Plasticity in Taproot Elongation Growth of Several Food Legume Species

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Abstract : Taproot elongation rates (TRERs) of seedlings were investigated with the slant tube method for 27 genotypes of six food legume species in spring, and six selected genotypes of three species in autumn under irrigated and non-irrigated conditions. Shoot growth was also evaluated for comparison. In these experiments, we aimed to evaluate the plasticity in TRER of the species and their genotypes. In spring, most of the species and their genotypes were significantly different in TRERs. Combined ANOVA across the environments revealed that TRERs significantly responded to the environments, especially growing seasons between which root-zone temperatures were markedly different. Under irrigated conditions, TRERs were generally slower in autumn- than spring-grown plants. However, the significant species (genotypes) $\times$ environment interactions indicated that the plasticity in TRER differed among species. Comparison between two seasons showed that TRERs of cowpea were more plastic than those of chickpea and lentil, while an opposite trend was evident for shoot growth. TRERs of cowpea, mung bean and black gram (warm-season species) were strongly root-zone temperature dependent, while those of chickpea, grasspea and lentil (cool-season species) were less dependent or independent. Non-irrigated conditions tended to promote shoot growth, but did not affect TRERs of the genotypes of three species. However, the significant genotype $\times$ environment interaction due to different soil moisture regimes for lentil genotypes showed that genotypic difference also existed in plasticity triggered by soil moisture regimes.

Key words : *Cicer arietinum* L., *Lathyrus sativus* L., *Lens culinaris* Medik., Plasticity, Taproot elongation, *Vigna mungo* (L.) Hepper, *Vigna radiata* (L.) Wilczek., *Vigna unguiculata* (L.) Walp.

数種食用マメ科作物の主根伸長生長における可塑性 : Md. Wahiduzzaman MIA・山内 章・河野恭廣 (名古屋大学農学部)

要 旨 : 食用マメ科作物 6 種 (27 品種・系統) の幼植物の生長を、とくに主根伸長速度に注目しつつ調べた。春期にはすべてを供試して灌漑条件下で、秋期には 3 種 (6 品種・系統) を選び、灌漑・無灌漑条件下で生育させ、主根伸長生長における可塑性の程度およびその種間・種内変異を評価した。春期実験で、ほとんどの種と品種・系統間で主根伸長速度に有意な差異を認めた。そこで生育環境条件の影響を分散分析によって解析した結果、とくに根域温度が明確に異なっていた、生育季節に対して主根伸長速度が有意に反応することがわかった。灌漑条件下では全体的に春期に比べ、秋期で主根生長速度が小さかったが、種 (品種・系統) と環境条件の交互作用が有意なことから、主根伸長の可塑性は種によって異なることが明らかとなった。2 季節間の比較によると、ササゲがヒヨコマメとレンズマメより可塑性が大きかった。また地上部生長はそれとは逆の傾向を示した。ササゲ、リョクトウ、ケツルアズキ (暑い気候に適応種) の日毎の主根伸長速度は、その日の平均根域温度に強く依存していたのに対し、ガラスマメ、ヒヨコマメ、レンズマメ (冷涼な気候に適応種) では、その依存性が低いか、まったく依存性がなかった。無灌漑条件 (秋期実験) は、供試 3 種の地上部生長を促進する傾向があったが、主根伸長速度に対しては有意な影響を与えなかった。しかし、レンズマメでは品種・系統と土壤水分条件間の交互作用が有意であり、土壤水分条件に起因する可塑性においても、品種・系統間差が存在することが明らかとなった。

キーワード : 可塑性, ガラスマメ, ケツルアズキ, ササゲ, 主根伸長, ヒヨコマメ, リョクトウ, レンズマメ,

Root system development is an important facet of crop production under conditions where available soil moisture is limited. Food legumes like 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.) are important grain legumes in south and south-east Asia, Mediterranean, Semi-arid and

Savanna regions. These crops are almost exclusively grown on residual soil moisture and often confront soil moisture stress in those regions^{9,14,15}). In these situations, crop production can be maintained by efficient use of available soil water that exists in root zone or by extending the rooting depth. The main characteristic that influences rooting depth is taproot elongation rate⁸) particularly in these crops that form taproot system. But, informa-

tion on taproot elongation rate of legume crops are insufficient or absent, except for a few species like soybean^{8,16)} and pea⁵⁾.

