CHAPTER V

CLASSIFICATION OF ROOT DISTRIBUTION PATTERNS AND THEIR CONTRIBUTIONS TO YIELD IN PLANT GENOTYPES UNDER MID-SEASON DROUGHT STRESS

Introduction

Peanut is largely grown under rain-fed conditions in the semi-arid tropics. In these conditions, drought is a major production constraint as rainfall is generally erratic and insufficient (Nageswara Rao et al. 1989, Reddy et al. 2003). The overall timing and intensity of drought stress has a very important impact on peanut productivity. Water deficit during the seed filling phase (50-80 DAP) results in the greatest reduction in yield, whereas pod yield can be increased by water deficit during the pre-flowering phase (Nageswara Rao et al., 1985; Nautiyal 1999; Meisner and Karnok 1992). The mechanisms of drought resistance in relation to above ground part have been demonstrated in literature (Nageswara Rao et al., 1985; El Hafid et al., 1998; Nautiyal et al., 1999; Awal and Ikeda, 2002; Jongrungklang et al., 2008; Puangbut et al., 2009). However, there is limited information on the root responses of peanut under water deficit environment.

Drought resistance may be enhanced by improving the ability of the crop to extract water from the soil (Wright and Nageswara Rao 1994). Deep rooting, root length density (RLD) and root distribution have been identified as drought adaptive traits (Passioura 1983, Turner 1986, Dardanelli et al., 1997, Matsui and Singh 2003, Taiz and Zeiger 2006).

This paper was submitted to Field Crops Research (Impact Factor=2.336)

Peanut roots are established both deeply and laterally in the soil profile early in the growth season. Ketring and Reid (1993) found that RLD increased significantly at each depth increment until 80 DAP under sufficient water conditions, while the upper soil profile depth had the highest mean RLD. Under drought conditions the root growth rate was significantly reduced in the upper soil layer during water stress from 20 to 50 DAP compared to sufficient irrigation (Meisner and Karnok 1992).

Peanut genotypes that have a high RLD at deeper soil depths may have enhanced drought tolerance and such a response could help maintain a high pod yield and harvest index. These genotypes are classified as drought responsive as they RLD increases in deeper soil layers in response to drought (Songsri et al., 2008). Pandey et al. (1984) reported that drought increased RLD in the lower soil profile of the peanut genotype 'Kidang'. However, Robertson et al. (1980) reported that RLD of peanut (Florunner) was not affected by different water management strategies.

Peanut root distribution patterns are not well understood and have not been studied extensively. The results reported so far have been limited to experiments under chamber conditions and with few peanut genotypes. Obviously, there is a lack of information on the classification of root distribution patterns for peanut genotypes under mid-season drought. This information could be useful for developing peanut breeding programs to enhance drought tolerance. Thus, the goal aim of this study was to classify the root distribution patterns of peanut genotypes under mid-season drought, and to determine the relationships between RLD in different soil depths and yield under these conditions.

Materials and Methods

Experimental design and treatments

The experiment was conducted under field conditions at the Field Crop Research station of Khon Kaen University located in Khon Kaen province, Thailand (latitude 16° 28′ N, longitude 102° 48′ E, 200 m. above sea level) from December 2007 to May 2008 and was repeated from November 2008 to April 2009. The soil type is Yasothon series (Yt: fine-loamy; siliceous, isohypothermic, Oxic Paleustults). A randomized complete block design with four replications was used in both years.

The plot size was 3 x 5 m with a spacing of 50 cm between rows and 20 cm between plants.

The main treatment of this study was the comparison of 40 peanut genotypes which differed in levels of drought tolerance and sources of origin. Nine genotypes from the United State Department of Agriculture (USDA) were identified for differences in drought tolerance using the percentage reduction of total dry matter as reported by Jongrungklang et al. (2008) (Table 1; entries no 1-9). Eleven commercially released cultivars in Thailand (KKU 40, KKU 60, KKU 1, KKU 72-1, KK 6, KK 4, KK5, KS 2, KK 60-2, KK 60-3, Tainan 9) were also included in this study (Table 1; entries no 10-20). KK 60-3 is a Virginia-type peanut cultivar sensitive to drought for pod yield, while Tainan 9 is a Spanish-type peanut cultivar having low dry matter production under drought conditions (Vorasoot et al., 2003). Eight elite drought resistant lines (ICGV 98300, ICGV 98303, ICGV 98305, ICGV 98308, ICGV 98324, ICGV 98330, ICGV 98348 and ICGV 98353) were provided by International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in India (Table 1; entries no 21-28). The ICRISAT drought resistant lines had been selected because of high total dry matter and pod yield under drought stressed experiments (Nageswara Rao et al., 1992; Nigam et al., 2003; Nigam et al., 2005). One (Tifton-8) was a Virginia-type drought-resistant line (Coffelt et al., 1985) introduced from USDA (Table 1; entry no 29). Eleven genotypes were selected based on different dry matter production, harvest index and specific leaf area under well-watered conditions (data from our previous study), (Table 1 entries no 30-37) provided by USDA, and three genotypes (Table 1; entries no 38-40) were received from China.

Table 1 Source of origin and drought tolerant level for the 40 peanut genotypes that were used in this study

Entry no	Identification	Source	Drought tolerance level	Entry no	Identification	Source	Drought tolerance level
1	306 PI 430237	Liaoning,China	Susceptible	21	ICGV 98300	ICRISAT[1]	drought tolerance
2	12 PI 430233	China	Susceptible	22	ICGV 98303	ICRISAT[1]	drought tolerance
3	187 PI 433352	China	Susceptible	23	ICGV 98305	ICRISAT[1]	drought tolerance
4	283 PI 234375	China	moderate tolerance	24	ICGV 98308	ICRISAT[1]	drought tolerance
5	204 PI 442572	Shandong, China	moderate tolerance	25	ICGV 98324	ICRISAT[1]	drought tolerance
6	5 PI 313160	China	moderate tolerance	26	ICGV 98330	ICRISAT[1]	drought tolerance
7	101 PI 268659	China	drought tolerance	27	ICGV 98348	ICRISAT[1]	drought tolerance
8	269 PI 157542	Jiangxi, China	drought tolerance	28	ICGV 98353	ICRISAT[1]	drought tolerance
9	89 PI 157549	Jiangxi, China	drought tolerance	29	Tifton – 8	USDA[4]	drought tolerance
10	KKU 40	KKU[3], Thailand	Unknown	30	248 Grif 13911	China	moderate tolerance
11	Tainan 9	KKFCRC[2], Thailand	Susceptible	31	35 Grif 13932	China	moderate tolerance
12	KK 5	KKFCRC[2], Thailand	Unknown	32	97 PI 158854	Jiangxi, China	Susceptible
13	KKU 1	KKU[3], Thailand	Unknown	33	100 PI 162604	China	moderate tolerance
14	KK 60-2	KKFCRC[2]and KKU[3], Thailand	Unknown	34	102 PI 268660	China	drought tolerance
15	KS 2	Thailand	Susceptible	35	106 PI 268949	China	moderate tolerance
16	KK 4	KKFCRC[2], Thailand	Susceptible	36	3 PI 313157	China	Susceptible
17	KK 60-3	KKFCRC[2]and KKU[3], Thailand	Susceptible	37	303 PI 430230	China	Susceptible
18	KKU 72-1	KKU[3], Thailand	Unknown	38	Taiwan 1	China	Unknown
19	KKU 60	KKU[3], Thailand	moderate tolerance	39	Taiwan 2	China	Unknown
20	KK 6	KKFCRC[2], Thailand	Unknown	40	Luhua 11	China	Unknown

