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Pre- or post- rice soybean production with phosphorus fertilization under rainfed conditions

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Abstract

The objective of the study was to investigate the response of three soybean cultivars to different phosphorus application rates, when the soybeans were grown before or after rice under rainfed conditions. Two experiments were conducted in farmers' fields in Khon Kaen Province in 2007-2008. A split- plot design with four replications was used. The three soybean cultivars were CM60, KKU74, and SJ5, assigned to the main plots. There were three levels of P fertilizer (0, 29, and 58 kg P_2O_5 ha^{-1}), which were assigned to the subplots. The results showed that P fertilizer had a significant effect on grain yield of soybean. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} gave the highest grain yield of soybean when grown before rice (365 kg ha^{-1}) and after rice (757 kg ha^{-1}). Phosphorus application increased the root length density, shoot dry weight per plant, leaf area index, number of pods per plant, and 100-seed weight. There were significant differences among cultivars for grain yield. The KKU74 cultivar had a higher grain yield than CM60 and SJ5 when grown either before or after the rice crop. This was due to the fact that KKU74 produced a higher root length density, and consequently had an increased number of seeds per pod and 100-seed weight. There was no significant interaction between phosphorus fertilizer rates and soybean cultivars on grain yield. Soybean grown after the rice crop showed a higher grain yield than soybean grown before the rice crop due to the fact that soybeans were not subjected to water deficit during their entire growing season, while the plants grown before rice suffered from waterlogging at reproductive stages, which resulted in decreased shoot and root growth and yield components.

Keywords: Ground water level, phosphorus, root length density, pre-rice crop, post-rice crop, soybean.
Abbreviations: DAE = days after emergence, CM60 = Chaingmai 60, LAI = leaf area index, RLD = root length density.

Introduction

Soybean (*Glycine max* L.) is an important crop worldwide due to its high protein and fat content. It is widely used for food, forage, and industrial uses. Its production and consumption increase every year. In Thailand, soybean production is not sufficient to meet human and animal needs. In 2010, about 1.8 million tons of soybeans were imported (OAE, 2011). Therefore, increasing soybean production in Thailand is an important policy of the government. The quantity of soybean production may increase by expanding planting areas and increasing yield per unit of land area. The rainfed paddy fields in northeastern Thailand occupy about 88% of the total agricultural land. Most of the farmers in this region transplant rice in the mid rainy season during July or August. During the early rainy season in April to July before rice transplanting a short-maturing upland crop can be successfully grown. Currently, the field crops grown before rice under rainfed conditions in this region are sesame (*Sesamum indicum* L.) in Buriram Province and kenaf (*Hibiscus cannabinus* L.) in Chaiyaphum Province. In some rainfed paddy field areas with sufficient residual soil moisture at the end of the rainy season, field crops, such as peanut (*Arachis hypogaea* L.) in Surin Province, can be grown after rice (Limpinuntana, 2001). Soybean is a potential legume crop that can be grown after rice using residual soil moisture at the end of the rainy season, when it can use additional soil moisture available by capillary action from the shallow water table. When it is grown before rice, it can use moisture available early in the rainy season. It is reported that when soybean was grown after rice, an additional 122-140 kg N ha^{-1} was returned to the soil by the nitrogen fixation process (Jifeng, 1990). Pookpakdee and On-Nim (2003) reported that soybean grown after rice in the dry season provided significantly higher seed yield (1939 kg ha^{-1}) than when soybean was grown in the upland areas during the rainy season (1385 kg ha^{-1}), which, consequently, provided higher net income (243 USD ha^{-1} compared to 194 USD ha^{-1}). They also found that the application of triple super phosphate at 62.5 kg ha^{-1} increased the yield of soybean to the highest level. In northeastern Thailand, regardless of the planting method, growing soybean before rice gave the highest net income when compared to cowpea (*Vigna sinensis* Savi) and mungbean (*Phaseolus aureus* Roxb.) (Polthanee, 2001). When soybean is grown in a rice-based cropping system, seed yield is varied according to different managements. Soybean grown before rice by using flat and ridging methods had seed yields of 1650 and 1709 kg ha^{-1}, respectively (Polthanee, 2001). However, when the soybean cultivar KKU Early No. 5 was grown after rice harvest using different methods and fertilized with 12-24-12 (N, P_2O_5, K_2O) at a rate of 156 kg ha^{-1}, seed yield ranged between 1016-1282 kg ha^{-1}, (Plothanee and Tre-loges, 2002). Therefore, soybean grown either before or after a rice crop may be successful in order to increase soybean production and farm income, and different crop managements could result in different yields. According to the bimodal rainfall pattern in northeastern Thailand, soybean grown before a rice crop may suffer from

Table 1. Yield and yield components of three soybean cultivars grown before rice (Experiment 1) with different phosphorus fertilizer rates.