In addition to the intrinsic taproot elongation rate, its response to various environmental conditions of different species and genotypes has not been well documented. The ability of a genotype to alter its phenotypic expression in response to environment is termed phenotypic plasticity¹²⁾. Agronomically, the evaluation of such plasticity is quite important to select suitable species or genotype for a particular environment. O'Toole and Bland¹²⁾ also emphasized the importance of evaluating the plasticity for successful genetic improvement of the root function of crop plants.

Indeed, research reports have elucidated that the growth of these crop species greatly varies with environmental conditions^{3,10,13,18)}. In most of the studies, however, the growth responses were evaluated mainly on shoot characteristics but not root characteristics. Like shoots, root growth is also largely influenced by many environmental factors like temperature^{1,5,16,19)} and soil moisture stress⁷⁾. However, our knowledge of such root growth responses is again fragmentary, especially for food legume species, and thus the growth response of plant as a whole, including roots to different environmental conditions, is not clear.

When interspecific comparisons are made, it is important to evaluate their growth under normal cultivating conditions. But, it is sometimes difficult to define such conditions because growing seasons and environment in which these crops are produced vary with growing regions^{4,9,13,15)}. In general, however, chickpea, lentil and grasspea are suited to cooler climate, while cowpea, black gram and mung bean are suited to warm and humid climates. Therefore, we paid special attention to these aspects in our study.

This study aimed to evaluate the plasticity in taproot growth of above mentioned species triggered by different environmental conditions, and to examine whether these species and their genotypes differ in plasticity. Shoot growth was also determined to understand the response of the whole plant growth to those conditions. To evaluate such plasticity, plants need to be grown under a wide range of varied conditions. As stated above, the species

examined differ in the adaptability to growing season (temperature), and our interest lies in the evaluation of taproot growth in relation to its significance to drought resistance of the crops. In this study, therefore, we chose different growing seasons, more specifically, growing temperature, and soil moisture regimes for the purpose.

Materials and Methods

Six food legume species, namely chickpea, cowpea, grasspea, lentil, black gram and mung bean were used as plant material. The experiments were conducted at Nagoya University campus, Nagoya, Japan in two successive seasons; spring and autumn.

1. Spring experiment

Based on the results of laboratory experiment reported previously¹¹⁾, four to six genotypes for each species and total of 27 genotypes (Table 1) were selected so that large genotypic variations in taproot growth could be obtained.

The plants were grown in half-split PVC tubes (7.5 cm diameter $\times$ 100 cm long) with a clear acrylic plate (3 mm thick) fixed on the cut face. Shading cloths fixed to the bottom of each tube allowed drainage excess water without disturbing the soil inside. The tubes were filled with sieved (in 2 mm mesh) and air-dried loamy sand soil. During filling, special care was taken to attain the uniform bulk density (1.3 g cm^{-3}) among the tubes.

The tubes were trimmed into a rack, kept in a glasshouse, in two rows with an inclination of 15° from the vertical. The racks were covered with styrofoam board (2 cm thick), leaving the top of the tube outside, and made light-proof to prevent drastic temperature fluctuations of the soil inside the tubes and exposure of roots to direct sunlight. Air temperature inside the racks were continuously recorded by thermograph. We assumed that the changes in soil temperature in the tube closely followed those in air temperature inside the racks, and thus the air temperature inside the rack is designated as root-zone temperature. The completely randomized design was employed, i.e., there were three racks, and each rack was considered to be a replication in which genotypes were randomly assigned.

