Australian Journal of Crop Science AJCS

AJCS 6(1):81-92 (2012) ISSN:1835-2707

Growth and yield of soybean cultivars as affected by ground water levels and phosphorus rates grown under greenhouse and field conditions

Rattiyaporn Jaidee[1], Anan Polthanee[1*], Patcharee Saenjan[1]

[1]Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, 40002, Thailand

*** Corresponding author: panan@kku.ac.th**

Abstract

Experiments were conducted under greenhouse and field conditions to investigate the effects of P application rates and the responses of soybean cultivars to different ground water levels. The results of the greenhouse experiment showed that ground water level recession reduced root dry weight, root length density, shoot growth, yield components, and consequently, the grain yields of KKU74 and SJ5cultivars. Rapid ground water recession affected soybean yield reduction more than slow recession. P application increased both root and shoots growth, and tended to produce higher grain yields than the absence of P application. With P application, KKU74 had a higher grain yield than SJ5. The results of field conditions showed that P application rates had no significant effect on leaf area, LAI, shoot dry weight and the grain yields of the three soybean cultivars. However, KKU74 with P applications at the maximum rate of 58 kg $p_2o_5ha^{-1}$ tended to produce the highest grain yields. Under both greenhouse and field conditions, KKU74 with P application had the highest grain yields, shoot growth and root length density (lower than the 75-cm depth from the soil's surface) with ground water level recession. These results indicate that this cultivar is better adapted to water stress and appropriate to growing after rice in a paddy field without irrigation. However, it is suggested that the ground water level before planting should be higher than 80 cm depth from the soil's surface.

Keywords: Ground water level, phosphorus, root length density, leaf water potential, stomatal resistance, soybean, yield.
Abbreviations: DAP-day after planting, DAE-day after emergence, LWP-leaf water potential, RLD-root length density, RWC-relative leaf water content.

Introduction

Soybean has a high protein and fat content, so it is widely used for both food and forage. It also has industrial uses. Thus, its worldwide production and consumption are increasing every year. However, in Thailand, its production is not sufficient to meet human and animal needs. In 2009, about 1.5 million tons of soybeans were imported (OAE, 2010). Therefore, increasing soybean production is an important priority in Thailand, and growing soybean after rice can be one way to increase production. In many rain-fed lowland rice-growing areas with shallow water tables, the production of a post-rice crop offers an alternative way for farmers to increase income. Late rains can be used to grow a short-maturing upland crop successfully (Polthanee, 1989). Soybean is a legume crop that can be grown after rice without irrigation by using residual soil moisture at the end of the rainy season and additional soil moisture is made available by capillary rising from a shallow water table. However, the plants may be subjected to drought at the grain-filling stage, especially during years in which rainfall stops early at the end of the rainy season. Drought is important to growth and yield reduction, especially drought stress occurring at reproductive stages, such as water stress at R1 (initial flowering), R3 (initial pod), R5 (beginning seed), and R6 (full seed) stages, resulting in substantial yield reduction as compared to full irrigation (Dogan et al., 2007; Desclaux et al., 2000; Frederick et al., 2001). Water stress during early pod formation causes the greatest reduction in the number of pods and seeds at harvest. The yield is reduced most by stress during early formation and pod filling (Sionit and Kramer, 1977). Ground water level depth in paddy fields before planting may differ from year to year depending on rainfall in the latter part of the rainy season. Ground water depth has effects on the growth and yield of soybean after rice without irrigation. Photosynthetic rates, stomatal conductance, and yield were higher when ground water was at 60 cm depth below the surface as compared to depths lower than 60 cm (Sarwar, 2002). Ground water depth of 70 cm below the soil surface had higher grain yields and yield components as compared to depths of 40 cm (Shimada et al., 1995). However, ground water at 75 cm depth increased grain yields more than ground water did at 50 cm depth (Mejia, 2000). Several researchers have found that ground water maintained at different depths had effects on the growth and yield of soybean. However, previous researches maintained the particular ground water depth and kept constantly until harvest stage. Nevertheless, the ground water level in the farmer's field decrease continuously but influence of ground water level recession on growth and yield of soybean was not clearly understood. Phosphorus is an essential element for the general health and vigor of all plants. Phosphorus stimulates root development, improves flower formation and seed production, promotes more uniform and earlier crop maturity, increases the nitrogen N-fixing capacity of legumes, improves seed quality, and increases resistance to plant diseases (Marshner, 1995). The development of a deep and vigorous root system is a key strategy for mitigating the effects of water stresses because of its essential role as a soil-plant interface (Vamerali et al., 2003; Jin et al., 2005). Root architecture is closely linked to the plant's uptake of water and nutrients that move with the water. Total root biomass, root length and surface area have been found to influence the nutrient uptake (Raper et al., 1978; Jin et al., 2002). Most paddy fields in rain-fed areas in the northeast of Thailand have low soil fertility and most of the soil texture is sandy (Bell and Seng, 2004). Therefore, P application could increase P availability in the soil and increase crop yield and development of the root system, which is one of the key factors for interpreting the effects of water stresses. The objective of this study was to investigate the effects of P application rates and the responses of soybean cultivars grown under greenhouse and field conditions to different ground water levels.

Results

Soil moisture content

In the greenhouse pot experiment, soil moisture content decreased after initiating ground water level treatments. The soil moisture content of the W0 treatment was maintained with available water (defined as the water content between field capacity and the permanent wilting point) at all growth stages (Fig. 2a). Soil moisture content of the W1 treatment decreased below the permanent wilting point (PWP) at the 40 and 60 cm soil depths at the R6 and R8 stages, respectively (Fig. 2b). The soil moisture content of the W2 treatment decreased below the PWP at the 60 and 80 cm soil depths at the R6 and R8 stages, respectively (Fig. 2c). Under field conditions, soil moisture content at the depths of 0-15 cm and 15-30 cm was mostly maintained in the available range during the entire growing period (Fig. 3a). Soil moisture content at depths of 0-15 cm and 15-30 cm declined until 13 weeks after planting, and had values close to PWP during the12th and 13th weeks after planting. Measured ground water depths ranged from 82 cm to 126 cm below ground surface during the growing period (Fig. 3b). The crops received 30.6 mm and 25.3 mm of rainfall at the 13th and 16th weeks after planting (Fig. 3b). Thus, the water available to crops was supplied mainly by the upward movement of water from shallow ground water and from residual soil moisture in the soil profile.

Yield and yield components

In the greenhouse experiment, ground water level recession significantly decreased grain yield, number of pods per plant, 100-seed weight, and harvest index (Table 1). The W2 water regime had the lowest number of pods per plant, 100-seed weight, harvest index, and grain yield (Table 2). P application had a significant effect on the harvest index, but it had no effect on yield and yield components. However, P application tended to have higher grain yield and yield components than without P application. There were significant differences between the two soybean cultivars for both yield and yield components. KKU74 had the highest yield, number of seeds per pod, 100-seed weight, harvest index, and shelling percentage, while SJ5 had the highest number of pods per plant (Table2). There were significant interactions among treatments for 100-seed weight. KKU74 with P fertilizer had the highest 100-seed weight. Under P fertilizer, KKU74 had a higher 100- seed weight under three ground water levels than SJ5 (Table 5, left-hand side). In the field experiment, P application rates had significant effects on the number of pods per plant, harvest index, and shelling percentage, but it had no effect on the number of seeds per pod, 100-seed weight and grain yield (Table 1). The highest number of pods per plant was obtained when soybean received P applied at the rate of 58 kg P_2O_5 ha^{-1}. The highest harvest index and shelling percentage were obtained when soybean received P applied at the rate of 29 kg P_2O_5 ha^{-1}. Soybean receiving P fertilizer at the rate 58 kg P_2O_5 ha^{-1} tended to have the highest grain yield and number of seeds per pod. Soybean receiving P fertilizer at the rate 29 kg P_2O_5 ha^{-1} tended to have the highest 100-seed weight. There were significant differences between the three soybean cultivars in grain yield and number of seeds per pod. KKU74 had the highest grain yield and number of seeds per pod (Table 2). There were no significant interaction effects between soybean cultivars and P application at any stage.