Treatment	Grain yield (kg/ha)	Pod per Plant (no)	Seed per pod (no)	100 seeds weight (g)	Harvest Index (HI)
P rates (P)					
0 kg P_2O_5/ha	201.76 c	14.90 b	2.05	13.05 b	0.27
29 kg P_2O_5/ha	271.28 b	16.62 ab	2.14	15.12 ab	0.30
58 kg P_2O_5/ha	364.71 a	20.48 a	2.17	15.79 a	0.35
Soybean cultivars (C)					
CM60	257.83 b	14.25 b	2.11 ab	14.59 ab	0.36 a
KKU74	336.46 a	15.86 ab	2.28 a	16.47 a	0.39 a
SJ5	243.46 b	21.89 a	1.98 b	12.90 b	0.17 b
F-test					
P fertilizer rates (P)	**	*	ns	**	ns
Soybean cultivars (C)	*	*	*	*	**
C x P	ns	ns	ns	ns	ns
CV (a) %	20.02	18.03	10.78	12.89	21.15
CV (b) %	19.18	16.88	11.19	12.35	20.08

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test

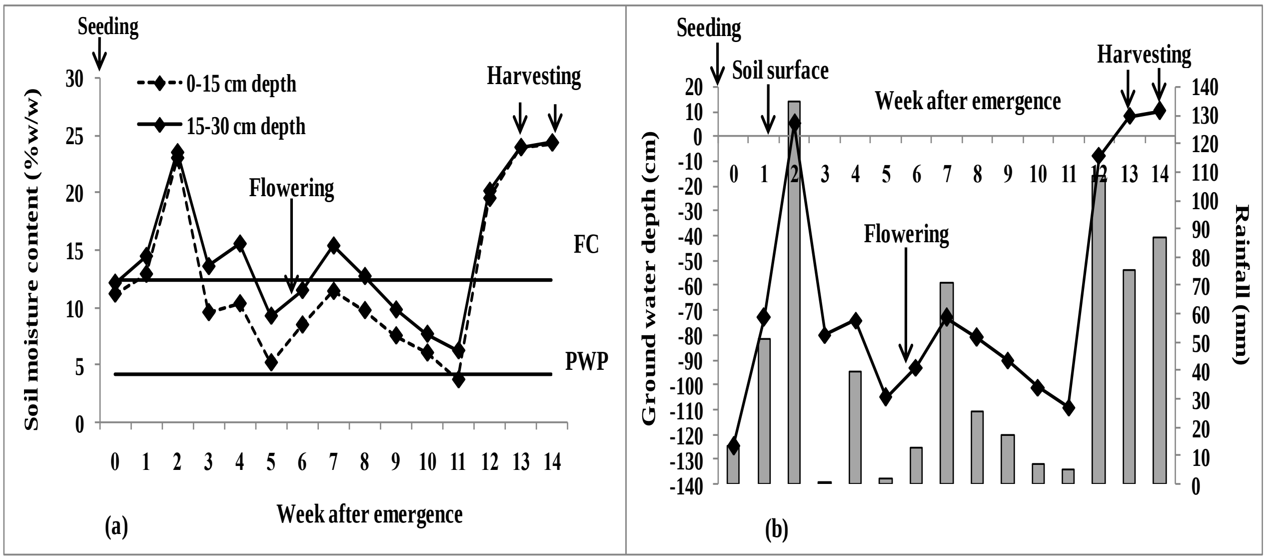

Fig 1. Average soil moisture content at the 0-15 and 15-30 cm depths (a), ground water depth, and weekly rainfall (b) of pre-rice crop growing period (27 April-9 August 2007).

waterlogging at the reproductive stage due to high intensity rainfalls. However, soybean planted after a rice crop may suffer from drought during the reproductive stage due to insufficient soil moisture (Polthanee, 1989). Flooding, as well as drought, reduces dry matter accumulation and subsequent growth of soybeans. Final seed yields of flooded soybeans were reduced significantly by 52 and 40% for the cultivars Essex and Forrest, respectively, when compared with full irrigation (Oosterhuis *et al*., 1990). In another study, seed yield of soybean subjected to water deficit at the reproductive and vegetative stages was decreased 55.4% and 19.6%, respectively, when compared with full irrigation (De costa and Shanmugathasan, 2002). Phosphorus (P) fertilizer has been shown to increase total root biomass, root length, and root surface area for water and nutrient uptake (Raper *et al.*, 1978; Jin *et al*., 2002; Jin *et al.*, 2005). Higher P application rates have been reported to partially overcome effects of a dry soil, as a result of higher P availability and improved water uptake (Fioretti *et al.*, 2008). Most paddy fields in the rainfed area of northeastern Thailand are low in soil fertility, because the soils are mainly 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 stress. Nevertheless, there is a lack of information about the responses of different soybean cultivars to P fertilizer, when applied either before or after rice. Therefore, the objective of this study was to investigate the response of three soybean cultivars to different P fertilizer rates when they were grown either before or after a rice crop under rainfed conditions.