1 ICRISAT = International Crop Research Institute for the Semi-Arid Tropics
2 KKFC = Khon Kaen Field Crop Research Centre
3 KKU = Khon Kaen University
4 USDA = United States Department of Agriculture

Crop management

Sub-soiling was done to destroy the hard pan soil from 0-60 cm of soil depth and disc plowing was performed three times to prepare the field for the experiment. Lime at the rate of 625 kg ha^{-1} was incorporated during soil preparation to adjust soil pH. Seeds were treated with Captan (3a,4,7,7a-tetrahydro-2-[(trichloromethyl)thio]-1H-isoindole-1,3(2H)-dione) at a rate of 5 g kg^{-1} seed prior to planting to prevent fungi, and the large seeded lines were treated with Ethrel 48% at a rate of 2 ml l^{-1} water to break seed dormancy before planting. Three seeds were planted per hill and the seedlings were thinned to one plant per hill at 15 days after planting (DAP). At 15 DAP nitrogen fertilizer was applied as urea at a rate of 23.4 kg ha^{-1}, phosphorus fertilizer was applied as triple superphosphate at a rate of 24.7 kg P ha^{-1} and potassium fertilizer was applied as muriate of potash (KCl) at a rate of 31.1 kg K ha^{-1}. Gypsum ($CaSO_4$) at a rate of 312 kg ha^{-1} was applied at 45 DAP to improve pod development.

Weeds were controlled by an application of alachlor (2-chloro-2',6'-diethyl-*N*-(methoxymethyl) acetanilide 48%, w/v, emulsifiable concentrate) at the rate of 3 l ha^{-1} at planting and plots were hand weeded during the remainder of the season. Carbofuran (2,3-dihydro-2,2-dimethylbenzofuran-7-ylmethylcarbamate 3% granular) was applied at the pod setting stage to control soil insects. Pests and diseases were controlled by weekly applications of carbosulfan [2-3-dihydro-2,2-dimethylbenzofuran-7-yl (dibutylaminothio) methylcarbamate 20% w/v, water soluble concentrate] at 2.5 l ha^{-1}, methomyl [*S*-methyl-*N*-((methylcarbamoyl)oxy) thioacetimidate 40% soluble powder] at 1.0 kg ha^{-1} and carboxin [5,6-dihydro-2-methyl-1,4-oxathine-3-carboxanilide 75% wettable powder] at 1.68 kg ha^{-1}.

A sprinkler irrigation system was installed prior to planting to supply water during the growing season. The water regime in this experiment was an imitated mid-season drought stress that would normally occur in a farmer's field. Peanut may show its largest range in drought tolerance potential under mid-season drought conditions, because drought during pod filling and seed filling development significantly reduces pod yield (Nageswara Rao et al., 1985, Meisner and Karnok, 1992). Therefore, all plots were supplied with water to obtain field capacity moisture level to the depth of 60 cm from planting to 50 DAP. After 50 DAP, water was withheld until 83 DAP in the first season to mimic mid-season drought conditions. Thermal degree day accumulation was calculated in both seasons for predicting crop growth stage and irrigation was withheld from 50 to 87 DAP for the second season. After the drought period, all plots were re-watered and maintained at F.C. level until harvest.

Soil moisture content and meteorological conditions

The soil water status was monitored at 7-day intervals using a neutron moisture meter (Type I.H. II SER. No N0152, Ambe Diccot Instruments CO.Ltd.,England). An aluminum access tube was installed between rows in each plot and 16-sec neutron moisture meter readings were made at depths of 30, 60 and 90 cm. Rainfall, relative humidity (RH), evaporation (E_0), maximum and minimum temperature and solar radiation were recorded daily from sowing until harvest by a weather station located 100 m away from the experimental field.

Top dry matter

Shoot dry weight and leaf dry weight were observed at the most water-stressed date (83 DAP during the first season and 87 DAP during the second season. Five plants were collected for each plot and fresh weight was recorded. The fresh samples were first separated into stems and leaves. Samples were oven dried (temperature 80 C^o 48 hours or until constant weight) and weighed. At harvest, ten plants were sun dried to reduce some moisture and sub-sampled. Then the sub-samples were oven dried and weighted.

Root length density percentage

Root samples were collected at the most water-stressed date using the auger method. Each plot was sampled for root length density at two positions; at the center of plants in the row and between row positions. Root samples were taken to 90 cm depth and separated into six layers as 0-15 cm, 15-30cm, 30-45 cm, 45-60cm, 60-75cm and 75-90 cm. Root samples of each layer were washed manually with tap water to remove the soil from the root samples. Then root length was analyzed with the WinRHIZO program (WinRHIZO Pro (s) V. 2004a by Regent Instruments inc).

Root length density (RLD) was calculated as the ratio between root length (cm) and soil volume (cm^3). For each peanut genotype the relative contribution to each layer was calculated and defined as root length density percentage (%RLD). The % RLD from the first (0–15 cm) and second (15–30 cm) layer were added together and defined as a single 0 to 30 cm layer (upper soil layer). The third (30–45 cm) and fourth (45–60 cm) layers were determined as a single 30 to 60 cm layer (middle soil layer), while %RLD at the lower layers (fifth and sixth layers) were combined to form a single 60 to 90 cm layer. Thus, in this study %RLD was separated into three layers, including upper, middle and lower layers based on the layers of the neutron soil moisture meter readings.

Pod yield and pod harvest index (PHI)

For each plot, plants in area of 9.0 m^2 were harvested at maturity (R8) (Boote 1982), the pods were air dried to approximately 8% moisture content, weighted then pod dry weight per harvested area was calculated. The PHI was calculated as pod dry weight per biomass excluding root.

Statistical analysis

Data for each year were analyzed separately because the G x E interaction was significant (data not shown), indicating that the response of peanut genotypes was different between the two seasons. Calculation procedures were done using MSTAT-C package (Bricker, 1989). The data were subjected to analysis of variance according to randomized complete block design. The mean comparison was based on Duncan's Multiple Range Test (DMRT) (Gomez and Gomez 1984).

Simple correlation was used to determine the relationship between pod yield and top dry weight at the most stressed date, top dry weight at harvest and pod harvest index. In addition the relationship between %RLD in each layer and pod yield and, top dry weight at the most stressed date, top dry weight at harvest and PHI. In each year, %RLD were categorized as either high or low using the mean of %RLD in each layer of all forty peanut genotypes. Then these peanut genotypes were segregated into combinative groups based on the high and low %RLD for each of the three soil layers i.e., upper, middle and lower layer.

Results and Discussion

Soil moisture content and meteorological conditions

The soil moisture content for both seasons was significantly reduced during the stress period at the soil depth of 30 cm (Figure 1) compared with soil moisture content before stress. The reduction in soil moisture content was less at 60 cm depth compared to 30 cm depth, and the smallest reduction was at the 90 cm depth. Soil moisture clearly indicated the pattern of mid-season drought and also reasonable management of water regimes.