Before sowing, 0.25 strength Hoagland's solution⁶⁾ (pH 6.8) was irrigated until it start-

ed to come out through the bottom of the tube (approximately 900 ml per tube). Uniform sizes of seeds were selected by weight for each genotype and were germinated in the dark at 20°C. On April 25, 1993, three days after irrigation, two pregerminated seeds were sown on the top of each of tube. After emergence, the seedlings were thinned to one per tube. The tubes were irrigated weekly in the same manner as the initial irrigation except that in every alternate irrigation, Hoagland's solution was replaced by water.

As the tubes were inclined 15° from the vertical, the taproots grew along the inside surface of acrylic plates of the tubes and could be seen easily. Every day, at a prefixed time, the position of taproot tip was marked on the acrylic plate for each plant. The root systems of each genotype were harvested when the taproot tip of one of the replications reached the bottom of the tube. Thus the growing period was different from one genotype to another, ranging from 28 days to 44 days.

After harvest, daily taproot elongations were determined by measuring the distance between the root tip positions marked on acrylic plate. Shoot dry weight was measured after drying at 80°C for 48 hours. As the growing periods were different among species and genotypes, the data for shoot dry weight are converted into daily increment basis. In a strict sense, however, using this parameter, precise comparison may not made among the plants of different growing periods because daily increment rate in shoot dry weight of given plant could not be constant throughout the growing period. Thus these values were used as reference data.

2. Autumn experiment

The experiment was started on October 8, 1993. Three species, namely chickpea, cowpea and lentil were used in this experiment. Based on the taproot elongation rate determined in spring experiment, the fastest and slowest genotypes in each species were selected (Table 1) and grown under two soil moisture regimes, i.e., irrigated and non-irrigated, for 38 days to 48 days with three replications.

The experimental procedures were the same as that described for spring experiment except non-irrigated treatment, in which irrigation was withheld after sowing. In non-irrigated tubes, the soil moisture contents were deter-

mined almost weekly at a 10-cm interval depth along the soil profile. For the measurement, a piece of filter paper (approximately 5 cm²) was inserted into the soil through pre-drilled hole at each depth of PVC tube and equilibrated for 24 hours, and then the moisture content of filter paper was determined. Based on the predetermined relationship between moisture content of the filter paper and that of the soil used, soil moisture content was determined. Further, the soil water potential equivalent to each soil moisture content was also estimated based on the predetermined soil characteristic curve.

During spring experiment, the ranges of minimum, maximum and mean root-zone temperatures were 11°C-19°C, 17°C-30°C and 16°C-23°C, respectively. In autumn experiment, they were 5°C-19°C, 13°C-27°C and 11°C-23°C, respectively. In spring, the day length increased from 13 h 15 min to 14 h 29 min while that in autumn decreased from 11 h 36 min to 10 h 3 min during the experimental period.

3. Data organization and statistical analysis

In both experiments, for uniformity and simplicity, the data obtained for taproot elongation rate (TRER) up to 28 days after sowing was considered. As described above, in this series of experiments, plants were grown under three different environmental conditions; under spring season, irrigated conditions (referred as spring hereafter), and under autumn season, irrigated (autumn : irrigated) and non-irrigated (autumn : non-irrigated) conditions. In this report, we considered those conditions as three independent environments. A statistical program IRRISTAT (ver. 3.1, International Rice Research Institute, Philippines)' was used to perform combined analysis of variance across the environments.

Results and Discussion

1. Inter- and intraspecific variations in taproot elongation rate

Mean and maximum TRERs of all genotypes grown in the spring experiment are presented in Table 1. The significantly highest mean TRER was found in cowpea followed by grasspea, chickpea, mung bean and lentil, and the lowest was found in black gram. The genotypes within the species of cowpea, chick-

pea, mung bean and lentil were significantly different in TRER, but those of the other species were not statistically different in this character.