Results

Soybean before rice crop (Experiment 1)

Soil moisture content

Soil moisture content at the 0-15 cm depth was mostly above field capacity and was in the available range (between field capacity and permanent wilting point level). At the 15-30 cm depth, soil moisture content was mostly in the available range. Soil moisture content at the 0-15 cm depth was reduced below the permanent wilting point by the 11th week

Table 2. Plant height and shoot dry weight of three soybean cultivars grown before a rice crop (Experiment 1) with different phosphorus fertilizer rates at 30, 45, and 60 days after emergence (DAE).

Treatments	Plant height (cm)			Shoot dry weight (g/plant)		
	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
P rates (P)						
0 kg P_2O_5/ha	26.49	42.37	46.23	1.46 b	4.71 b	7.91 b
29 kg P_2O_5/ha	25.48	44.95	49.88	2.34 a	7.33 ab	10.63 ab
58 kg P_2O_5/ha	27.82	47.16	50.61	2.52 a	9.19 a	11.57 a
Soybean cultivars (C)						
CM60	24.38	44.07	48.53	2.37	8.13	9.80
KKU74	27.38	45.11	51.44	2.07	6.53	10.64
SJ5	28.04	45.30	46.75	1.89	6.58	9.67
F-test						
P fertilizer rates (P)	ns	ns	ns	**	**	*
Soybean cultivars (C)	ns	ns	ns	ns	ns	ns
C x P	ns	ns	ns	ns	*	ns
CV (a) %	19.37	18.29	16.16	12.48	18.77	17.10
CV (b) %	18.19	15.14	16.02	10.01	11.73	14.58

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test.

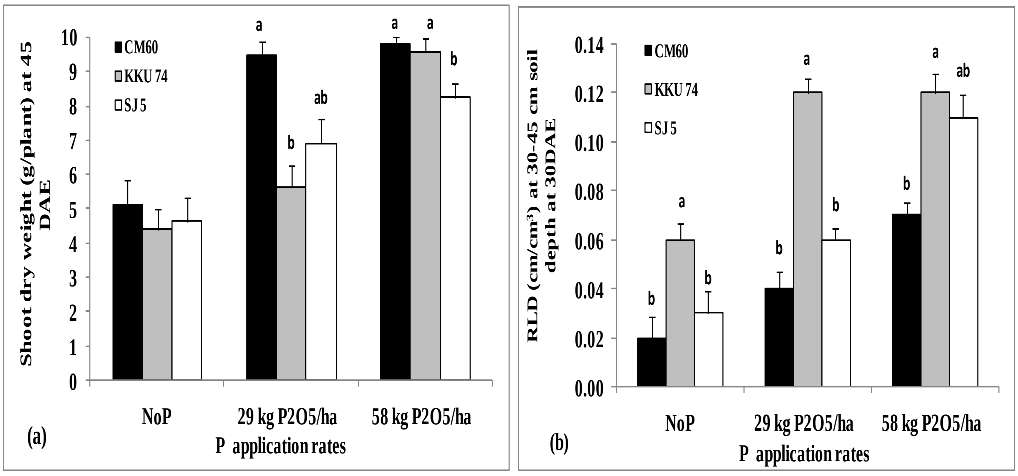

Fig 2. Shoot dry weight of three soybeans cultivars grown with different P application rates at 45 DAE (a) and root length density (RLD) at the 30-45 cm depth on 30 DAE (b). Soybean was grown before a rice crop.

after emergence (Fig. 1a). Soil moisture content at the 0-15 and 15-30 cm depths was higher than field capacity at the 1st, 2nd, 12th, 13th, and 14th weeks after emergence. Ground water level was observed above the soil surface at the 2nd, 13th, and 14th week after emergence, when the crops had received 134.7, 75.6, and 87.1 mm of rainfall, respectively (Fig. 1b). The crop suffered from waterlogging at the third trifoliate growth stage (V3) and at the beginning of maturity (R7) to full maturity growth stage (R8).

Plant height

Plant height was not significantly affected by P fertilizer rates at 30, 45, and 60 DAE. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} produced taller plants than the other P rates. Soybean cultivars were not significantly different for plant height at 30, 45, and 60 DAE. Nevertheless, the KKU74 cultivar was taller than the other cultivars. There was no significant interaction between the soybean cultivars and P fertilizer rates on plant height (Table 2, right-hand side).

Shoot dry weight

At 45 DAE, a significant interaction of soybean cultivars and P fertilizer rates was observed for shoot dry weight. Cultivar CM60 that received P at the rate of 58 kg P_2O_5 ha^{-1} gave the highest shoot dry weight (Fig. 2a). The shoot dry weight was significantly affected by P application rates at 30, 45, and 60 DAE. Phosphorus applications at the rate of 58 kg P_2O_5 ha^{-1} gave the highest shoot dry weight. Soybean cultivars showed no significant differences in shoot dry weight at 30, 45, and 60 DAE. However, the cultivar KKU74 produced a higher shoot dry weight than the other cultivars (Table 2, left-hand side).

