PC1 value. In mung bean, Chittagong local (#106), a local high yielding cultivar, and Kanti (#109), an improved cultivar, showed high PC1 values and produced large root lengths in the species.

As far as the genotypes discussed here are concerned, a general trend was recognized that the genotypes which have been evaluated to be high yielding, drought tolerant, or deep rooting, based on the field trials, tend to show high PC1 value and large root length except those early maturing and short cultivars in grasspea and lentil.

From these results on inter- and intraspecific differences, characteristics of root system structure of each species can be summarized as follows: chickpea formed a relatively large root system by producing longer individual lateral root while cowpea formed large root system by producing more lateral roots, which was clearly reflected in PC2 (Fig. 1). Grasspea also formed relatively large root system due to relatively long individual lateral root as compared with those of the species with small root system. It is very important to note, however, that chickpea and cowpea showed considerably large genotypic variations.

In contrast, lentil, black gram and mung bean formed relatively small root system. They produced similar total root length, but their lateral root development patterns were different. Lentil produced a smaller number of lateral roots, while black gram and mung bean produced short lateral roots. Root system structures of black gram and mung bean were very similar with each other in all aspects, including genotypic variations.

It is also to be noted that, in general, the genus *Vigna* had higher lateral root density than the other three genera, i.e., *Cicer*, *Lathyrus* and *Lens*.

4. Relationship of root growth parameters between plants grown in growth pouches and in PVC tubes with soil

It is of great interest whether the characteristics of root system structures of seedlings grown in growth pouches remain in later growth stage of plants grown in soil. In this respect, root growth parameters of the plants in seedling stage examined in growth pouches were correlated with those of the plants in seedling as well as later growth stages grown in soil media by using PVC tubes. As shown in Table 5, taproot length at 10 DAP in growth pouch experiment showed significant correlation with that of the tube experiment at 10 DAP. A similar relationship was found between daily taproot elongation in growth pouch experiment and that in tube experiment calculated from the final taproot length at harvest. Moreover, a strong relationship was found between daily total root elongation in the growth pouch experiment and that in the tube experiment. Similarly, daily lateral root production in growth pouch experiment showed high correlation with that of the tube experiment.

These results indicate that the trends of

Table 5. Correlation of root growth parameters between plants grown in growth pouches (seedling stage) and in PVC tubes (seedling and later growth stages) of six food legume species.

Root growth parameters	No. of genotypes examined	Correlation coefficient (r)	Significant levels
Taproot length at 10 DAP	28	0.679	1%
Daily taproot elongation rate	28	0.587	1%
Daily total root elongation rate	16	0.922	1%
Daily lateral root production rate	16	0.847	1%

genotypic differences in root growth remained similar when the plants were grown in growth pouches under controlled conditions for 10 days and in soil media under glass-house conditions for longer periods. These facts suggest that the growth pouch technique can be a useful tool for screening the root growth of a large number of genotypes at a time. Further study is needed to examine if trends would remain when the plants are grown in the field for a still longer period.

Acknowledgement

The authors thank Mr. Hiroshi Hasegawa, Hokuriku National Agricultural Experiment Station, Jouetsu, Niigata, Japan for his help in performing principal component analysis. The authors also thank all the people from different institutes who supplied us with the seeds for these experiments. A part of this study was carried out under the Cooperative Research Programme of ALRC, Tottori University (A-III), Japan.

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