The first experiment was conducted from December 2007 to May 2008. The mean air temperature ranged from 32.1 to 21.0°C during the season. There was no rainfall during the drought stress period and total rainfall during the season was 459.2 mm. The second experiment was conducted from November 2008 to April 2009. The mean air temperature ranged from 31.6 to 19.8°C during this season. There was no rainfall during the drought stress period and total rainfall during this season was 60.5 mm (Figure 2). Even though total rainfall was large in the first season, it did not occur during the mid-season drought period. Therefore, rainfall should not have an impact on the overall outcomes of this study.

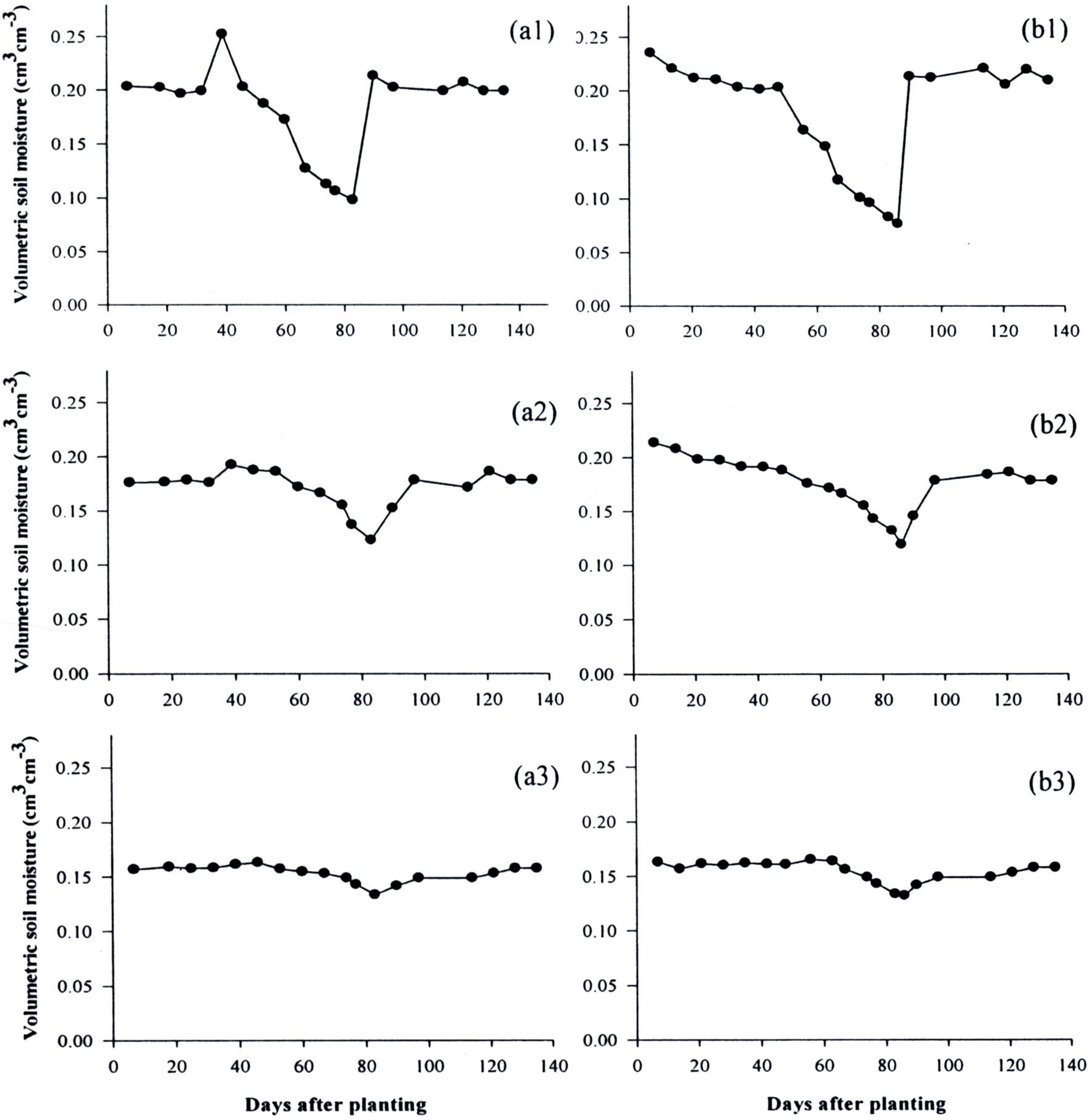

Figure 1 Volumetric soil moisture (fraction) for the in mid-season drought experiments conducted at Khon Kaen from December 2007 to May 2008 at a depth of 30cm (a1), 60cm (a2) and 90 cm (a3) and from during November 2008 to April 2009 season at a depth of 30 cm (b1), 60 cm (b2) and 90 cm (b3).

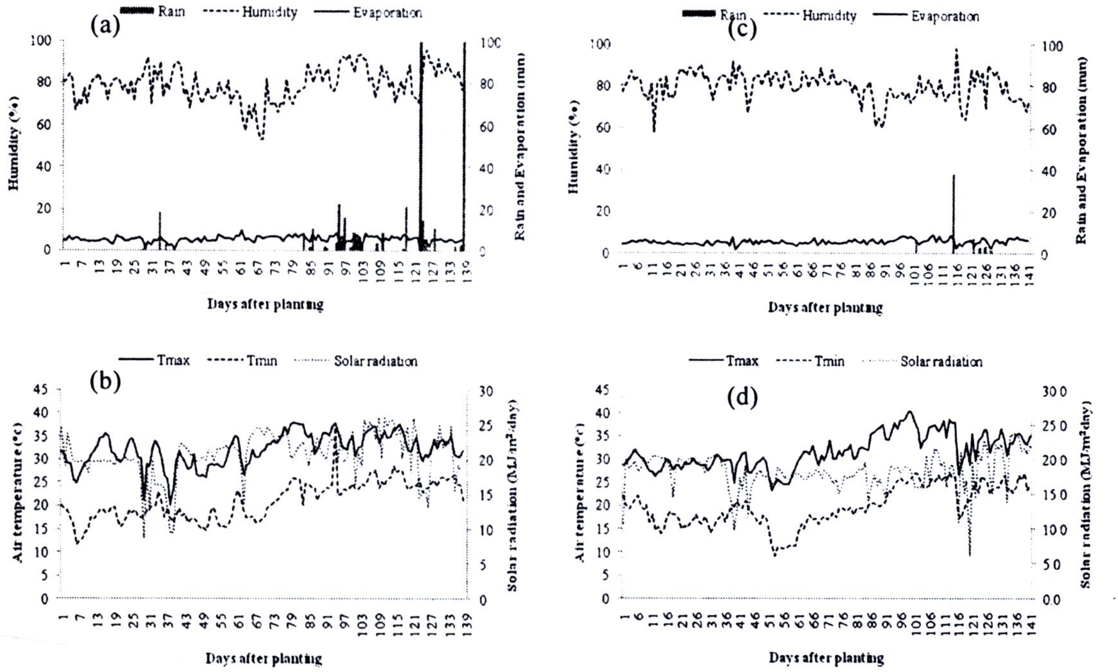

Figure 2 Rainfall, relative humidity (RH), evaporation (E0), maximum (T-max) and minimum (T-min) temperature and solar radiation from December 2007 to May 2008 (a,b) and from November 2008 to April 2009 (c,d) recorded at the meteorological station of Khon Kaen University, Khon Kaen, Thailand.