Leaf area index (LAI)

The LAI was significantly affected by P application rates at 30, 45, and 60 DAE. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} gave the highest LAI. Soybean cultivars were not significantly different in LAI at 30, 45, and 60 DAE, even though LAI was higher in the cultivar KKU74 than in the other cultivars. There was no significant interaction between soybean cultivars and P fertilizer rates for LAI at 30, 45, and 60 DAE (Table 3, right-hand side).

Stomatal resistance

Phosphorous fertilizer rates had no significant effects on stomatal resistance at 30, 45, and 60 DAE, and there were no differences among cultivars in stomatal resistance. However, cultivar KKU74 tended to show the highest stomatal resistance. Application of P fertilizer at the rate of 58 kg P_2O_5

Table 3. Leaf area index and stomatal resistance of three soybean cultivars grown before a rice crop (Experiment 1) with different phosphorus fertilizer rates at 30, 45, and 60 days after emergence (DAE).

Treatments	Leaf area index (LAI)			Stomatal resistance (s/cm)		
	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
P rates (P)						
0 kg P_2O_5/ha	0.46 b	1.01 b	1.09 b	0.21	0.51	1.10
29 kg P_2O_5/ha	0.76 a	1.52 ab	1.57 ab	0.25	0.58	1.12
58 kg P_2O_5/ha	0.83 a	1.85 a	1.78 a	0.32	0.79	1.33
Soybean cultivars (C)						
CM60	0.75	1.53	1.60	0.25	0.44	0.88
KKU74	0.67	1.50	1.77	0.29	0.75	1.43
SJ5	0.63	1.34	1.37	0.24	0.69	1.24
F-test						
P fertilizer rates (P)	**	**	*	ns	ns	ns
Soybean cultivars (C)	ns	ns	ns	ns	ns	ns
C x P	ns	ns	ns	ns	ns	ns
CV (a) %	20.98	21.94	21.23	40.13	68.87	69.03
CV (b) %	18.75	20.79	20.45	21.67	54.85	63.42

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test.