Shoot dry weight

In greenhouse conditions, shoot dry weight was affected by the interaction of phosphorus rates with ground water levels at the R5, R6 and R8 stages (Table 3). Under the W0 water regime, the soybeans receiving P fertilizer had the highest shoot dry weight. The P application achieved higher shoot dry weight than without the P application under three water regimes (Table 5, left-hand side). Groundwater level recession had significant effects on shoot dry weight at the R6 and R8 stages. The W2 treatment had the lowest shoot dry weight. Application of P had no effect on shoot dry weight at the R5 and R6 stages, except for at the R8 stage. Soybean cultivars were significantly different in shoot dry weight at the R8 stages. KKU74 had a higher shoot dry weight than SJ5 at the R8 stage (Table 3). In field conditions, shoot dry weight was affected by the interaction of soybean cultivars and P application rates at 45 DAE (Table 6). CM60 and KKU74 had higher shoot dry weight than SJ5 when receiving P fertilizer at the rate of 29 kg P_2O_5 ha^{-1} (Table 7). P application had no significant effects on shoot dry weight at 30, 45 and 60 DAE, although P application at the highest rate of 58 kg P_2O_5 ha^{-1} tended to produce the highest shoot dry weight. There were significant differences between soybean cultivars in shoot dry weight at 30, 45 and 60 DAE. The highest shoot dry weight was obtained with KKU74.

Leaf area and leaf area index (LAI)

In greenhouse conditions, leaf area was affected by the interaction of soybean cultivars and phosphorus rates at the R6 stage (Table 4). KKU74 with P had a higher leaf area than SJ5 with P (Table 5). Ground water level recession significantly decreased leaf area at the R6 stage. The W2 water regime had the lowest leaf area. P application at 31 mg P_2O_5 kg^{-1}soil increased leaf area significantly at the R6 stage. There were no significant differences in leaf area between soybean cultivars at the R5 and R6 stages, although KKU74 tended to have higher leaf area than SJ5 (Table 4). In field conditions, leaf area and LAI were affected by the interaction of the soybean cultivars with P application rates at 45 DAE (Table 6). The highest leaf area was obtained in CM60 at P rate of 29 kg $p_2o_5$ha^{-1}. Without P application, KKU74 and CM60 had higher leaf areas and higher LAI than did SJ5 (Table 7). P application had no significant effects on leaf area and LAI at 30 or 45, 60 DAE, but P application at the rate of 58 kg $p_2o_5$ha^{-1} tended to produce the highest leaf area. Soybean cultivars differed significantly in leaf area and LAI

Table 1. Mean squares from analysis of variance (ANOVA) for yield and yield components of soybean cultivars under greenhouse and field conditions.

		Greenhouse condition					
Source of variation	DF	Grain yield (g/pot)	Seed per pod (no.)	100 seeds weight (g)	Pod per plant (no.)	Harvest Index (HI)	Shelling (%)
Rep	2	2.22	0.08	1.01	1.44	0.002	11.82
Soybean cultivars (C)	1	183.60**	4.00**	253.18**	1308.03**	0.235**	2476.56**
Phosphorus rates (P)	1	0.61	0.11	3.91	34.03	0.021*	57.58
Ground water levels (W)	2	128.25**	0.25	59.88**	840.11**	0.015*	33.13
CxP	1	3.42	0.44	24.42*	0.25	0.016	65.26
CxW	2	10.77	0.08	4.09	122.11	0.004	38.44
PxW	2	11.83	0.19	7.08	56.78	0.007	291.75
CxPxW	2	1.94	0.03	19.15*	36.00	0.002	34.14
Error	22	11.08	0.24	3.41	79.72	0.004	126.27
Total	35						
		Field condition					
Source of variation	DF	Grain yield (kg/ha)	Seed per pod (no.)	100 seeds weight (g)	Pod per plant (no.)	Harvest Index (HI)	Shelling (%)
Rep	3	32394	0.18	2.23	207.88	0.020	292.56
Soybean cultivars (C)	2	111500*	4.53**	4.27	44.19	0.019	509.71
Error	6	18469	0.23	1.35	117.60	0.008	243.26
Phosphorus rates (P)	2	13212	0.11	0.22	106.36**	0.056**	535.37*
CxP	4	2055	0.28	0.29	29.61	0.005	23.63
Error	18	10353	0.19	0.16	8.86	0.005	123.59
Total	35						

*,** = significant at p<0.05 and p<0.01, respectively.

Table 2. Yield and yield components of soybean under greenhouse and field conditions.

	Greenhouse condition					
Treatments	Grain yield (g/pot)	Seed per pod (no.)	100 seeds weight (g)	Pod per plant (no.)	Harvest Index (HI)	Shelling (%)
Ground water levels (W)						
W0	14.18 a	1.33	15.30 a	40.08 a	0.30 a	51.30
W1	10.55 ab	1.58	12.03 b	29.42 b	0.27 ab	48.85
W2	7.65 b	1.58	11.03 b	23.58 b	0.23 b	48.13
Phosphorus rates (P)						
No P	10.66	1.44	12.46	30.06	0.24 b	48.16
31 mg P_2O_5/kg soil	10.92	1.56	13.18	32.00	0.29 a	50.69
Soybean cultivars (C)						
KKU74	13.05 a	1.83 a	15.44 a	25.00 b	0.34 a	57.72 a
SJ5	8.53 b	1.17 b	10.14 b	37.06 a	0.18 b	41.13 b
	Field condition					
	Grain yield (kg/ha)	Seed per pod (no.)	100 seeds weight (g)	Pod per plant (no.)	Harvest Index (HI)	Shelling (%)
Phosphorus rates (P)						
No P	273.34	2.25	12.60	13.75 b	0.16 b	36.58 b
29 kg P_2O_5/ha	287.82	2.25	12.85	18.33 a	0.29 a	49.41 a
58 kg P_2O_5/ha	336.67	2.42	12.80	19.33 a	0.24 a	39.76 b
Soybean cultivars (C)						
CM60	258.63 b	2.08 b	12.42	19.00	0.19	34.60
KKU74	409.33 a	3.00 a	13.44	15.17	0.27	44.05
SJ5	229.86 b	1.83 b	12.39	17.25	0.24	47.10

Mean in the same column with the same letters are not significantly different by LSD at p<0.05 and p<0.01, respectively.

at 30 and 45 DAE. The highest leaf area was obtained with KKU74.

Relative leaf water potential (LWP) and relative leaf water content (RWC) under greenhouse condition

Ground water level recession significantly decreased LWP at the R5, R6 and R7 stages (Table 4). The W2 water regime had the lowest LWP. P application had significant effect on LWP at the R5 stage only. There were significant difference in LWP among soybean cultivars at the R6, and R7 stages. KKU74 had the highest LWP. Interactions among treatments had no significant effects on LWP at R5, R6 and R7. RWC was affected by the interactions of the soybean cultivars with ground water levels at the R5 and R6 stages. KKU74 had a higher RWC than did SJ5 under the W1 and W2 water regimes (Table 5, right-hand side).

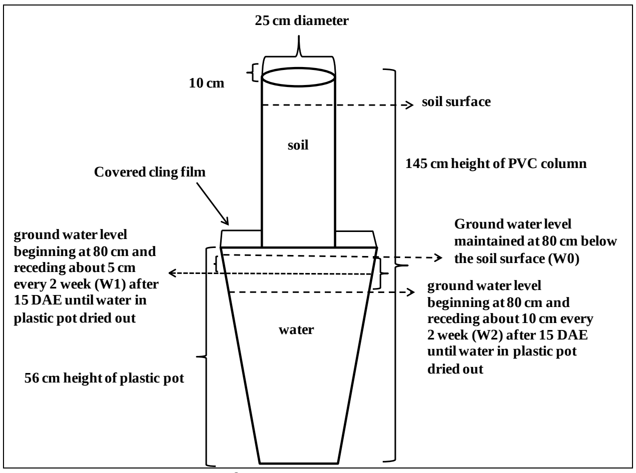

Fig 1. Diagram of the soil column and pot water holding containers in the greenhouse experiment.