TRERs were not uniform during the growing period, but remarkable day to day fluctuations were observed in all species. The degree of those fluctuations varied with species as well as genotypes within the species. The maximum TRER of a species, recorded in a particular genotype on a particular day, was highest in cowpea and chickpea (8.8 cm day^{-1}) followed by mung bean, grasspea and black gram while, that was lowest in lentil (4.5 cm day^{-1}) (Table 1). The average minimum TRERs were about 1 cm day^{-1} in cowpea, grasspea, chickpea and lentil, and less than 1 cm day^{-1} in mung bean and black gram (data not shown).

Reported values of these characteristics for some leguminous crops are available for comparison. The minimum and maximum TRERs of a garden pea cultivar grown in vermiculite under five temperature levels ranged from 1.2 to 2.3 cm day^{-1} and 2.7 to 4.1 cm day^{-1} , respectively⁵⁾. Similarly, Stone and Taylor¹⁶⁾ investigated TRERs of four cultivars of soybean grown in vermiculite under four temperature levels for 19 days, and found that the TRERs varied significantly with temperatures and cultivars ranging from 1.7 to 6.8 cm day^{-1} . According to another report, the average TRERs in soybean grown in vermiculite for 35 days varied from 3.0 to 5.3 cm day^{-1} among cultivars⁸⁾. These facts strongly indicate that the values we obtained fall almost in the range obtained for other legume species, which however, would be largely altered when grown in different environment.

2. Environmental effects on taproot elongation rate

(1) Overall environmental effects

From spring experiment, three species namely cowpea, chickpea and lentil and two genotypes per species were chosen and grown in autumn under two soil moisture regimes, i.e., irrigated and non-irrigated conditions as described in Materials and Methods.

The combined analysis of variance across three environments (spring, autumn : irrigated, autumn : non-irrigated) showed that TRERs were significantly different among species as well as genotypes within the species,

and among the plants grown under the three environments. Significant species (genotype) $\times$ environment interactions also existed for TRER (Table 2). However, the relative magnitude of variances differed greatly. The variance due to the environment was larger than that due to the genotypes, which was in turn larger than that due to the interaction. This result shows that the TRER was greatly affected by different environments, and the response of TRER to the environment varied depending on the species or genotypes.

Partitioning of variance due to species into a single degree of freedom revealed that the species were significantly different in TRER. Genotypes within each species were also significantly different in TRER.

Further partitioning of environmental variance showed that spring environment was significantly different from autumn : irrigated and autumn : non-irrigated environments, but there was no statistical difference between the latter two. These facts show that the TRERs were greatly affected by growing seasons, but were not affected by soil moisture regimes of our experimental conditions. This result seems to indicate that the moisture conditions of the non-irrigated treatment could have too mild to affect the root growth. Thus, the effect of soil moisture is discussed later for more details.

Separation of species (genotypes) $\times$ environment variance indicated that the genotypes mainly interacted with two growing seasons, i.e., spring and autumn, but not with soil moisture regimes except for the two lentil genotypes. In other words, the responses in TRER to two different growing seasons differed among species and genotypes of each species while their responses to irrigated and non-irrigated conditions were different between the two lentil genotypes but not among the other genotypes nor interspecifically.

To examine more specifically the growth responses to different environmental conditions, and species (genotype) $\times$ environment interactions, the average performance of the species (mean of two genotypes) and individual genotype under the three environmental conditions are presented in Fig. 1. Interspecifically, TRER of cowpea was statistically higher than that of chickpea in spring experiment, but that was significantly slower than

Table 1. Mean and maximum taproot elongation rates of different genotypes of six food legume species grown for 28 days (spring experiment).