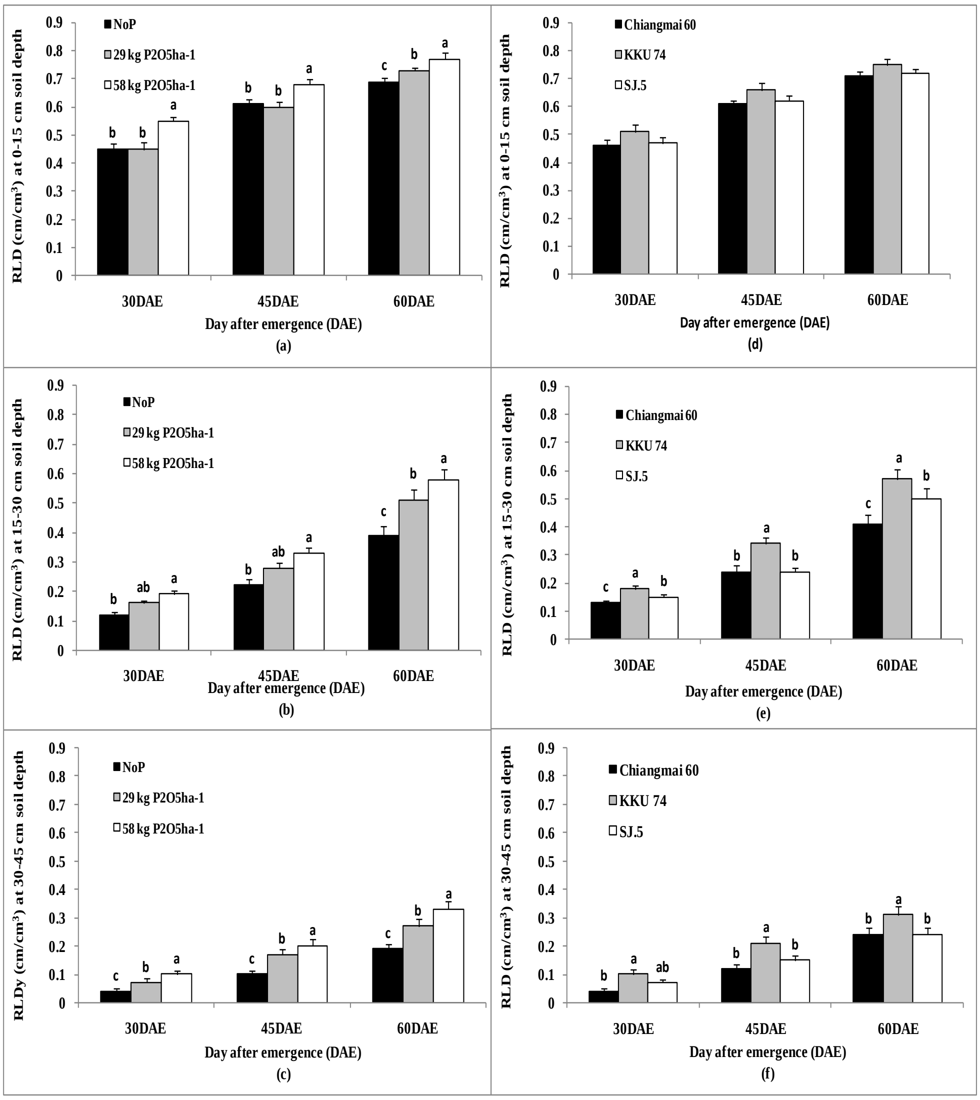

Fig 3. Root length density of three soybean cultivars grown with different P application rates at the 0-15, 15-30, and 30-45 cm soil depths on 30, 45, and 60 DAE. Soybean was grown before a rice crop.

ha^{-1} tended to produce the highest stomatal resistance. There was no significant interaction between soybean cultivars and P fertilizer rates on stomatal resistance (Table 3, left-hand side).

Root length density (RLD)

Root length density was significantly different among the P application rates at the 0-15, 15-30, and 30-45 cm soil depths at 30, 45, and 60 DAE. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} gave the highest RLD (Fig. 3a-3c). Soybean cultivars were significantly different for RLD at the 15-30 and 30-45 cm soil depths on 30, 45, and 60 DAE, but they did not differ at the 0-15 cm soil depth. Cultivar KKU74 gave the highest RLD (Fig. 3e and 3f). There was a significant interaction between soybean cultivars and P fertilizer rates on RLD at the 30-45 cm soil depth on 30 DAE. Cultivar KKU74 that received P at the rate of 58 kg P_2O_5 ha^{-1} had the highest RLD (Fig. 2b).

Grain yield and yield components

Phosphorous fertilizer rates had significant effects on grain yield, number of pods per plant, and 100-seed weight. But they had no significant effects on number of seeds per pod and harvest index. Phosphorus application at 58 kg P_2O_5 ha^{-1} gave the highest grain yield, resulting from the highest number of pods per plant and 100-seed weight. Phosphorus application at 58 kg P_2O_5 ha^{-1} also produced highest number of seeds per pod and harvest index. Soybean cultivars showed significant differences for grain yield, number of pods per plant, number of seeds per pod, 100-seed weight, and harvest index. The cultivar SJ5 gave the highest number of pods per plant, while the cultivar KKU74 gave the highest number of seeds per pod, 100-seed weight, harvest index, and grain yield. There were no significant interactions between soybean cultivars and P fertilizer rates on grain yield, number of pods per plant, number of seeds per pod, 100-seed weight, and harvest index (Table 1).

Soybean after rice crop (Experiment 2)

Soil moisture content

Soil moisture content at the 0-15 and 15-30 cm depths remained close to field capacity during the growing season (Fig 4a). The crops received soil moisture mainly by capillary action from the shallow ground water (Fig. 4b). The measured ground water depths ranged from 40 to 86 cm below the soil surface during the growing period.

Plant height

Plant height was not significantly affected by P application rates at 30, 45, and 60 DAE. Phosphorus applications at the rate of 58 kg P_2O_5 ha^{-1} produced taller plants than the other P rates. Soybean cultivars had significantly different plant heights at 30, 45, and 60 DAE. The cultivar KKU74 was the tallest. There were no significant interactions between soybean cultivars and P fertilizer rates on plant height (Table 5, right-hand side).

Shoot dry weight

Shoot dry weight was significantly affected by the P application rates at 60 DAE, but had no appreciable effects on the parameter at 30 and 45 DAE. Phosphorus applications at the rate of 58 kg P_2O_5 ha^{-1} gave the highest shoot dry weight compared to the other P rates. Soybean cultivars showed significantly different shoot dry weights at 30 DAE. The cultivar CM60 had the highest shoot dry weight, which was, however, not significantly different from that of cultivar KKU74. There were no significant interactions between soybean cultivars and P fertilizer rates on shoot dry weight (Table 5, left-hand side).

Leaf area index (LAI)

The LAI was significantly affected by the P application rates at 60 DAE. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} gave the highest LAI compared to the other P rates. Soybean cultivars were not significantly different for LAI at 30, 45, and 60 DAE, even though the cultivar KKU74 produced the highest LAI. There were no significant interactions between the soybean cultivars and P fertilizer rates on LAI at 30, 45, and 60 DAE (Table 6, right-hand side).