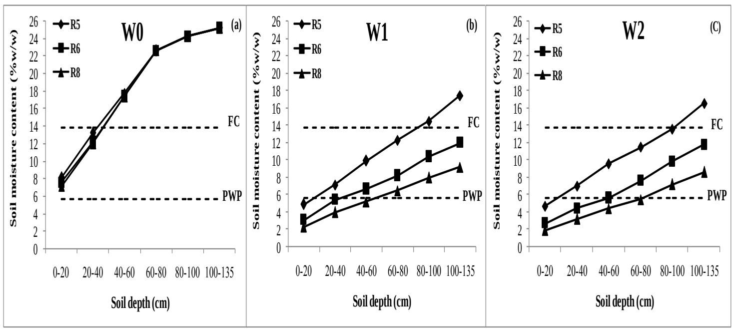

Fig 2. Average soil moisture content of three water table levels: (a) W0, (b) W1 and (c) W2 at 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm and 100-135 cm of soil depths at the R5, R6 and R8 stages in the greenhouse experiment.

Ground water level recession significantly decreased RWC at R5, R6 and R7 stages. The W2 water regime had the lowest RWC. P application significantly increased RWC only at the R6 stage. KKU74 had higher RWC than did SJ5.

Stomatal resistance

Under greenhouse conditions, the stomatal resistance was affected by the interactions of soybean cultivars with ground water levels at the R6, and R7stages (Table 3). Under the W1 and W2 water regimes, KKU74 had the highest stomatal resistance as compared to SJ5 (Table 5, right-hand side). Ground water level recession significantly increased stomatal resistance at the R5, R6 and R7 stages. The W2 water regime had the highest stomatal resistance. P application significantly increased stomatal resistance at the V6 stage. Stomatal resistance differed significantly between the two soybean cultivars at the R5, R6 and R7 stages. KKU74 had the highest stomatal resistance. Under field conditions, stomatal resistance was affected by the interaction of P fertilizer rates with the soybean cultivars at 45 DAE (Table 6). P application at the rate 58 kg P_2O_5 ha^{-1}, KKU74 had a higher stomatal resistance than CM60 and SJ5 (Table 7). P application rates significantly increased stomatal resistance at 45 DAE. Soybean cultivars had significant effects on stomatal resistance at 45 DAE. KKU74 had the highest stomatal resistance.

Root dry weight

In the greenhouse experiment, ground water level recession had significant effects on root dry weights at the R6 and R8 stages. The W2 water regime had the lowest root dry weight (Fig. 4a). P application at a rate of 31 mg P_2O_5 kg^{-1} soil had no significant effect on root dry weight at the R5, R6 and R8 stages. Soybean cultivars had significantly different root dry weights at the R5 stage. SJ5 had the highest root dry weight (Fig. 4b). The interaction among the three factors of ground water levels, P rates and soybean cultivars had no significant effects on root dry weight at the R5, R6 and R8 stages. Under field conditions, the density of the root dry weight was significantly affected by P application rates at 30 DAE. The highest density of root dry weight was obtained with 58 kg $p_2o_5ha^{-1}$ (Fig. 4c). Soybean cultivars had significant effects on the density of the root dry weight at 30 and 45 DAE. Among the three cultivars used in this study, the highest density of the root dry weight was obtained in KKU74, while SJ5 had the lowest density (Fig. 4d). No interaction was found between the soybean cultivars and P application rates. Root growth was not detected at the soil depths of15-30 cm and 30-45 cm, due to inhibition of root penetration by a soil hardpan.

Root length density (RLD)

In greenhouse conditions, the RLD was affected by the interaction of ground water levels and the soybean cultivars at soil depths of 45-75 cm at the R5 and R8 stages (Table 8). At the R5 stage, SJ5 had a higher RLD than did KKU74 under the W0 and W1 water regimes. KKU74 had the highest RLD under the W2 water regime. At the R8 stage, SJ5 had higher RLD than did KKU74 at all water regimes (Table 9). Interactions among ground water levels, P rates and soybean cultivars had significant effects on RLD at 45-75 cm soil depth at the R8 stage. At the W1 and W2 water regimes, SJ5with P had higher RLD than KKU74 with P, while SJ5 with P had lower RLD than KKU74 with P under the W0 water regime (Table 9). P application significantly increased RLD of both KKU74 and SJ5 cultivars under the three water regimes. Ground water level recession significantly reduced RLD at the R5, R6 and R8 stages (Table 8). At the W2 water regime, the RLD was lower than W0, and the W1 water regime at soil depths of 0-45 cm and 45-75 cm, while the highest RLD was obtained with the W2 water regime at 75-135 cm soil depth. P application significantly increased RLD at the R6 and R8 stages. P application had higher RLD than did the absence of P application. There were significant differences in RLD between the two soybean cultivars at the R5, R6 and R8 stages. At the three water regimes, SJ5 had higher RLD than did KKU74 at soil depths of 0-45 cm and 45-75 cm, while KKU74 had the highest RLD at 75-135 cm soil depth (Fig. 5). RLD distribution with depth of two soybean cultivars at R8 stage, SJ5 with P had higher RLD than did KKU74 with P at 0-75 cm depth from soil surface at all water regimes. KKU74 with P had higher RLD than did SJ5 with P at 75-135 cm depth from soil surface under W2 water regime (Fig.5). In field conditions, P application had no effect on RLD at 30 DAE, but RLD significantly increased with P application at the rate of 58 kg P_2O_5 ha^{-1} at 45 and 60 DAE, resulting in a RLD of 0.086 cm/ cm^3 (Fig. 4d). Soybean

Table 3. Shoot dry weight and stomatal resistance of soybean under greenhouse conditions.

	Shoot dry weight (g/pot)			Stomatal resistance (s/cm)				
Treatments	R5	R6	R8	V2	V6	R5	R6	R7
Ground water levels (W)								
W0	29.11	44.87 a	29.22 a	0.51	0.99	0.89 b	1.79 b	2.08 b
W1	27.73	35.77 b	21.33 b	0.52	0.99	1.44 a	6.25 a	7.61 a
W2	26.66	32.08 b	19.17 b	0.64	1.52	1.67 a	6.63 a	12.69 a
Phosphorus rates (P)								
No P	27.49	37.49	17.99 b	0.55	0.59 b	1.17	4.25	5.76
31 mg P_2O_5/kg soil	28.17	37.66	21.81 a	0.57	1.75 a	1.50	5.53	6.80
Soybean cultivars (C)								
KKU74	26.74	38.25	27.47 a	0.53	1.48	1.97 a	8.71 a	9.59 a
SJ5	28.92	36.89	24.34 b	0.59	0.86	0.70 b	1.07 b	2.97 b
Ground water levels (W)	ns	**	**	ns	ns	*	*	*
Phosphorus rates (P)	ns	ns	*	ns	**	ns	ns	ns
Soybean cultivars (C)	ns	ns	*	ns	ns	**	**	**
CxP	ns	ns	ns	ns	ns	ns	ns	ns
CxW	ns	ns	ns	ns	ns	ns	*	*
PxW	*	**	*	ns	ns	ns	ns	ns
CxPxW	ns	ns	ns	ns	ns	ns	ns	ns
C.V. (%)	12.37	13.25	19.86	33.11	66.17	39.64	63.84	54.17

V2, V6, R5, R6, R7, R8 = second trifoliate, sixth trifoliate, beginning seed, full seed, beginning maturity and full maturity stages, respectively. *, ** = significant at $p<0.05$ and $p<0.01$, respectively. Mean in the same column with the same letters are not significantly different by LSD at $p<0.05$ and $p<0.01$, respectively.

Table 4. Leaf area, leaf water potential (LWP) and relative leaf water content (RWC) of soybean under greenhouse conditions.