Root distribution patterns of peanut

Forty peanut genotypes were categorized as either high or low %RLD depending on the mean of %RLD of each layer for the three soil layers defined previously as upper (0-30 cm soil depth), middle (30-60 cm soil depth) and lower (60-90 cm soil depth). For the first season, the range for the high %RLD genotypes for the upper layer was 67.3-56.1%, whereas the range for the low %RLD genotypes was 54.9-39.1%. For the middle layer, the range of the high %RLD genotypes was 33.4-27.2%, while the range for the low %RLD was 27.0-17.8%. For the lower layer, the range for the high %RLD genotypes was 28.7-17.4%, while the range for the low %RLD genotypes was 17.0-5.6% (Table 2). For the second season, the range for the high %RLD genotypes for the upper layer was 77.8-50.5%, whereas the range for the low %RLD genotypes was 49.8-33.5%. The range of the high %RLD genotypes represented as 41.4-31.1% in middle layer, whereas the range of the low %RLD genotypes was 30.7-15.1%. In lower layer, there was 32.0-19.5% for the range of the high %RLD genotypes, while the range of the low %RLD genotypes was defined as 19.0-6.5% (Table 2).

Table 2 The range of root length density percentage (%RLD) for high and low groups for three layers as upper, middle and lower layers in season1 (December 2007- May 2008) and in season 2 (November 2008- April 2009) at Khon Kaen University, Khon Kaen, Thailand.

Season	Layer	Soil depth (cm)	High %RLD (range)	Low %RLD (range)
Season 1	Upper layer	0-30	67.3-56.1	54.9-39.1
	Middle layer	30-60	33.4-27.2	27.0-17.8
	Lower layer	60-90	28.7-17.4	17.0-5.6
Season 2	Upper layer	0-30	77.8-50.5	49.8-33.5
	Middle layer	30-60	41.1-31.1	30.7-15.1
	Lower layer	60-90	32.0-19.5	19.0-6.5

RLD and %RLD were the highest in the top soil, and they gradually decreased with increasing soil depths under both sufficient water conditions (Pandey et al., 1984; Ketring and Reid 1993), and similar results were also observed under long-term drought conditions (Songsri et al., 2008). In this study, %RLD under mid-season drought was reduced with increasing soil depths similar to other conditions. However, the observed genotypic variation was high. This may be due to the large number of genotypes that were used in this study. The impact of genetics for root growth was shown by Songsri et al. (2008). They studied the change in %RLD for the 40 to 100 cm soil layer for an extended period of drought conditions and they reported that 11 peanut genotypes had different %RLD in deeper soil layers under adequate water, mild water stress and severe water stress conditions. Furthermore, Benjamin and Nielsen (2006) demonstrated that water stress resulted in smaller proportions of chickpea and field pea roots in the upper soil layer (0.23 m) compared to adequate water conditions, and suggested that these species are suited for dry-land conditions. Therefore, there may be a relationship between %RLD in the deeper soil layers and yield under drought environments.

Forty peanut genotypes were categorized into six combinative groups (Table 3), based on the high and low %RLD for each of the three layers as upper, middle and lower layers. Five peanut genotypes were defined HHL, four genotypes categorized as HLL, five peanut lines were classified as LHL, 10 peanut genotypes were defined as LHH, seven peanut genotypes were defined as low LLH, and two peanut lines were classified as HLH (Figure 3; Table 3).

Table 3 Classification of 33 peanut genotypes for six root distribution patterns from the experiment conducting during December 2007- May 2008 and during November 2008- April 2009 at Khon Kaen University, Khon Kaen, Thailand.

Patterns	Peanut lines				
HHL	Tainan 9	KK60-2	KS2	KK 4	35 Grif 13932
HLL	306 PI 430237	248 Grif 13911	97 PI 158854	303 PI 430230	
LHL	187 PI 433352	283 PI 234375	KKU 40	ICGV 98305	100 PI 162604
LHH	101 PI 268659	89 PI 157549	KK60-3	KKU 60	ICGV 98300
	ICGV 98330	102 PI 268660	Taiwan 2	Luhua 11	KK 6
LLH	269 PI 157542	KKU 72-1	ICGV 98324	ICGV 98348	106 PI 268949
	Taiwan 1	Tifton – 8			
HLH	ICGV 98353	204 PI 442572			

HHL=high RLD in upper and middle layers but low RLD in lower layer, HLL= high RLD at upper but low RLD at middle and lower layers, LHL= low RLD in upper and lower layers but high RLD in middle layer, LHH= low RLD in upper layer but high RLD in middle and lower layers, LLH= low RLD in upper and middle layers but high RLD in lower layer, HLH= high RLD in upper and lower layers but low RLD in middle layer.