Stomatal resistance

Stomatal resistance was neither significantly affected by the P fertilizer rates nor by the type of soybean cultivar at 30, 45 and 60 DAE (Table 3). The cultivar KKU74 tended to have the highest stomatal resistance, while P fertilizer at the rate of 58 kg P_2O_5 ha^{-1} tended to produce the highest stomatal resistance. There were no significant interactions between soybean cultivars and P fertilizer rates on stomatal resistance (Table 6, left-hand side).

Root length density (RLD)

Root length density was significantly different among the P application rates at the 0-15, 15-30, and 30-45 cm soil depths at 30, 45, and 60 DAE. Phosphorus application at the rate of 58 kg P_2O_5 ha^{-1} gave the highest RLD (Fig. 5a-5c). At the 0-15 cm soil depth, different soybean cultivars had significant effects on RLD at 45 and 60 DAE. The cultivar KKU74 had the highest RLD (Fig. 5d). At the 15-30 cm soil depth, different soybean cultivars were significantly different in RLD at 30, 45, and 60 DAE. The cultivar KKU74 had the highest RLD (Fig. 5e). At the 30-45 cm soil depth, the different soybean cultivars had significant differences in RLD at 60 DAE. The cultivar KKU74 had the highest RLD (Fig. 5f). There were significant interactions between the soybean cultivars and P fertilizer rates on RLD at the 15-30 cm soil depth at 30 DAE. The cultivar KKU74 that received P at the rate of 58 kg P_2O_5 ha^{-1} had the highest RLD (Fig. 6).

Grain yield and yield components

Phosphorus fertilizer rates had significant effects on grain yield, number of pods per plant, 100-seed weight, but had no appreciable effects on number of seeds per pod and harvest index. Phosphorus fertilizer at the rate of 58 kg P_2O_5 ha^{-1} gave the highest grain yield, due to the highest number of pods per plant and 100-seed weight compared to the other P rates. Phosphorus fertilizer at the rate of 58 kg P_2O_5 ha^{-1} also gave a higher number of seeds per pod and harvest index. Soybean cultivars had significantly different grain yield, number of seeds per pod, 100-seed weight, and harvest index, but they did not differ in the number of pods per plant. The cultivar KKU74 had the highest number of seeds per pod, 100-seed weight, harvest index, and grain yield. There were no significant interactions between the soybean cultivars and

Table 4. Yield and yield components of three soybean cultivars grown after a rice crop (Experiment 2) with different phosphorus fertilizer rates.

Treatment	Grain yield (kg/ha)	Pod per Plant (no)	Seed per pod (no)	100 seeds weight (g)	Harvest Index (HI)
P rates (P)					
0 kg P_2O_5/ha	597.36 b	16.29 b	2.67	14.62 b	0.41
29 kg P_2O_5/ha	714.28 a	19.50 a	2.67	15.77 a	0.41
58 kg P_2O_5/ha	757.28 a	21.97 a	2.75	16.13 a	0.42
Soybean cultivars (C)					
CM60	548.75 b	20.92	2.83 a	15.57 ab	0.40 b
KKU74	713.56 a	18.25	3.00 a	16.20 a	0.46 a
SJ5	706.48 ab	18.59	2.25 b	14.76 b	0.39 b
F-test					
P fertilizer rates (P)	**	**	ns	**	ns
Soybean cultivars (C)	*	ns	**	**	*
C x P	ns	ns	ns	ns	ns
CV (a) %	20.14	21.45	12.88	8.55	10.01
CV (b) %	19.07	19.48	12.37	4.45	7.69

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test.

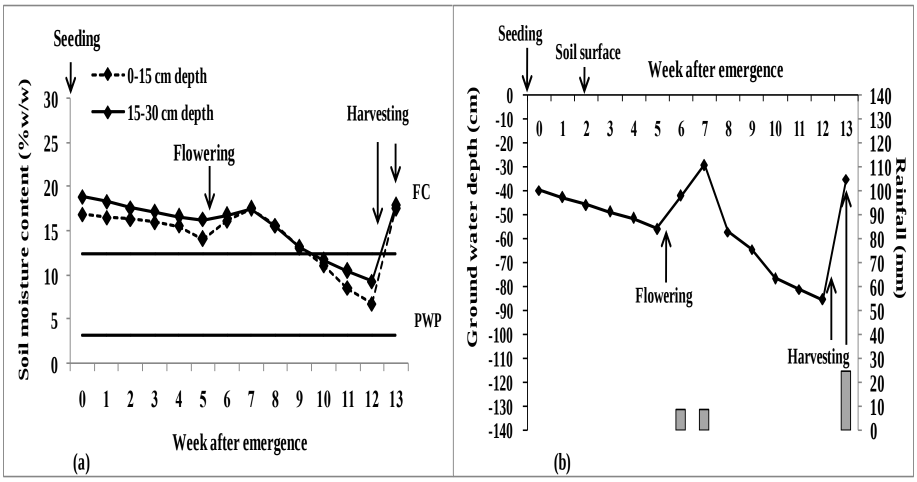

Fig 4. Average soil moisture content at the 0-15 and 15-30 cm depths (a), ground water depth, and weekly rainfall (b) during the post-rice growing period (14 December 2007-17 March 2008).