	Leaf area (cm^2/pot)		LWP (bar)			RWC (%)		
Treatments	R5	R6	R5	R6	R7	R5	R6	R7
Ground water levels (W)								
W0	2036.02	1848.38 a	-10.60 a	-11.27 a	-12.31 a	87.45 a	86.64 a	84.91 a
W1	1752.85	877.28 b	-17.77 b	-22.04 b	-27.06 b	83.30 b	77.87 b	72.25 b
W2	1728.75	808.00 b	-22.44 c	-27.69 c	-31.17 c	81.90 b	76.19 b	66.50 b
Phosphorus rates (P)								
No P	1959.85	963.50 b	-18.81 b	-21.33	-24.36	83.75	79.45 b	74.49
31 mg P_2O_5/kg soil	2118.56	1325.61 a	-15.07 a	-19.33	-22.67	84.69	81.02 a	74.61
Soybean cultivars (C)								
KKU74	2096.06	1149.79	-15.93	-18.99 a	-22.11 a	87.12 a	84.13 a	78.14 a
SJ5	1982.36	1139.43	-17.94	-21.68 b	-24.92 b	81.31 b	76.34 b	70.96 b
Ground water levels (W)	ns	**	**	**	**	**	**	**
Phosphorus rates (P)	ns	*	**	ns	ns	ns	*	ns
Soybean cultivars (C)	ns	ns	ns	*	*	**	**	**
CxP	ns	*	ns	ns	ns	ns	ns	ns
CxW	ns	ns	ns	ns	ns	**	**	ns
PxW	ns	ns	ns	ns	ns	ns	ns	ns
CxPxW	ns	ns	ns	ns	ns	ns	ns	ns
C.V. (%)	25.70	26.50	18.18	16.63	14.98	3.69	2.76	6.76

R5, R6, R7 =, beginning seed, full seed, and beginning maturity stages, respectively. *, ** = significant at $p<0.05$ and $p<0.01$, respectively. Mean in the same column with the same letters are not significantly different by LSD at $p<0.05$ and $p<0.01$, respectively.

cultivars had no significant effect on RLD at 0-15 cm soil depth at 30 DAE, but subsequently, KKU74 had the highest RLD, reaching 0.88 cm cm^3 at 60 DAE (Fig. 4f). There was no effect on RLD from the interaction between the soybean cultivars and P application rates. In the greenhouse and field conditions, P application significantly increased RLD when the soybean suffered from the drying of the soil.

Discussion

In the greenhouse experiment, interactions among treatments had significant effects on 100-seed weight. SJ5 with P grown under the most severe W2 water recession regime had lower100-seed weight than did KKU74 with P, and consequently decreased grain yield due to the lowest root and shoot growth. This may be the result of less favorable plant water status resulting from decreased water uptake due to lower root length density at deeper soil depths (75 cm below the soil surface). This in turn resulted in decreased leaf area and shoot dry weight. This may be the result of decreased photosynthesis as well as reduced partitioning of photosynthase into the seed under drought condition, as evidenced by decreased 100-seed weight, shelling percentage and consequent grain yield reduction. In addition, water deficits have been shown to increase seed abortion, and the duration of the maturation period has been reduced by stress during seed filling, leading to accelerated senescence (Desclaux and Roumet, 1996) and decreased seed yield and

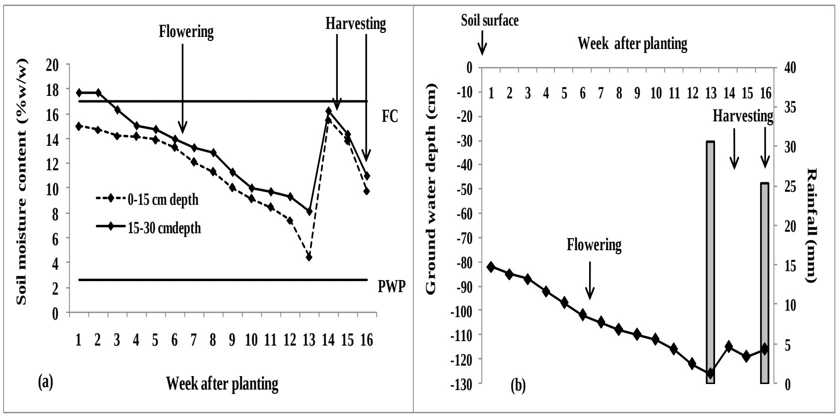

Fig 3. Average soil moisture content at (a) 0-15 cm, 15-30 cm depth and (b) ground water depth, rainfall during the field experimental period in 2006-2007 (1 December-22 March). Recorded by Khon Kaen meteorological station.

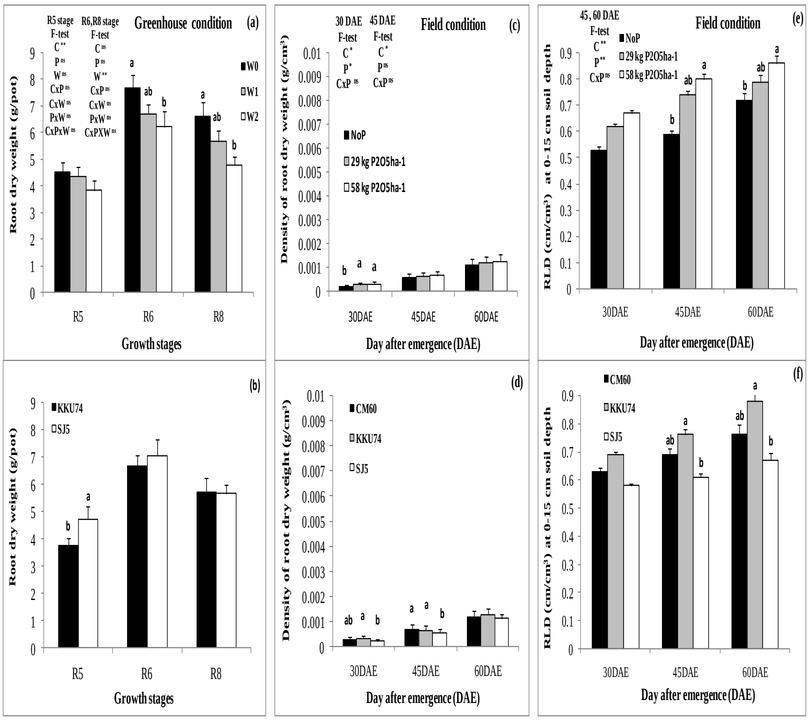

Fig 4. Root dry weight, density of root dry weight, and root length density (RLD) of soybeans cultivars, three water table levels, and phosphorus rates under greenhouse and field conditions. Values followed by the same letter at each growth stage were not significantly different at 0.05 and 0.01 probability. Error bars represent standard errors.

yield components (Sincik et al., 2008). Ground water level recession had significant negative effects on the grain yield of the soybeans. The most rapid ground water level recession regime (W2) had the lowest grain yield due to the soybeans suffering from a water deficit at the R5 stage, resulting in decreased root dry weight, root length density, leaf area, total shoot dry weight, RWC, LWP, the number of pods per plant, 100-seed weight and harvest index. Root dry weight and root length density have been shown to decrease under water deficits and have resulted in decreased water and nutrient uptake (Stanley et al., 1980; Shimada et al., 1995), reduced water content of soybean leaves, and reduced leaf area (Shimada et al., 1997; Gutierrez-Boem and Thomas, 2001).

A decrease in leaf area under water stress resulted in decreased photosynthesis (Boyer, 1982; Sarwar, 2002), reduced transpiration and cell expansion (Boyer, 1982), and consequently reduced total top dry weight and yield components (Liu et al., 2004). Water deficits increased total soluble carbohydrates and sucrose, reduced carbohydrates, and caused accumulation of proline and free amino acids in the leaves of soybeans (Da Silva Lobato et al., 2008) and other plants, resulting in decreased LWP. Under water stress, soybean leaves had a RWC less than 80%, and the LWP of soybean leaves was less than –10.2 bar, resulting in a rapid decrease in net photosynthesis (Flexas et al., 2006; Lei et al., 2006). Soybean stomatal resistance increased during dry periods due to plants adapting to drought by closing part of their stomata to reduce transpiration (Sionit and Kramer, 1976). In this study, P application rates had no significant effects on grain yield. However, P application tended to produce higher grain yields than without P application due to increased root and shoot growths, increased stomatal resistance, improved plant water status, and increased harvest index. P has been shown to contribute to greater

Table 5. The interaction among treatments of 100-seed weight, shoot dry weight, stomatal resistance, leaf area and relative leaf water content (RWC) under greenhouse conditions.