Species	Genotypes	Taproot elongation rate	
		Mean (cm day ⁻¹)	Maximum (cm day ⁻¹)
Cowpea	HAF-43 †	3.2 ^a	7.8
	SSD-90	2.8 ^{bc}	8.5
	SSD-693 †	2.7 ^c	8.1
	TV × 289-4G	3.1 ^{ab}	8.8
	Species mean	2.9 ^{*A}	8.3
Grasspea	8603	2.7	5.3
	Charbadna	2.8	5.7
	RU-7	2.7	5.4
	RU-21	2.9	6.2
	Species mean	2.8 ^B	5.7
Chickpea	E-153 †	2.4 ^b	6.9
	ICCL 4320 †	2.9 ^a	8.8
	ICC 4958	2.6 ^a	6.5
	Nabin	2.8 ^a	5.9
	Sabur-4	2.9 ^a	6.2
	Species mean	2.7 ^{*B}	6.9
Mung bean	BM 7715	2.4 ^a	5.2
	BM 84-2-7-1	2.4 ^a	6.5
	Cht. local	1.6 ^b	5.1
	MOSK-1	2.2 ^c	5.4
	Species mean	2.2 ^{*C}	5.6
Lentil	B-77	2.1 ^a	4.3
	BLL 84143 †	2.3 ^a	4.5
	BLL 84248	2.2 ^a	3.3
	ILL 4400	2.1 ^a	4.5
	ILL 5582	1.9 ^a	3.9
	Utfala †	1.5 ^b	3.4
	Species mean	2.0 ^{**D}	4.0
Black gram	B-23	1.8	4.7
	MAK-2	1.5	4.8
	RU-69	1.8	5.4
	RU-158	1.8	4.7
	Species mean	1.7 ^E	4.9

* and ** indicates significant difference among the genotypes within the species at 5% and 1% level, respectively. Genotypic mean within a column section of species followed by the same letter are not statistically different by DMRT ($P \geq 0.05$). Species means within a column followed by the same letter are not statistically different by DMRT ($P \geq 0.05$).

† indicates the genotypes used in autumn experiment.

Table 2. Combined analysis of variance for taproot elongation rates of two genotypes of chickpea, cowpea and lentil grown under three environmental conditions.

Source of variations	DF	Mean square
		Taproot elongation rate
Replications	2	0.001
Treatments	17	0.71**
Genotypes (G)	5	1.29**
CWP Vs CHK & LEN	1	1.04**
CHK & LEN	1	4.54**
HAF-43 Vs SSD-693	1	0.08*
ICCL 4320 Vs E-153	1	0.30**
BLL 84143 Vs Utfala	1	0.51**
Environments (E)	2	1.94*
E1 Vs (E2 & E3)	1	3.86**
E2 Vs E3	1	0.016
G × E	10	0.17**
(CWP Vs CHK & LEN) × (E1 Vs E2 & E3)	1	0.82**
(CHK Vs LEN) × (E1 Vs E2 & E3)	1	0.006
(HAF-43 Vs SSD-693) × (E1 Vs E2 & E3)	1	0.25**
(ICCL 4320 Vs E-153) × (E1 Vs E2 & E3)	1	0.13*
(BLL 84143 Vs Utfala) × (E1 Vs E2 & E3)	1	0.33**
(CWP Vs CHK & LEN) × (E2 Vs E3)	1	0.01
(CHK Vs LEN) × (E2 Vs E3)	1	0.001
(HAF-43 Vs SSD-693) × (E2 Vs E3)	1	0.03
(ICCL 4320 Vs E-153) × (E2 Vs E3)	1	0.003
(BLL 84143 Vs Utfala) × (E2 Vs E3)	1	0.08*
Error	34	0.018
CV (%)		6.45

* and ** indicates significant difference at 5% and 1% level, respectively.

CWP, cowpea ; CHK, chickpea ; LEN, lentil : E1, spring ; E2, autumn (irrigated) E3, autumn (non-irrigated). Cowpea genotypes ; HAF-43, SSD-693 : Chickpea genotypes ; ICCL 4320, E-153 : Lentil genotypes ; BLL 84143, Utfala.

chickpea in autumn experiment, both in irrigated and non-irrigated environments (Fig. 1A). Average performance of lentil for TRER was significantly lower than the other two species in all environments.