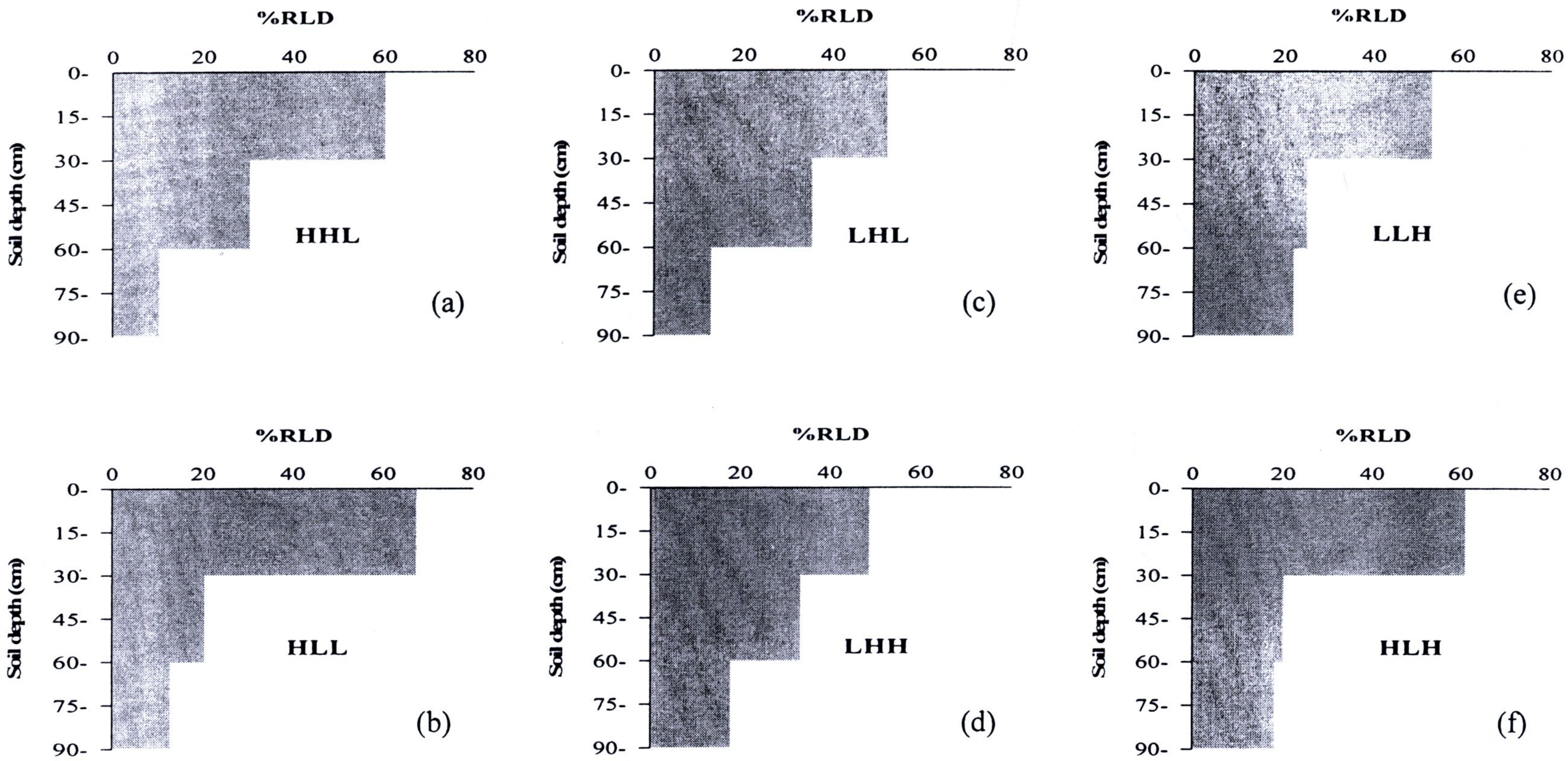

Figure 3 Six root distribution patterns of 40 peanut genotypes from the experiments conducting during December 2007- May 2008 and during November 2008- April 2009 at Khon Kaen University, Khon Kaen, Thailand.

HHL= high RLD in upper and middle layers but low RLD in lower layer (a), HLL= high RLD at upper but low RLD at middle and lower layers (b), LHL= low RLD in upper and lower layers but high RLD in middle layer (c), LHH= low RLD in upper layer but high RLD in middle and lower layers (d), LLH= low RLD in upper and middle layers but high RLD in lower layer (e), HLH= high RLD in upper and lower layers but low RLD in middle layer (f).

In this experiment, under mid-season drought conditions, 19 peanut genotypes had a greater %RLD in the lower soil layer appeared in LHH, HLH and LLH. These observations agreed with Pandey et al. (1984), who reported that the drought environment increased RLD of peanut in the lower soil profile. However, the previous report observed only a single peanut genotype. Under these conditions, there were 14 peanut genotypes which had a smaller %RLD in the deeper soil layer under these conditions as HHL, LHL and HLL. Even though this investigation has different drought conditions from Songsri et al. (2008), these results confirmed the previous report that different peanut genotypes responded differently for RLD in deeper soil when subject in long period droughts. There were seven peanut lines i.e., 12 PI 430233, 5 PI 313160, KK 5, KKU 1, ICGV 98303, ICGV 98308 and 3 PI 313157 that could not be classified into root distribution patterns due to inconsistent results in %RLD patterns between seasons.

Pod yield, top dry weight and PHI under mid-season drought conditions and relationships between those traits

Pod yield, top dry weight and pod harvest index (PHI) exhibited significant genotypes x environment interaction (data not shown). Therefore, the results were analyzed by year (Table 4 and 5). All traits i.e., top dry weight at the most drought-stressed date (the first season at 83 DAS and the second season at 87 DAS), top dry weight at harvest, pod yield and PHI showed highly differences among peanut lines for both seasons under mid-season stress (Table 4 and 5).

Table 4 Pod yield (PY), top dry weight at 83 days after sowing (TDW at 83 DAS), top dry weight at harvest (TDW at harvest) and pod harvest index (PHI) of peanut genotypes evaluated during December 2007- May 2008 at Khon Kaen University, Khon Kaen, Thailand.

Genotypes	PY (kg/ha)		TDW at 83 DAS (kg/ha)		TDW at harvest (kg/ha)		PHI	
KKU 60	2923	a	3348	a-d	7702	a	0.270	ab
Luhua 11	2913	a	2941	a-g	7286	abc	0.279	a
Taiwan 1	2587	ab	3422	abc	7441	ab	0.228	a-g
KKU 72-1	2499	abc	3058	a-f	6988	a-d	0.256	abc
Tifton – 8	2302	a-d	2617	b-h	6352	a-f	0.248	a-d
35 Grif 13932	2275	a-e	3557	ab	7265	abc	0.235	a-e
KK 5	2142	a-f	2956	a-g	6530	a-e	0.244	a-e
106 PI 268949	2057	a-f	2641	b-h	6130	a-h	0.250	a-d
KK60-3	1932	a-g	2427	c-h	5791	c-i	0.232	a-f
101 PI 268659	1799	b-h	3020	a-f	6250	a-g	0.223	a-h
269 PI 157542	1776	b-h	2873	a-g	6080	b-h	0.220	a-i
ICGV 98353	1664	b-i	2693	b-h	5789	c-i	0.197	c-m
ICGV 98305	1659	b-i	2802	a-g	5893	b-h	0.219	a-i
89 PI 157549	1655	b-i	2638	b-h	5724	c-i	0.209	b-j
KK 6	1620	b-i	2214	e-h	5821	b-h	0.218	a-i
Taiwan 2	1615	b-i	2955	a-g	6002	b-h	0.199	c-m
204 PI 442572	1568	b-i	2504	b-h	5504	d-i	0.215	a-i
ICGV 98324	1518	c-i	2417	c-h	5368	e-i	0.188	d-m
12 PI 430233	1486	c-i	2288	d-h	5206	e-i	0.206	b-k
KKU 1	1465	c-i	2850	a-g	5747	c-i	0.198	c-m
ICGV 98330	1461	c-i	2596	b-h	5489	d-i	0.180	e-n
KS2	1437	d-i	2407	c-h	5275	e-i	0.214	a-i
97 PI 158854	1353	d-i	2274	d-h	5060	e-j	0.207	b-k
KK60-2	1304	d-i	2144	e-h	4880	f-j	0.201	c-m
KKU 40	1278	d-i	3030	a-f	5740	c-i	0.180	e-n
ICGV 98348	1270	d-i	2715	a-h	5417	d-i	0.190	d-m
102 PI 268660	1268	d-i	2688	b-h	5389	d-i	0.188	d-m
ICGV 98303	1234	e-i	1888	gh	4554	hij	0.204	c-l
ICGV 98308	1177	f-i	2907	a-g	5515	d-i	0.168	f-n
3 PI 313157	1099	f-i	2010	e-h	4541	hij	0.190	d-m
248 Grif 13911	1095	f-i	2919	a-g	5446	d-i	0.167	f-n
303 PI 430230	1089	f-i	2483	b-h	5004	e-j	0.165	g-n
5 PI 313160	1046	ghi	3843	a	6321	a-g	0.156	i-n
KK 4	895	ghi	3118	a-e	5444	d-i	0.139	lmn
187 PI 433352	864	ghi	1977	fgh	4273	ij	0.164	g-n
283 PI 234375	837	ghi	2459	b-h	4728	g-j	0.143	k-n
100 PI 162604	789	hi	2378	c-h	4599	hij	0.147	j-n
Tainan 9	749	hi	2421	c-h	4602	hij	0.136	mn
ICGV 98300	719	hi	3016	a-g	5167	e-j	0.121	n
306 PI 430237	538	i	1605	h	3575	j	0.120	n
Mean	1524		2677		5647		0.198	

Mean in the same column with the same letters are not significantly different Duncan's multiple range test (DMRT) at $p \leq 0.05$.