P fertilizer rates on grain yield, number of pods per plant, number of seeds per pod, 100-seed weight, and harvest index (Table 4).

Discussion

Phosphorus fertilizer rates had a significant, positive effect on grain yield of soybeans grown either before or after a rice crop. The maximum grain yield of both experiments was increased when soybean received P application at the rate of 58 kg P_2O_5 ha^{-1}. This was due to P fertilizer increasing the number of pods per plant and 100-seed weight. Phosphorus fertilizer at the rate of 58 kg P_2O_5 ha^{-1} gave a higher P availability in the soil and allowed the crop to produce a higher RLD for water uptake and, consequently, an increased LAI and shoot dry weight. Other experiments have shown that P fertilizer increased root dry weight and RLD and resulted in an increased water and nutrient uptake (Jin et al., 2006; Jin et al., 2005). Consequently, P increased leaf area, LAI, shoot dry weight, yield, and yield components (Jin et al., 2004; Jin et al., 2002). Phosphorus application increased plant height, leaf area, number of branches, crop growth rate, relative growth rate, number of pods per plant (Mahamood et al., 2009), P absorption and concentration, seed number, seed size, and grain yield (Gutierrez-Boem and Thomas, 1999). A high level of P increases leaf appearance rate, leaf area, aboveground biomass, and dry weight of roots (Fioretti et al., 2008). In the both experiments, P fertilizer application at the rate of 29 and 58 kg P_2O_5 ha^{-1} significantly increased RLD compared to the rate of 0 kg P_2O_5 ha^{-1}. In both experiments, stomatal resistance was not significantly affected by P application rates, and cultivars did not differ in stomatal resistance. However, stomatal resistances tended to increase when soybean received P fertilizer compared with no P application. This was probably due to partial stomatal closure of the soybeans 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 (Bearsell and Cohen, 1975). When soybean was grown before a rice crop, it was responsive to P fertilizer rates due to the fact that the amount of residual P in the soil was very low (2 ppm). When soybean was grown after a rice crop, the grain yield was increased when soybean received P at the rate of 58 kg P_2O_5 ha^{-1}, but yields did not differ from P fertilizer added at the rate of 29 kg P_2O_5 ha^{-1}. This was probably due to the high residual P in the soil (11 ppm), which is almost at the critical level of available P (12 ppm) in soil for soybeans (Rattanarat, 1999). The three soybean cultivars had a significant difference in grain yield in both experiments. The

Table 5. Plant height and shoot dry weight of three soybean cultivars grown after a rice crop (Experiment 2) with different phosphorus fertilizer rates at 30, 45, and 60 days after emergence (DAE)

Treatments	Plant height (cm)			Shoot dry weight (g/plant)		
	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
P rates (P)						
0 kg P_2O_5/ha	27.63	39.08	39.10	5.03	13.22	13.50 c
29 kg P_2O_5/ha	28.29	39.94	39.95	5.26	13.15	16.54 b
58 kg P_2O_5/ha	29.45	41.38	40.08	4.88	15.73	19.90 a
Soybean cultivars (C)						
CM60	29.00 a	40.65 ab	40.08 a	5.51 a	15.48	15.64
KKU74	30.17 a	43.71 a	44.00 a	5.48 a	14.72	17.92
SJ5	25.21 b	36.04 b	36.92 b	4.18 b	11.91	15.93
F-test						
P fertilizer rates (P)	ns	ns	ns	ns	ns	**
Soybean cultivars (C)	**	*	**	*	ns	ns
C x P	ns	ns	ns	ns	ns	ns
CV (a) %	6.62	9.71	11.45	18.96	16.58	18.80
CV (b) %	7.11	11.88	8.19	15.14	15.40	16.11