As for the genotypic comparison within each species, responses of individual genotype in TRER also largely varied with growing environments. Cowpea genotypes, HAF-43 had significantly faster TRER than SSD-693 in spring, but they were statistically similar in autumn irrigated and non-irrigated environments (Fig. 1B). Similar trends in responses were shown by chickpea genotypes, ICCL 4320 and E-153. In lentil, BLL 84143 had significantly higher TRER than Utfala during spring and autumn : irrigated environments,

but statistically they were not different in autumn : non-irrigated environment. In general, the degree of TRER reduction in autumn were more pronounced for the genotypes which showed faster TRERs in spring (Fig. 1 B).

(2) Effect of growing seasons

As described above, TRER sharply responded to varied environment, especially growing seasons. The taproot growth was generally reduced in autumn. However, the degree of reduction was different among the species and genotypes. To quantify the responses, the ratios of TRER of autumn : irrigated to spring-grown plants for cowpea, chickpea and lentil genotypes are presented in Table 3. Further, the ratios of shoot dry weight

Fig. 1. Average performance in taproot elongation rate of species (A) and genotypes within the species (B) grown under different environmental conditions.

Species : Δ Cowpea, $\circ$ Chickpea, $\square$ Lentil.
 Genotypes : Cowpea ; $\blacktriangle$ HAF-43, $\triangle$ SSD-693 ;
 Chickpea ; $\bullet$ ICCL 4320, $\circ$ E-153 ; Lentil ;
 $\blacksquare$ BLL 84143, $\square$ Utfala). Spr, spring ;
 Aut (IR), autumn (irrigated) ; Aut (NIR),
 autumn (non-irrigated)

increment were also included in this table to understand the response of the whole plant growth. Table 3 revealed that TRER was much more reduced in cowpea (31% (species mean)) than chickpea (13%) and lentil (16%), while the reduction of shoot dry weight increment was more pronounced in chickpea (73%) and lentil (82%) than in cowpea (62%). These results suggest that the TRERs of the cool-season species (chickpea and lentil) were less influenced by growing seasons than the warm-season species (cowpea). In contrast, shoot growth was more

influenced in the cool-season species than in warm-season species.

It may be expected that growth of warm-season species would be better in a warmer environment, while that of the cool-season species would be better in a cooler environment. However, our results showed that root as well as shoot growth were reduced in autumn not only for cowpea, but also for chickpea and lentil. In this respect, some reports showed that root and shoot growth of chickpea in vegetative stage was very slow during winter, but increased rapidly when the temperature went up in spring^{2,18,19}). Therefore, further study is necessary to specify the optimum temperature for root growth for each species, which may be different from that for shoot growth.

Differences between the two experimental seasons must involve differences in various environmental factors. One possible main factor is temperature. In fact, root-zone temperature was markedly different between the two seasons as stated earlier. In this respect, correlation between TRER in each day and mean root-zone temperature on the corresponding day throughout the growth period was determined to evaluate the effects of root-zone temperature on the TRER (Table 4).

The relationship was significant for all genotypes of six species in spring experiment, except for two grasspea genotypes. In contrast, in autumn experiment in which the genotypes of cowpea, chickpea and lentil were compared, it was so only for cowpea genotypes in both irrigated and non-irrigated and one lentil genotype in autumn : irrigated conditions. In the spring experiment, a stronger relationship was generally found for cowpea, mung bean and black gram (warm-season species) compared to chickpea, grasspea and lentil (cool-season species). In the autumn experiment, cowpea genotypes also showed highly significant correlation, while the correlations were not significant for chickpea and lentil genotypes except one lentil genotype BLL 84143 for which, however, the correlation was considerably weak. Additionally, in spring, the slope of regression lines tended to be higher for the former species than the latter although those of chickpea and black gram genotypes fell into almost the same range. These facts strongly indicate that the TRERs of warm-

Table 3. Ratio of taproot elongation rate and shoot dry weight increment per day in autumn : irrigated to those in spring-grown plants for six genotypes of three food legume species.