Table 5 Pod yield (PY), top dry weight at 87 days after sowing (TDW at 87 DAS), top dry weight at harvest (TDW at harvest) and pod harvest index (PHI) of peanut genotypes evaluated during November 2008- April 2009 at Khon Kaen University, Khon Kaen, Thailand.

Genotypes	PY (kg/ha)	TDW at 87 DAS (kg/ha)	TDW at harvest (kg/ha)	PHI
Luhua 11	1751 a	1390 c-f	3775 d-l	0.315 a
KKU 60	1536 a	1586 bc	5213 a	0.234 b
KK 6	1102 b	1975 a	3462 c-i	0.245 b
ICGV 98353	905 bc	1514 bcd	4941 ab	0.155 d-g
Taiwan 1	862 bcd	1956 a	3259 d-k	0.206 bc
ICGV 98348	797 cde	1122 e-l	3932 b-e	0.170 cde
KKU 72-1	646 def	1317 c-h	3317 d-j	0.161 c-f
ICGV 98305	602 ef	1342 c-g	3770 c-f	0.138 d-i
ICGV 98330	559 efg	888 j-o	2968 e-m	0.153 d-h
Tifton – 8	557 efg	1053 f-m	4508 abc	0.113 f-k
ICGV 98324	528 fgh	1267 c-i	3429 c-i	0.133 d-j
ICGV 98303	496 f-i	1229 d-j	3638 c-g	0.118 f-k
106 PI 268949	490 f-j	810 l-o	3324 d-j	0.130 d-j
KKU 1	488 f-j	1050 f-m	2625 f-m	0.153 d-h
101 PI 268659	484 f-j	1834 ab	4286 a-d	0.103 i-l
KKU 40	471 f-k	1408 cde	3267 d-k	0.124 e-j
KK60-2	453 f-l	965 h-o	2117 klm	0.175 cd
ICGV 98308	433 f-l	1001 g-n	3908 b-e	0.098 i-m
204 PI 442572	419 f-m	1023 g-n	3015 e-m	0.124 e-j
KK 5	417 f-m	860 k-o	3273 d-k	0.111 g-k
ICGV 98300	410 f-n	1314 c-h	3772 c-f	0.098 i-m
Taiwan 2	406 f-n	1118 e-l	2837 e-m	0.127 d-j
KK60-3	396 f-o	980 h-n	3382 c-i	0.103 i-l
269 PI 157542	332 g-o	735 mno	2131 klm	0.131 d-j
248 Grif 13911	325 g-o	937 i-o	2807 e-m	0.102 i-l
12 PI 430233	323 g-o	1041 f-m	2526 g-m	0.114 f-k
102 PI 268660	313 g-o	1075 e-m	3471 c-i	0.099 i-m
3 PI 313157	303 g-o	1177 d-k	2457 h-m	0.099 i-m
KK 4	296 h-o	1019 g-n	2708 f-m	0.097 i-m
187 PI 433352	289 h-o	1025 g-n	2206 j-m	0.117 f-k
303 PI 430230	269 i-o	1086 e-m	2304 i-m	0.106 h-l
306 PI 430237	264 i-o	740 mno	1960 m	0.120 f-k
Tainan 9	234 j-o	1047 f-m	2774 e-m	0.074 k-n
89 PI 157549	221 k-o	940 i-o	2052 lm	0.095 i-m
100 PI 162604	211 l-o	682 no	2581 g-m	0.075 k-
KS2	203 l-o	613 o	1976 m	0.095 i-m
35 Grif 13932	166 mno	1020 g-n	1925 m	0.089 j-m
5 PI 313160	153 no	919 i-o	2502 g-m	0.059 lmn
97 PI 158854	147 o	1162 d-l	3472 c-h	0.039 n
283 PI 234375	140 o	893 j-o	2582 g-m	0.053 mn
Mean	485	1128	3111	0.126

Mean in the same column with the same letters are not significantly different Duncan's multiple range test (DMRT) at $p \leq 0.05$.

According to the results, all traits exhibited poor productivity under mid-season drought conditions. Pod yield of peanut is very sensitive to severe mid-season drought (Pallas et al., 1979; Nageswara Rao et al., 1985; Meisner and Karnok 1992; Nautiyal 1999). However, we observed some lines which produced relatively high pod yield, top weight and PHI under mid-season conditions. The top ten lines which showed high pod yield under mid-season drought conditions and consistency during both seasons were KKU 60, Luhua 11, Taiwan 1, KKU 72-1, Tifton – 8, 106 PI 268949, 101 PI 268659, ICGV 98353, ICGV 98305 and KK 6. For top dry weight at the most drought stressed date, the top seven lines having high top weight under these conditions and consistent values for both seasons were KKU 60, KKU 40, Luhua 11, Taiwan 1, KKU 72-1, 101 PI 268659 and ICGV 98300. For top dry weight at harvest , the top five lines under severe mid-season water stress with consistent values in both seasons were Luhua 11, KKU 60, KKU 72-1, Tifton-8 and 101 PI 268659. For PHI, the following seven lines showed consistent high PHI during both seasons: KKU 60, Luhua 11, Taiwan 1, KKU 72-1, 106 PI 268949, ICGV 98348 and 269 PI 157542.

The relationship of those traits under mid season drought conditions were also defined in this study. Pod yield had highly significant correlation coefficients with top dry weight and PHI, the correlation between pod yield and top dry weight at the most stressed date were 0.49 and 0.51 for the first and the second seasons, respectively (Table 6), whereas top dry weight at harvest and pod yield had highly significant correlations of 0.89 for the first season and 0.58 for the second season (Table 6). Even though these observations were from mid-season drought conditions, they supported the relationship between pod yield and top dry weight from a previous report under different conditions (Del Rosario and Fajardo 1988). There was a positive correlation between pod yield and PHI of 0.94 and 0.83 in the first and the second season, respectively (Table 6). The harvest index determines pod yield under sufficient water conditions (Duncan et al., 1978) and moisture-limited environment (Passioura 1977; Nautiyal et al., 2002). For this study, PHI is an important trait that contributes to pod productivity under mid-season drought, but improved water extraction associated with deeper rooting may be the basis for sustaining the PHI.

Table 6 Correlation coefficients (r) (n = 40) between top dry weight (TDW) at 83 DAS, TDW at harvest, pod harvest index (PHI) and pod yield (PY) in season1 (December 2007- May 2008) and TDW at 87 DAS, TDW at harvest, PHI and PY in season 2 (November 2008- April 2009) at Khon Kaen University, Khon Kaen, Thailand.