100-seeds weight (g)		
Cultivars	No P	31 mg P_2O_5 /kg soil
KKU74	14.29 a	16.59 a
SJ5	9.64 b	10.63 b
Mean	11.97	13.61

100-seeds weight (g)			
Cultivar*Phosphorus	W0	W1	W2
KKU74 without P	17.01 ab	12.10 ab	12.31 a
KKU74 with P	19.83 a	17.64 a	13.74 a
SJ5 without P	10.48 c	8.86 b	8.48 b
SJ5 with P	13.87 bc	9.53 b	9.58 ab
Mean	15.30	12.03	11.03

Shoot dry weight (g/pot)			
		R5 stage	
Phosphorus rates	W0	W1	W2
No P	26.60 b	27.28	25.60
31 mg P_2O_5 /kg soil	31.62 a	28.17	27.72
Mean	29.11	27.73	26.66
		R6 stage	
No P	40.85 b	35.07	29.02
31 mg P_2O_5 /kg soil	48.88 a	36.47	35.15
Mean	44.87	35.77	32.09
		R8 stage	
No P	42.45 b	39.58	34.32
31 mg P_2O_5 /kg soil	57.52 a	43.05	35.20
Mean	49.99	41.32	34.76

Stomatal resistance (s/cm)			
		R6 stage	
Cultivars	W0	W1	W2
KKU74	2.76 a	11.29 a	12.08 a
SJ5	0.82 b	1.22 b	1.27 b
Mean	1.79	6.26	6.68
		R7 stage	
KKU74	2.38	12.22	14.18 a
SJ5	1.77	5.66	6.47 b
Mean	2.08	8.94	10.33

Leaf area (cm^2/pot)		
		R6 stage
Cultivars	No P	31 mg P_2O_5 /kg soil
KKU74	726.80	1572.5 a
SJ5	1078.70	1200.2 b
Mean	902.75	1386.35

RWC (%)			
		R5 stage	
Cultivars	W0	W1	W2
KKU74	87.80	86.88 a	86.89 a
SJ5	87.10	79.72 b	77.12 b
Mean	87.45	83.30	82.01
		R6 stage	
KKU74	87.71	83.15 a	81.53 a
SJ5	85.52	72.59 b	70.85 b
Mean	86.62	77.87	76.19

W0, W1, W2 = ground water level maintained at 80 cm depth, ground water level recession at 5 cm, and 10 cm every 2 weeks, respectively. R5, R6, R7, R8 =beginning seed, full seed, beginning maturity and full maturity stages, respectively. Mean in the same column with the same letters are not significantly different by LSD at $p<0.05$ and $p<0.01$, respectively.

root dry weight and root length density, resulting in increased water and nutrient uptake (Jin et al., 2005; Jin et al., 2004). Stomatal resistance increased when soybean received P fertilizer due to the soybean plant closing part of its stomata to keep water from leaving the plant and thereby maintaining plant water status. The fact that P fertilizer contributed to stomatal closure may be due to increased abscisic acid (ABA) translocation into guard cells. ABA levels rose rapidly to 20 times greater than non-stressed plants when plants were subjected to water stress for 120 minutes (Beardsell and Cohen, 1975). Phosphorus deficiency in plants resulted in reduced leaf conductance and inhibited import and transport in the xylem (Jeschke et al., 1997). LWP and RWC were higher when the soybeans received P than when they had not as the P application stimulated root growth, and thereby increasing water and nutrient uptake, enabling the plant to maintain plant water status under drought conditions. The harvest index increased with P application due to higher root and shoot growths, and greater LWP and RWC. These results suggest that the soybean partitioned more photosynthase into the soybean seed, as evidenced by greater 100-seed weight with P application. This is similar to the results of Desclaux and Roumet (1996), in which P fertilizer increased root growth, shoot growth, plant water status and harvest index. These results are also similar to Jin et al. (2005) and Jin et al. (2004). Soybean cultivars differed in grain yield. KKU74 had higher grain yield than did SJ5, due to its higher root length density, leaf area, shoot dry weight, LWP, RWC, stomatal resistance, number of seeds per pod, 100-seed weight, harvest index and shelling percentage. KKU74 adapted to drought by producing roots at deeper soil depth (75 cm below the soil surface), enabling it to increase water and nutrient uptake, and maintain plant water status. This was evidenced in increased LWP, RWC, leaf area, shoot dry weight, and yield components. KKU74 appeared to keep more water in the plant by closing some parts of its stomata, resulting in increased stomatal resistance. Other studies have also found differences in the ability of different cultivars to partition photosynthase into roots, main stems, branches and seeds (Desclaux and Roumet, 1996), and differences in shoot-root ratios, reflecting different partitioning into biomass of stems, leaves and seed yield in soybean (Jin et al., 2006; Zhang et al., 2004). Some soybean cultivars produce fewer roots but may have a greater proportion of their roots deeper in the profile, enabling greater water and nutrient uptake under water stress (Brown and Scott, 1984). Taken as a whole, the above results showed that KKU74 was better adapted to drought than was SJ5. Under field conditions, the maximum grain yield, number of pods per plant, and number of seeds per pod were obtained when the soybean received fertilizer at the rate of 58 kg p_2o_5 ha^{-1}. This was likely due to the crop having a higher leaf area per plant, LAI, total shoot dry weight, plant height, density of root dry weight, and root

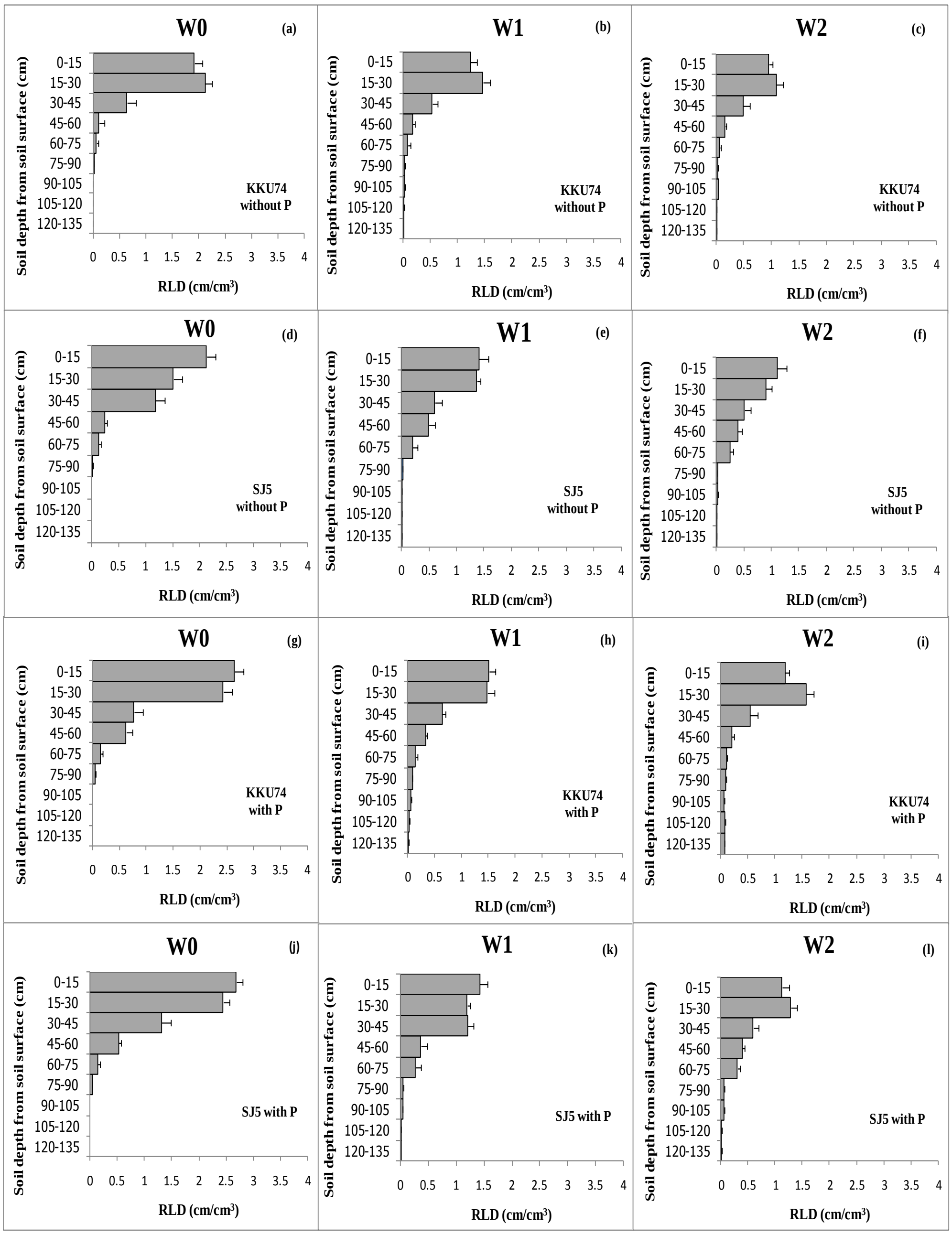

Fig 5. Root length density distribution with depth of soybean cultivars grown with three ground water levels at R8 stage under greenhouse condition. Error bars represent standard errors.