Species	Genotypes	Taproot elongation rate	Shoot dry weight
Cowpea	HAF-43	0.64	0.33
	SSD-693	0.73	0.42
	Mean	0.69	0.38
Chickpea	ICCL 4320	0.80	0.26
	E-153	0.93	0.28
	Mean	0.87	0.27
Lentil	BLL 84143	0.76	0.21
	Utfala	0.92	0.14
	Mean	0.84	0.18

season species are heavily dependent on growing temperature over the wide range of growing temperatures, while the cool-season species are less dependent or independent from growing temperatures, especially when grown under cooler temperature conditions.

In addition, x-intercepts were also higher for the warm-season species than the cool-season species. This tends to show that the former species need relatively high temperature to start taproot elongation, while the latter could elongate in lower temperature. As such, characteristics of these species in terms of adaptation to favorable growing temperature were well expressed in TRER.

It is important to point out here that when the TRER of a given genotype is compared between spring- and autumn-grown plants at the same root-zone temperature, the former plants generally showed higher TRERs (data not shown). This fact suggests that other environmental factors than root-zone temperature like solar radiation also affected the root growth.

(3) Effect of soil moisture conditions

The ratio of TRERs and shoot dry weight increment of autumn : non-irrigated to autumn : irrigated plants are presented in Table 5. As stated earlier, their TRERs were scarcely affected, except lentil genotype BLL 84143, by the non-irrigated treatment induced in our experiment. In contrast, the shoot dry weight increment tended to be promoted especially in winter species.

To examine more in detail the effects of soil moisture on the taproot growth, moisture distribution along the soil profile is presented

in Fig. 2.

Soil moisture distribution was determined at almost weekly interval as explained in Material and Methods. However, since TRERs were evaluated up to 28 days after sowing for uniformity, the soil moisture at 26 days after sowing, which is the closest available data, is presented together with the data at sowing. Although the non-irrigated treatment was commenced at the same time (three days before sowing) for all genotypes, the final moisture distribution along the soil depth were different among them, ranging from 14.3% (ICCL 4320) to 17.0% (Utfala) at 10 cm depth and from 19.7% (ICCL 4320) to 22.3% (Utfala) at 80 cm depth. When these soil moisture contents were converted into equivalent soil water potential, however, the differences were estimated to be quite small. The estimated water potentials were all approximately -0.02 MPa at 10 cm depth, and -0.01 MPa for Utfala and -0.02 MPa for the others at 80 cm depth. It means that all the genotypes were grown at almost the same soil water potential at least up to 26 days after sowing under non-irrigated conditions.

Taylor¹⁷⁾ pointed out that controversy exists in the literature about the effects of soil moisture stress of higher than -1 MPa on plant root growth. Our results also showed that the taproot growth responses tended to be different among species and genotypes, even when they were grown under almost uniform but considerably mild water stress. Furthermore, the genotype $\times$ environment (soil moisture conditions) interaction was significant for lentil genotypes (Table 2).

Table 4. Correlation between daily taproot elongation rate and daily mean root-zone temperature of plants grown in spring and autumn experiments.