Season		TDW at 83 or 87 DAS	TDW at harvest	PHI
Season 1	PY	0.49**	0.89 **	0.94 **
Season 2	PY	0.51**	0.58 **	0.83 **

** = significant at 1 % level

Relationship between %RLD and pod yield, top dry weight and PHI

Simple correlation coefficients between %RLD for three soil depths and pod yield, top dry weight and PHI were calculated for each season. For the upper layer (0-30 cm), the relationship between %RLD and pod yield was negative for both seasons (Figure 4 a, d), but was only significant for the second season. There was no significant correlation for in either season between pod yield and %RLD for the middle layer (30-60 cm) (Figure 4 b, e), indicating that %RLD in middle soil depth layer did not affect pod dry weight. For the lower layer (60-90 cm), %RLD was positively correlated with pod yield during both seasons (r = 0.42 and 0.58 for the first and the second seasons, respectively) (Figure 4 c, f). This shows that the amount of RLD in the lower layer is an important trait for pod yield under mid-season drought conditions. The relationships between %RLD and top weight at the most drought stressed date, top dry weight at harvest, and PHI all had similar responses under these water-stressed conditions (Table 7). There was a negative correlation between %RLD and these traits for the upper layer, except for PHI during the first season, whereas, for the middle layer there were no significant correlations for all variables. For both seasons, %RLD in the lower layer was positively correlated with top weight at the most drought-stressed date, top dry weight at harvest, and PHI.

Based on correlation between %RLD of deeper soil layers and pod yield, top dry weight, and PHI, the genotypes that partitioned root length density to the deeper soil layers produced higher pod yield, top dry weight, and PHI under mid-season drought conditions than the genotypes that did not. The relationship between %RLD in deeper soil at 60-90 cm and yield traits under mid-season drought has not been reported previously. However, these results support Songsri et al. (2008), who observed changes in root distribution in deeper soil layers and proposed that it could be a mechanism that helps peanut to maintain pod yield and HI under long periods of drought.

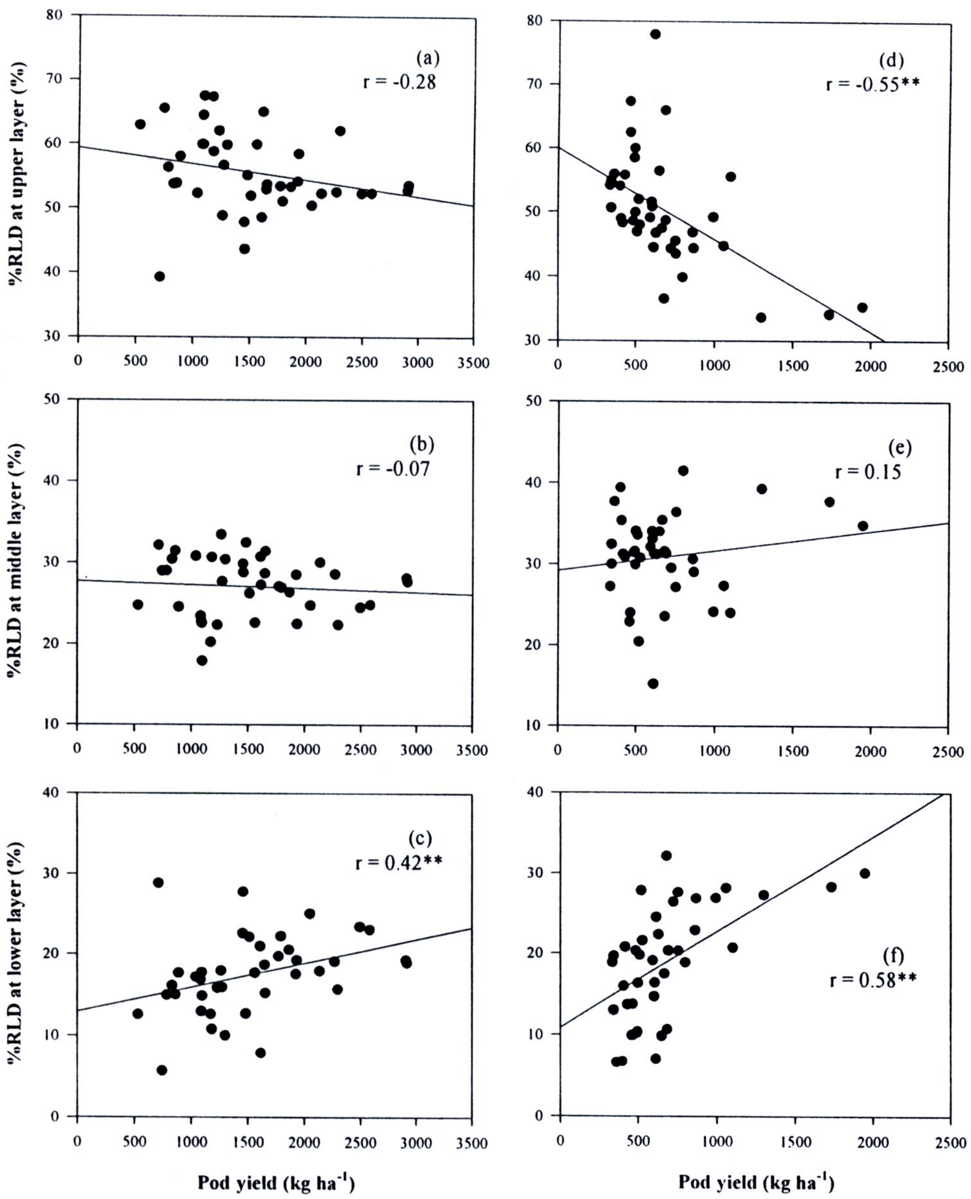

Figure 4 Relationship between pod yield and % root length density (%RLD) for three layers as upper (a), middle (b) and lower (c) in the first season (December 2007- May 2008) and upper (d), middle (e) and lower (f) in the second season (November 2008- April 2009) at Khon Kaen University, Khon Kaen, Thailand.

Table 7 Correlation coefficients (r) (n = 40) between top dry weight (TDW) at 83 or 87 DAS, TDW at harvest, pod harvest index (PHI) and % root length density (%RLD) for three layers as upper middle and lower in season1 (December 2007- May 2008) and season 2 (November 2008- April 2009) at Khon Kaen University, Khon Kaen, Thailand.

Season 1		TDW at 83 DAS	TDW at harvest	PHI
%RLD	upper layer	-0.42 **	-0.39 *	-0.21
%RLD	middle layer	0.14	0.02	-0.12
%RLD	lower layer	0.44 **	0.47 **	0.36 *

Season 2		TDW at 87 DAS	TDW at harvest	PHI
%RLD	upper layer	-0.48 **	-0.43 **	-0.37 *
%RLD	middle layer	0.25	0.01	0.14
%RLD	lower layer	0.42 **	0.55 **	0.36 *

*, ** = significant at 5, 1 % level, respectively

Conclusions

In summary, peanut genotypes were categorized into six combinative groups, based on the %RLD for each of the three layers (upper, middle and lower layers). The six combination groups were HHL, HLH, HLL, LHH, LHL and LLH. Forty peanut genotypes exhibited different top dry weight, pod yield and PHI under mid-season stress. The relationship between %RLD in the lower level and yield traits was highly positive, indicating that %RLD in the lower layer is an important trait that affects pod yield under mid-season drought conditions, probably because of more sustained water extraction during drought. The %RLD in middle soil layers did not affect yield under mid-season drought. Moreover, these observations also indicated that PHI is a very important trait affecting pod yield under mid-season drought. A higher PHI may be a result of sustained water extraction associated with greater %RLD in deeper layers, because the PHI was also positively correlated with the %RLD at depth.

Acknowledgments

The authors are grateful for the financial support of the Royal Golden Jubilee PhD Program (Grant no. PHD/0025/2548), the Senior Research Scholar Project of Professor Dr. Aran Patanothai under the Thailand Research Fund and the Office of Higher Education Commission (Thailand) and support of the Basic Research for Supporting Groundnut Varietal Improvement for Drought Tolerance Project under the Thailand Research Fund, Khon Kaen University. We thank the work of many people in field data collection and processing.