length density. Soybean yield was very low (229 to 409 kg ha^{-1}) due to the plants having suffered from drought and consequently having reduced root and shoot growth. This was indicated by soil moisture content reduced close to PWP in the 12^{th} and 13^{th} weeks at 0-15 cm depth from the soil's surface. The root could not also penetrate to deeper soil layer by soil hardpan for water uptake. P application at the rate of 58 kg P_2O_5 ha^{-1} significantly increased the density of root dry weight and root length density over the control. This indicated that P contributed to root growth. However, in this experiment, root growth did not extend below15 cm soil depth due to root growth having been inhibited by a soil hardpan. This result is similar to the result of Grecu et al. (1988), who reported that a clay pan soil inhibited root growth and water uptake. Sub-soiling tends to produce higher root growth of soybean than no-sub soiling. Application of P at any rate had no significant effect on leaf area per plant, LAI, and total shoot dry weight compared to the control of no P application. This was probably due to the presence of sufficient amounts of phosphorus (13 ppm) in the soil for soybean growth. The critical level of available P in soil for soybeans is 12 ppm (Rattanarat, 1999). In general, farmers applied 16-16-8 (N, P_2O_5, K_2O) fertilizer at a rate of 94 kg ha^{-1} to rice at the panicle initiation growth stage. Some P remains in the soil after rice harvesting. Kirchhof et al. (2000) reported that residual fertilizer effects from the previous rice crop could limit the response of soybean to P fertilizer. Suwanarit et al. (1978) reported that the addition of P of 11.3 ppm in the soil did not affect soybean growth. However, in the present experiment, P application at the rate of 58 kg $p_2o_5ha^{-1}$ resulted in better growth than P application at the rate of 29 kg $p_2o_5ha^{-1}$. This was probably due to an increased quantity of P in the soil. Under both greenhouse and field conditions, KKU74 with P fertilizer had the highest

Table 6. Mean squares from analysis of variance (ANOVA) for shoot dry weight, stomatal resistance leaf area, and leaf area index (LAI) under field conditions.

		Shoot dry weight (g/plant)			Stomatal resistance (s/cm)		
Source of variation	DF	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
Rep	3	0.10	3.27	19.16	1.29	0.14	0.36
Soybean cultivars (C)	2	0.25**	2.10*	15.15*	5.21	4.35**	0.69
Error	6	0.01	0.34	2.77	2.42	0.23	0.59
Phosphorus rates (P)	2	0.02	0.22	0.91	0.64	1.85**	0.71
CxP	4	0.01	0.99*	0.35	0.06	0.69*	0.04
Error	18	0.02	0.30	1.28	0.74	0.19	0.36
Total	35						
		Leaf area (cm^2/plant)			LAI		
Source of variation	DF	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
Rep	3	2547	42329	139492	0.010	0.169	0.552
Soybean cultivars (C)	2	4997**	18792*	67657	0.019**	0.076*	0.271
Error	6	217	3905	19124	0.001	0.016	0.076
Phosphorus rates (P)	2	720	2857	11944	0.003	0.011	0.050
CxP	4	295	13590*	5689	0.001	0.054*	0.023
Error	18	288	4615	11730	0.001	0.019	0.047
Total	35						

DF, DAE = degrees of freedom and days after emergence, respectively. *, ** = significant at $p<0.05$ and $p<0.01$, respectively.

Table 7. Shoot dry weight, stomatal resistance, leaf area, and LAI of three soybean cultivars at 45 DAE grown under different phosphorus rates under field conditions.

	Shoot dry weight (g/plant)			Stomatal resistance (s/cm)		
Cultivars	No P	29 kg P_2O_5/ha	58 kg P_2O_5/ha	No P	29 kg P_2O_5/ha	58 kg P_2O_5/ha
CM60	2.73 ab	3.41 a	2.36	0.74	0.86	1.07 ab
KKU74	2.80 a	2.56 ab	2.69	0.85	0.86	1.16 a
SJ5	1.60 b	1.95 b	2.59	0.91	0.73	0.83 b
Mean	2.38	2.64	2.55	0.83	0.82	1.02
	Leaf area (cm^2/plant)			Leaf area index (LAI)		
CM60	299.6 ab	360.99 a	260.07	0.60 ab	0.72 a	0.52
KKU74	329.07 a	295.74 ab	332.79	0.66 ab	0.59 ab	0.67
SJ5	193.49 b	221.35 b	321.17	0.39 b	0.45 b	0.64
Mean	274.05	292.69	304.68	0.55	0.59	0.61

Mean in the same column with the same letters are not significantly different by DMRT at $p<0.05$.

grain yield and was better adapted to drought. This was due to higher root growth, shoot growth, RWC, LWP, leaf area, and LAI than the other cultivars with P application. Shoot and root growth and yield decreased when soybean subjected to water stress of the both conditions. The results of these experiments indicated that ground water level beginning before planting at lower than 80 cm depth below soil surface could not appropriate to growing soybean after rice. Ground water level recession rapidly reduced growth and yield significantly at all soybean cultivars due to the plants subjected to water deficit at the reproductive stage under greenhouse and field conditions. These results overall indicate that not only a shallow water table, but also gradual depletion of the water table and adequate P in the soil are essential conditions for good post-rice soybean production. Soil mulching may help retard rapid water table reduction, and so, may be a useful and important strategy to improve the growth and yield of soybeans after rice harvesting.

Materials and methods

Greenhouse experiment

Experimental design and treatments

A pot experiment was conducted from March to June 2009 in the greenhouse of the Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Thailand, under natural sunlight and photoperiods. The experimental design was a randomized complete block design (RCBD) with 3 replications of a 2x2x3 factorial arrangement of treatments. Each experimental unit contained 3 sets of plants, for destructive sampling at different stages. The experimental conditions constituted: two soybean cultivars, KKU74 (an improved cultivar by Khon Kaen University of Thailand) and SJ5 (a traditional Thai variety); two P rates, 0 and 31 mg P_2O_5 kg^{-1} soil; and three ground water level regimes, ground water level at 80 cm depth below soil surface maintained during the entire growing period (control or W0), ground water level beginning at 80 cm depth and receding about 5 cm every 2 weeks (W1), and ground water level beginning at 80 cm depth and receding about 10 cm every 2 weeks (W2).

Plant materials and culture

The containers used in the experiment were columns made of PVC plastic, 145 cm in height and 25 cm in diameter. A hole was drilled at the bottom of each PVC column to permit water diffusion up through the soil profile. Each PVC column was put in a plastic pot (56 cm height and 42 cm diameter) for ground water level control. In the W1 and W2 treatments, ground water levels were reduced by using a hand water pump to remove water from the plastic pot, while in the W0

Table 8. Mean squares from analysis of variance (ANOVA) for root length density (RLD) and root dry weight under greenhouse conditions.

		RLD (cm/cm^3)								
		0-45 cm soil depth			45-75 cm soil depth			75-135 cm soil depth		
Source of variation	DF	R5	R6	R8	R5	R6	R8	R5	R6	R8
Rep	2	0.06	0.25	1.58	0.34	0.16	0.04	0.00	0.00	0.02
Cultivars (C)	1	5.35**	0.16	0.21	0.39	2.22**	1.10**	0.00	0.01	0.02
Phosphorus rates (P)	1	0.16	1.88*	0.16	0.10	0.05	0.32*	0.01	0.02*	0.14**
Ground water levels (W)	2	2.96**	25.44**	16.70**	0.55*	0.10	0.14	0.01	0.01	0.03
CxP	1	0.13	0.97	0.12	0.03	0.01	0.10	0.00	0.01	0.03
CxW	2	0.27	0.01	0.54	0.66*	0.26	0.26*	0.01	0.01	0.02
PxW	2	0.50	0.42	0.73	0.09	0.02	0.11	0.00	0.01	0.01
CxPxW	2	0.26	0.25	0.22	0.03	0.01	0.28*	0.01	0.01	0.03
Error	22	0.35	0.45	1.10	0.16	0.17	0.06	0.01	0.01	0.01
Total	35									

DF, = degree of freedom. R5, R6, R8 = beginning seed, full seed and full maturity stages, respectively.
*, ** = significance at $p<0.05$ and $p<0.01$, respectively.