Species	Genotypes	r value	Slope	x-intercept
Cowpea	HAF 43	0.752** (0.831**) (0.914**)	0.479(0.212) (0.238)	12.5(8.0) (9.2)
	SSD-90	0.795**	0.456	12.7
	SSD-693	0.800** (0.878**) (0.838*)	0.441(0.301) (0.258)	13.0(10.9) (9.0)
	TV×289-4G	0.816**	0.624	14.3
Chickpea	E-153	0.736** (0.238) (0.034)	0.347	11.3
	ICCL 4320	0.738** (0.385) (0.354)	0.383	11.4
	ICC 4958	0.597**	0.212	6.2
	Nabin	0.621**	0.254	8.7
	Sabur-4	0.756**	0.384	11.5
Grasspea	8603	0.277	—	—
	Charbadna	0.342		
	RU-7	0.526**	0.283	9.3
	RU-21	0.471*	0.230	6.4
Mung bean	BM 7715	0.822**	0.481	14.1
	BM 84-2-7-1	0.840**	0.508	14.4
	Cht. local	0.742**	0.354	14.4
	MOSK-1	0.829**	0.431	14.1
Lentil	B-77	0.565**	0.126	3.8
	BLL 84143	0.685** (0.398) (0.095)	0.157	5.0(−29.7)
	BLL 84248	0.685**	0.164	6.0
	ILL 4400	0.545**	0.113	1.6
	ILL 5582	0.517**	0.137	4.8
	Utfala	0.517** (0.101) (0.153)	0.115	4.6
Black gram	B-23	0.733**	0.245	12.5
	MAK-2	0.707**	0.252	13.5
	RU-69	0.793**	0.374	14.3
	RU-158	0.780**	0.306	13.5

* and ** indicates significant difference at 5% and 1% level, respectively. Number within paranthesis indicate the data obtained from autumn : irrigate (upper) and autumn : nonirrigated (lower). The others were from spring experiments. Slope and x-intercept are presented only when the correlation was significant.

These results suggest that the responses to the soil moisture regime were different between taproot elongation growth and shoot growth, and that genotypic variations also existed for the responses in taproot growth to different soil moisture regimes, at least for lentil. Therefore, the more detailed evaluation of impact of soil moisture on the taproot growth of different species and genotypes is

another important subject for further study.

3. Evaluation of the plasticity in taproot elongation growth

When the species and their genotypes were grown under a given environmental condition (in spring under irrigated condition in the case of this study), clear inter- and intraspecific differences were found in taproot elongation growth (Table 1). The above-

Table 5. Ratio of taproot elongation rate and shoot dry weight increment per day of non-irrigated to irrigated plants for six genotypes of three food legume species (autumn experiment).

Species	Genotypes	Taproot elongation rate	Shoot dry weight increment
Cowpea	HAF-43	0.95	1.00
	SSD-693	1.05	1.06
	Mean	1.00	1.03
Chickpea	ICCL 4320	0.98	1.19
	E-153	0.95	1.42
	Mean	0.98	1.19
Lentil	BLL 84143	0.88	1.22
	Utfala	1.08	1.43
	Mean	0.98	1.33

Fig. 2. Soil moisture content along the soil profile of the tubes in which non-irrigated plants were grown. Soil moisture was measured at the time of sowing and 26 days after sowing (DAS).

Sowing : ■

26 DAS : Cowpea ; ○ HAF-43, ● SSD-693

Chickpea ; □ ICCL 4320, ■ E-153 Lentil ; △

BLL 84143, ▲ Utfala

described results on the responses of taproot elongation growth to the different environmental conditions showed, however, that the growth was clearly altered by the different conditions (Table 2), which means that these species and genotypes have the plasticity in that root character. Furthermore, we found that the plasticity also differed among species and genotypes.

The interspecific difference was well recognized especially in the plasticity triggered by different growing temperatures (Table 2 and 3, Fig. 1). The difference was clear between warm-season and cool-season species, i.e., the former species were more plastic than the latter. Such differences in the plasticity seemed to be caused by the differences in the responsiveness of daily TRER to root-zone temperature. The TRERs of the former species were strongly temperature dependent, while those of the latter species were much less dependent or independent (Table 4). Marked genotypic differences were also present in this plasticity (Table 2 and 3, Fig. 1). On the other hand, the plasticity triggered by different soil moisture conditions was not different among the species, but was different between the two lentil genotypes (Table 2 and 5, Fig. 1).

The plasticity in a given character is specific for that character and may be greatly different for other parameters¹²⁾. It is thus necessary to further examine various root characters under different growing conditions to fully understand the plasticity of whole root system.

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