References

Awal, M. A., Ikeda, T., 2002. Recovery strategy follow the imposition of episodic soil moisture deficit in stands of peanut *(Arachis hypogaea* L.*)*. J. Agron. Crop Sci. 188, 185−192.

Benjamin, J. G., Nielsen, D. C., 2006. Water deficit effects on root distribution of soybean, field pea and chickpea. Field Crops Res. 97, 248–253.

Boote, K. J., 1982. Growth stage of peanut (*Arachis hypogaea* L.). Peanut Sci. 9, 35–40.

Bricker, A.A., 1989. MSTAT-C user's guide. Michigan State University.

Coffelt, T. A., Hammons, R. O., Branch, W. D., Mozingo, R.W., Phipps, P. M., Smith, J. C., Lynch, R. E., Kvien, C.S., Ketring, D.L., Porter, D.M., Mixon, A.C., 1985. Registration of Tifton-8 peanut germplasm. Crop Sci. 25, 203-203.

Dardanelli, J.L., Bachmeier, O.A., Śereno, R., Gil, R., 1997. Rooting depth and soil water extraction patterns of different crop in silty loam Haplustoll. Field Crops Res. 54, 29-38.

Del Rosario, D.A., Fajardo, F.F., 1988. Morphophysiological responses of ten peanut *(Arachis hypogaea* L.*)* varieties to drought stress. Philippine Agriculturist. 71, 447-459.

Duncan, W.G., McCloud, D.E., McGraw, R.L., Boote, K.J., 1978. Physiological aspects of peanut yield improvement. Crop Sci. 18, 1015-1020.

El Hafid, R., Smith, D. H., Karrou, M., Samir, K., 1998. Morphological attributes associated with early-season drought tolerance in spring durum wheat in Mediterranean environment. Euph. 101, 273−282.

Gomez, K. A., Gomez, A. A., 1984. Statistical procedures for agricultural research, 2nd edn. John Wiley & Sons, New York.

Jongrungklang, N., Toomsan, B., Vorasoot, N., Jogloy, S., Kesmala, T., Patanothai, A., 2008. Identification of peanut genotypes with high water use efficiency under drought stress conditions from peanut germplasm of diverse origins. Asian J. of Plant Sci. 7, 628-638.

Ketring, D.L., Reid, J.L., 1993. Growth of peanut roots under field conditions. Agron. J. 85, 80-85.

Matsui, T., Singh, B. B., 2003. Root characteristics in cowpea related to drought tolerance at the seedling stage. Exp. Agric. 39, 29–38.

Meisner, C. A., Karnok, K. J., 1992. Peanut root response to drought stress. Agron. J. 84, 159–165.

Nageswara Rao, R. C., Singh, S., Sivakumar, M. V. K., Srivastava, K. L., Williams, J. H., 1985. Effect of water deficit at different growth phase of peanut. I Yield response. Agron. J. 77, 782–786.

Nageswara Rao, R. C., Williams, J. H., Singh, M., 1989. Genotypic sensitivity to drought and yield potential of peanut. Agron. J. 81, 887-893.

Nageswara Rao, R. C., Reddy, L.J., Mehan, V.K., Nigam, S. N., McDonald, D., 1992. Drought research on groundnut at ICRISAT. In: S. N. Nigam, ed. Groundnut – A Global Perspective. Proc. International Workshop, p. 455. ICRISAT Center, Andhra Pradesh, India, 25–29 November 1991.

Nautiyal , P. C. , Ravindra, V., Zala, P. V., Joshi, Y.C., 1999. Enhancement of yield in groundnut following the imposition of transient soil-moisture stress during the vegetative phase. Exp. Agric. 35, 371–385.

Nautiyal, P. C., Nageswara Rao, R. C., Joshi, Y. C., 2002. Moisture-deficit induced changes in leaf water content, leaf carbon exchange rate and biomass production in groundnut cultivars differing in specific leaf area. Field Crops Res. 74, 67–79.

Nigam, S. N., Basu, M. S., Cruickshank, A. W., 2003. Hybridization and description of the trait-based and empirical selection programs. In: Breeding for drought-resistant peanuts, Report of a workshop held at ICRISAT Centre, Andhra Pradesh, India, 25–27 February 2002. pp. 15–17. ACIAR, Canberra, Australia.

Nigam, S. N., Chandra, S., Rupa Sridevi, K., Manoha Bhukta, A., Reddy, G. S., Nageswara Rao, R. C., Wright, G. C., Reddy, P. V., Deshmukh, M. P., Mathur, R. K., Basu, M. S., Vasundhara, S., Vindhiya Varman, P., Nagda, A. K., 2005. Efficiency of physiological trait-based and empirical selection approaches for drought tolerance in groundnut. Ann. App. Biol. 146, 433–439.

Pallas, J. E., Stansell, J. R., Koske, T. J., 1979. Effects of drought on Florunner peanuts . Agron. J. 71, 853–858.

Pandey, P. K., Herrera, W. A. T., Villegas, A. N., Pendleton, J. W., 1984. Drought response of grain legumes under irrigation gradient: III. Plant growth. Agron. J. 76, 557–560.

Passioura, J. B., 1977. Grain yield, harvest index and water use of wheat. J. Aust. Inst. Agric. Sci. 43, 117-120.

Passioura, J. B., 1983. Roots and drought resistance. Agric. Water Manage. 7, 265–280.

Puangbut, D., Jogloy, S., Vorasoot, N., Akkasaeng, C., Kesmala, T., Patanothai, A., 2009. Variability in yield responses of peanut (*Arachis hyogaea* L.) genotypes under early season drought. Asian J. of Plant Sci. 8(4), 254-264.

Reddy, T. Y., Reddy, V. R., Anbumozhi, V., 2003. Physiological responses of peanut (*Arachis hypogaea* L.) to drought stress and its amelioration: a critical review. Plant Growth Regul. 41, 75–88.

Robertson, W. K., Hammond, L. C., Johnson, J. T., Boote, K. J., 1980. Effects of plant-water stress on root distribution of corn, soybeans, and peanuts in sandy soil. Agron. J. 72, 548–550.

Songsri, P., Jogloy, S., Vorasoot, N., Akkasaeng, C., Patanothai, A., Holbrook, C.C., 2008. Root distribution of drought-resistant peanut genotypes in response to drought. J. Agron. Crop Sci. 19, 92-103.

Taiz, L., Zeiger, E., 2006. Stress physiology. In: L. Taiz, and E. Zeiger, eds. Plant Physiology, 4th edn, pp. 671–681. Sinauer Associates, Inc., Sunderland, MA.

Turner, N. C., 1986. Adaptation to water deficits: A changing perspective. Aust. J. Plant Physiol. 13, 175–190.

Vorasoot, N., Songsri, P., Akkasaeng, C., Jogloy, S., Patanothai, A., 2003. Effect of water stress on yield and agronomic characters of peanut (*Arachis hypogaea* L.). Songklanakarin J. Sci. Technol. 25, 283–288.

Wright, G. C., Nageswara Rao, R. C., 1994. Peanut water relations. In: J. Smartt, ed. The Peanut Crop. pp. 281–325. Chapman & Hall, London.