Table 9. Root length density (RLD) at 45-75 cm soil depth from soil surface under greenhouse conditions.

	RLD (cm/cm^3)		
		R5 stage	
Cultivars	W0	W1	W2
KKU74	0.077	0.230 b	0.483 a
SJ5	0.228	0.932 a	0.252 b
Mean	0.153	0.581	0.368
Cultivars		R8 stage	
KKU74	0.467	0.357 b	0.268 b
SJ5	0.502	0.972 a	0.667 a
Mean	0.485	0.665	0.468
Cultivar*Phosphorus		R8 stage	
KKU74 without P	0.170 b	0.247 b	0.233 b
KKU74 with P	0.763 a	0.467 ab	0.303 b
SJ5 without P	0.370 b	0.690 ab	0.643 a
SJ5 with P	0.633 ab	1.253 a	0.690 a
Mean	0.484	0.664	0.467

W0, W1, W2 = ground water level maintained at 80 cm depth, ground water level recession at 5 cm and 10 cm every 2 weeks, respectively. R5, R8 =beginning seed and full maturity stages, respectively. Mean in the same column with the same letters are not significantly different by LSD at $p<0.05$.

treatment ground water level was maintained in soil column at 80 cm from the surface by adding water to the plastic pot (Fig.1). The soil used in the pot experiment was a Typic Hapludalf in the order Alfisols. The texture of the soil was a sandy loam, 5.7 pH, with 15 ppm extractable P (Bray II test), 14 ppm exchangeable K, 0.037% total N, and 0.61% organic matter content. The soil was air-dried and sieved through a 4-mm mesh sieve. Urea at the rate of 13 mg N kg^{-1} soil, KCl at the rate of 13 mg K_2O kg^{-1} soil and triple super phosphate at the rate of 31 mg P_2O_5 kg^{-1}soil were added to the soil in the P fertilizer treatment and were thoroughly mixed. Each PVC column was filled with 118 kg of soil (1.7 g/cm^3, and 1.8 g/cm^{3}of bulk density at 0-30, and 31-135 cm depth, respectively). All pots were watered to keep the soil surface at field capacity before seeding. Three days after sowing, water was added to the plastic pots up to 55 cm height from the bottom to maintain ground water levels below soil surface at 80 cm of soil column. Each plastic pot was covered with cling film to prevent water evaporation. Soybean seeds of each cultivar were inoculated with rhizobium before sowing. Five seeds of similar size were put 3 cm deep into the soil in each pot. Seedlings were thinned to 2 plants per pot 10 days after planting (DAP). At 15 days after emergence (DAE), ground water level treatments were initiated. Water was managed in the plastic pots every 2 days until the water in the plastic pots dried out. After that time, pots were not irrigated until the harvest stage. Carbosulfan and lambda-cyhalotrin were sprayed 3 times at 45, 60, and 75 DAE, to control aphids, leaf rollers, leaf miners and pod borers.

Recorded data

Soil moisture content at 0-20, 20-40, 40-60, 60-80, 80-100 and 100-135 cm depths were determined by the gravimetric method at the R5 (beginning of seed formation), R6 (full seed), and R8 (full maturity) stages. Leaf water potential (LWP) of the second, fully expanded trifoliate leaf from the top of the main stem was measured between 11:00 hr and 12:00 hr using a pressure chamber (PMS instrument Co., Corvallis, Oregon, USA) at the R5, R6, and R7 (beginning maturity) stages. Stomatal resistance was measured on first fully expanded leaf from the top of main stem at the V2 (second-node), V6 (sixth-node), R5, R6, and R7 stages between 12:00 and 13:30 hr by using a porometer (Delta-T Devices in Cambridge, U.K.). Relative leaf water content (RWC) was measured between 10:00 hr and 11:00 hr at these same stages using three leaflets of the first fully expanded trifoliate leaf from the top of the main stem of one plant in each pot. Relative leaf water content was calculated according to Barr and Weatherley's method (1962). Shoot dry weight was also determined at the R5, R6 and R8 stages. Each plant was carefully removed from its column by cutting off its stem above the soil surface. Each plant was separated into leaves, stems and pods. Leaf area was measured using a Li-COR 3100 leaf area meter (Lincoln, NE, USA). Plant parts were dried in an oven at 80^0C for 48 hours before dry-weight measurements were made. For root sampling, each soil column was divided into 15-cm depth intervals. Roots were extracted from each segment by washing them with water until they were free of soil. During the washing, a sieve with a mesh size of 1 mm was used to recover fine roots. Roots were scanned and total root length was measured by analyzing pictures taken with a WinRHIZO pro V2004a (Reagent Instruments Inc. Canadian company, Que, Canada). Root length density was calculated by dividing total root length (cm) by soil volume (cm^3). Root dry weight was determined by drying the roots at 80^0C for 48 hours. Plant samples were taken at the R8 stage for measurement of numbers of pods and branches per plant. Ten pods were taken at random to determine the number of seeds per pod. Hundred seeds weight was determined from two plants in each pot. Grain yield was calculated as the seed dry weight obtained from two plants in each pot. Harvest index was calculated by dividing seed dry weight by shoot dry weight. Shelling percentage was calculated by dividing the seed dry weight by the pod dry weight and multiplied by one hundred.

Statistical analysis

Analysis of variance (ANOVA) for all data was performed using Statistix 8 software (Analytical Software, Tallahassee, Florida, USA). The significance of mean differences was determined at the 0.05 and 0.01 probability levels. The Least Significant D (LSD) was used to compare means.

Field experiment

Plant culture and treatments

The field experiment was conducted from December 2006 to March 2007 in a farmer's field in Ban Fang district, Khon Kaen province. The soil was a Typic Hapludalf of the order Alfisols. The texture of soil was a sandy loam, 5.9 pH, with 0.033% total N, 13 ppm available P (Bray II test), 15 ppm exchangeable K, 0.72% organic matter content, 17.02% field capacity, and 2.61% permanent wilting point. A randomized complete block design with three replications of a split plot arrangement of treatments was used. Three soybean cultivars (high yield, widely used cultivar in northeast of Thailand and recommended by the Department of Agriculture), Chiangmai 60 (CM60), KKU74, and SJ5 were assigned as main plots, with three levels of P application: 0, 29, and 58 kg P_2O_5 ha^{-1} as sub plots. Plot size was 5 m × 4 m with spacing of 50 cm between rows and 20 cm between each plant in a row. The entire experimental area was ploughed twice and harrowed prior to planting. Urea at the rate of 19 kg N ha^{-1} and KCl at the rate of 19 kg K_2O ha^{-1} were applied into the soil before seeding in all treatments. The three rates of P were also applied into the soil before seeding. The seeds of all cultivars were inoculated with rhizobium before seeding. Four to five seeds were dropped in the furrows and covered using a Planet Junior hand-pushed seeder. Plants were thinned to 2 plants per hill at 15 days after planting (DAP) with plant population of 200,000 plants ha^{-1}. Plants were not irrigated throughout growing season. Hand weeding was done at 15 and 30 DAP. For insect control, triazophos and carbosulfan were sprayed 4 times at 30, 45, 60 and 75 DAE to control leaf rollers, leaf miners and pod borers.

Recorded data

The moisture content of soil samples from 0-15 cm and 15-30 cm depths was determined by using the gravimetric procedure at 7 DAP and at weekly intervals thereafter until harvesting. Ground water depth was measured at 7 DAP and weekly intervals thereafter until harvesting by using an observation well of perforated PVC tube 2 m long installed to a 1.50 m depth in each replication. Rainfall was recorded at weekly intervals thereafter until harvest at the Khon Kaen meteorological station. Four plants from each plot were taken at 30, 45 and 60 days after emergence (DAE) for shoot dry weight and leaf area measurements. LAI was calculated as the ratio between leaf area and the corresponding ground surface area. Stomatal resistance, yield, yield components, HI and Percentage of shelling were measured as in the greenhouse experiment. The harvesting area in each plot was 3 m^2. Root samples were taken by using soil cores at 0-15 cm, 15-30 cm and 30-45 cm soil depths. Root growth was also measured as in the greenhouse experiment.

Statistical analysis

Analysis of variance (ANOVA) for all data was performed using MSTAT-C software (Analytical Software, Michigan State University, Michigan, USA). Duncan's Multiple Range Test (DMRT) was used to compare treatment means when the F-test was significant. Density of root dry weight was calculated by dividing total root dry weight (g) by soil volume (cm^3).

Acknowledgements

This research was financially supported by the Royal Golden Jubilee Program of the Thailand Research Fund (Grant no. PHD/0083/2548). The authors thank Prof. Dr. Mary Beth Kirkham, Department of Agronomy, Kansas State University, for reviewing this manuscript and making useful suggestions.

References

Barr HD, Weatherley PE (1962) A re-examination of the relative turgidity technique for estimating water deficit in leaves. Aust J Biol Sci 15:413-428

Beardsell MF, Cohen D (1975) Relationships between leaf water status, abscisic acid levels, and stomatal resistance in maize and sorghum. Plant Physiol 56:207-212

Bell RW, Seng V (2004) Rainfed lowland rice-growing soils of Cambodia, Laos, and Northeast Thailand. In: Seng V, Craswell E, Fuikai S, Fischer K (eds) Water in Agriculture. ACIAR Proceedings No.116e, p 161-173

Boyer JS (1982) Plant productivity and environment. Science 218:443-448

Brown DA, Scott HD (1984) Dependence of crop growth and yield on root development and activity. *In*: Roots, nutrient and water influx, and plant growth, publication No. 49. American Society of Agronomy, Madison, Wisconsin. 101-136

Da Silva Lobato AK, De Oliveira Neto CF, Dos Santos Filho BG, Da Costa RCL, Cruz FJR, Neves HKB, Dos Santos Lopes MJ (2008) Physiological and biochemical behavior in soybean (*Glycine max* cv. Sambaiba) plants under water deficit. Aust J of Crop Sci 2(1):25-32

Desclaux D, Huynh TT, Roumet P (2000) Identification of soybean plant characteristics that indicate the timing of drought stress. Crop Sci 40: 716-722

Desclaux D, Roumet P (1996) Impact of drought stress on the phenology of two soybean (*Glycine max* L. Merr.) cultivars. Field Crops Res 46:61-70

Dogan E, Kirnak H, Copur O (2007) Deficit irrigations during soybean reproductive stages and CROPGRO-soybean simulations under semi-arid climatic conditions. Field Crops Res 103:154-159

Flexas J, Ribas-Carbo M, Bota J, Galmes J, Henkle M, Martinez-Canellas S, Medrano H (2006) Decreased Rubisco activity during water stress is not induced by decreased relative water content but related to conditions of low stomatal conductance and chloroplast CO_2 concentration. New Phytol 127: 73-82

Frederick JR, Camp CR, Bauer PJ (2001) Drought-stress effects on branch and main stem seed yield and components of determinate soybean. Crop Sci 41: 759-763

Grecu SJ, Kirkham MB, Kanemasu ET, Sweeney DW, Stone LR, Milliken GA (1988) Penetration resistance, root growth and water content in a subsoiled claypan. J Agron Crop Sci 161:195-206

Gutierrez-Boem FH, Thomas GW (2001) Leaf area development in soybean as affected by phosphorus nutrition and water deficit. J of Plant Nutr 24: 1711-1729

Jeschke WD, Peuke AD, Pate JS, Hartung W (1997) Transport, synthesis and catabolism of abscisic acid (ABA) in intact plants of castor bean (*Ricinus communis* L.) under phosphate deficiency and moderate salinity. J of Exp Bot 48 (314):1737-1747

Jin J, Liu XB, Wang GH (2002) Advance in root research of soybean [*Glycine max* (L.) Merrilt]. Soybean Sci 21: 223-228

Jin J, Wang G, Liu X (2004) Phosphorus nutrient affects root morphology response to water deficit at different reproductive stages in an early soybean cultivar. Proceedings of the International Crop Science Congress, Brisbane, Australia, 26 Sep.-1Oct. 2004 (Cited July 21, 2006). www. cropscience.org.au

Jin J, Wang G, Liu X, Pan X, Herbert SJ (2005) Phosphorus application affects the soybean root response to water deficit at the initial flowering and full pod stages. Soil Sci Plant Nutr 51 (7): 953-960

Jin J, Wang G, Liu X, Pan X, Herbert SJ, Tang C (2006) Interaction between phosphorus nutrition and drought on grain yield, and assimilation of phosphorus and nitrogen in two soybean cultivars differing in protein concentration in grains. J of Plant Nutr 29: 1433–1449

Kirchhof G, So HB, Adisarwanto T, Utomo WH, Priyono S, Prastowo B, Basir M, Lando TM, Subandi, Dacanay EV, Tan-Elicano D, Sanidad WB (2000) Growth and yield response of grain legumes to different soil management practices after rain-fed lowland rice. Soil & Tillage Res 56:51-66

Lei W, Tong Z, Shengyan D (2006) Effect of drought and rewatering on photosynthetic physioecological characteristics of soybean. Acta Ecologica Sinica 26:2073-2078

Liu F, Jensen CR, Andersen MN (2004) Drought stress effect on carbohydrate concentration in soybean leaves and pods during early reproductive development: its implication in altering pod set. Field Crops Res 86:1-13

Marschner H (1995) Mineral nutrition of higher plants. 2nd ed. Academic Press, New York. 312-104

Mejia MN, Madramootoo CA, Broughton RS (2000) Influence of water table management on corn and soybean yields. Agric Water Mang 46:73-89

Office of Agricultural Economics (2010) Thailand foreign agricultural trade statistics 2009. (Cited January 7, 2011). Available at http://www.oae.go.th/statistic/

Polthanee A (1989) Field-level drainage requirement of pre-rice mungbean crop in a waterlogged prone environment. Ph.D. thesis, Graduate School University of the Philippines, Los Banos, Philippines

Raper CDJ, Osmond DL, Wann M, Weeks WW (1978) Interdependence of root and shoot activities in determining nitrogen uptake rate of roots. Bot Gaz (Chicago) 139: 289-294

Rattanarat S (1999) Guidelines to improve soil and fertilizer for soybean and peanut. Report of the conference, soil management and fertilizer application to improve crop yield. Department of Agriculture, Bangkok, Thailand. 55-79

Sarwar T (2002) Physiological response of soybean to shallow water table depths. Pakistan J of Biol Sci 5:1300-1308

Shimada S, Kokubun M, Matsui S (1995) Effects of water table on physiological traits and yield of soybean: I. Effects of water table and rainfall on leaf chlorophyll content, root growth and yield. Jpn J Crop Sci 66:294-303

Shimada S, Kokubun M, Matsui S (1997) Effects of water table on physiological traits and yield of soybean: II. Effects of water table and rainfall on leaf water potential and photosynthesis. Jpn J Crop Sci 66:108-117

Sincik M, Candogan BN, Demirtas C, Buyukcangas H, Yazan S, Goksoy AT (2008) Deficit irrigation of soya bean [*Glycine max* (L.) Merr.] in a sub-humid climate. J Agron Crop Sci 194(3):200-205

Sionit N, Kramer PJ (1976) Water potential and stomatal resistance of sunflower and soybean subjected to water stress during various growth stages. Plant Physiol 58:537-540

Sionit N, Kramer PJ (1977) Effect of water stress during different stages of growth of soybean. Agron J 69:274-278

Stanley CD, Kaspar TC, Taylor HM (1980) Soybean top and root response to temporary water tables imposed at three different stages of growth. Agron J 72:341-346

Suwanarit A, Potichan A, Quadir M, Suwanarit C (1978) Soil factors limiting growth and yield of soybean growth on Korat and Roi-et soil. Thai J Agri Sci 11:273-286

Vamerali T, Saccomani M, Bona S, Mosca G, Guarise M, Ganis A (2003) A comparison of root characteristics in relation to nutrient and water stress in two maize hybrids. Plant Soil 255: 157-167

Zhang M, Duan L, Zhai Z, Li J, Tian X, Wang B, He Z, Li Z (2004) Effect of plant growth regulators on water deficit-induced yield loss in soybean. Proceedings of the International Crop Science Congress, Brisbane, Australia, 26 Sep.–1 Oct. 2004 (Cited July 21, 2006). www. cropscience.org.au