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test

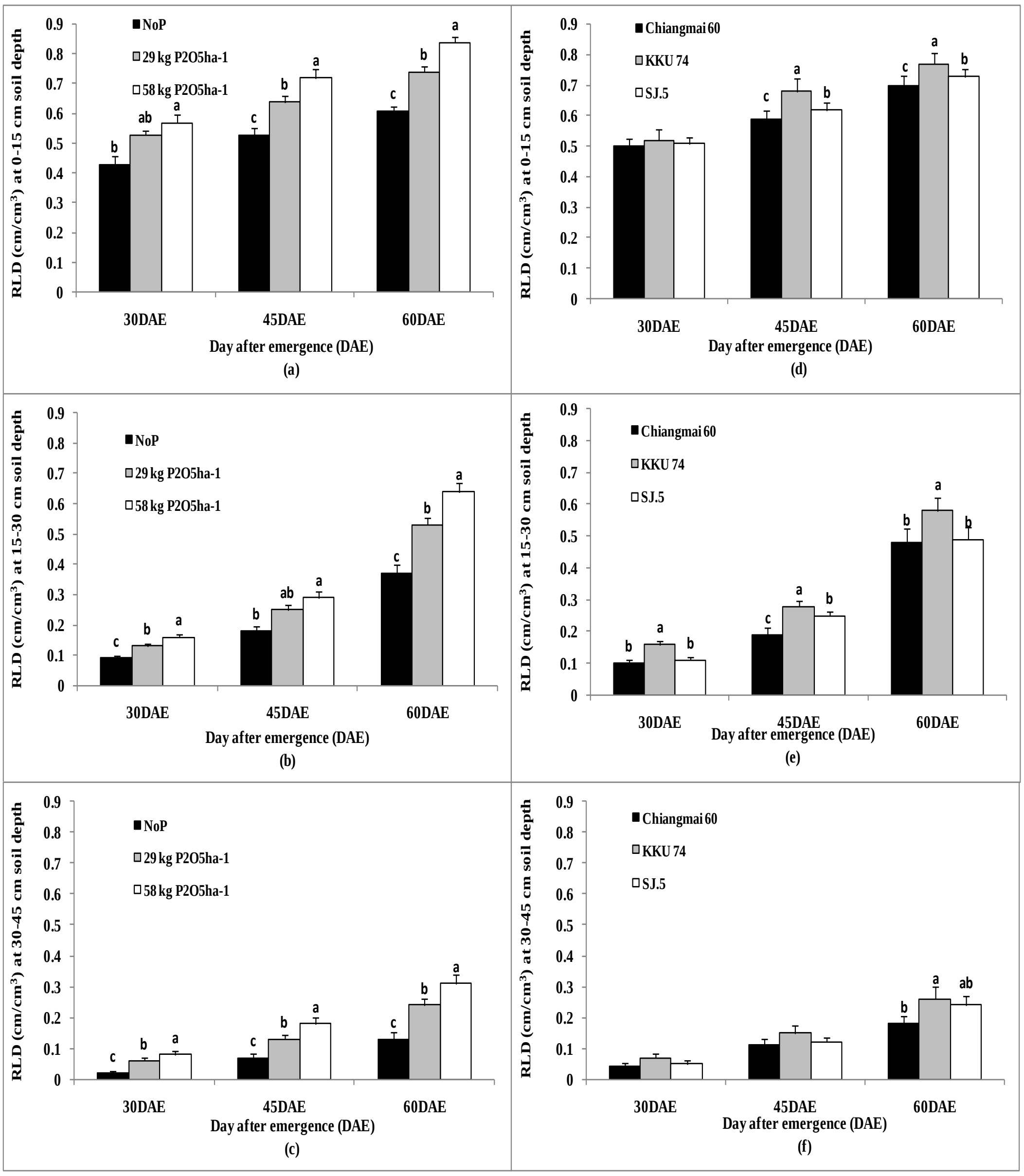

Fig 5. Root length density of soybeans grown with different P application rates and of three soybean cultivars (d-f) at the 0-15, 15-30, and 30-45 cm soil depths on 30, 45, and 60 DAE. Soybean was grown before a rice crop.

cultivar KKU74 had the highest grain yield due to the fact that KKU74 produced a higher number of pods per plant, number of seeds per pod, 100-seed weight, and harvest index. This was due to KKU74 producing the highest RLD for water uptake. In this experiment, cultivar KKU74 tended to give the highest stomatal resistance on 60 DAE, but it did not differ from stomatal resistances for the cultivars CM60 and SJ5. This indicated that the cultivar KKU74 was better adapted for saving water in plants by partial stomatal closure to reduce transpiration compared to SJ5 when waterlogged and when availability of soil moisture and ground water are reduced. This indicated that the cultivar KKU74 was better adapted to waterlogging stress (pre-rice crop) and drought stress (post-rice crop). Selecting soybean cultivars resistant to waterlogging may help reduce the reduction of soybean yield. It may be one of the strategies to improve growth and yield of soybean grown before a rice crop. When soybean was grown before rice, its yield (201 to 365 kg ha^{-1}) was very low due to the plants suffering from waterlogging at the third trifoliate (V3) growth stage and at the beginning of maturity (R7) to full maturity (R8) growth stages. This resulted in a decreased number of pods per plant, 100-seed weight, shoot dry weight, LAI, and RLD. Waterlogging decreased root dry weight, RLD, plant height, leaf area and, consequently, decreased shoot dry weight and yield of soybean (with faster decrease in N_2 fixation) (Bacanamwo and Purcell, 1999). Other work showed that stomatal conductance was reduced about 48% at the R2 growth stage and photosynthesis declined with flooding (Oosterhuis et al., 1990). The number of pods per plant and leaf P and nitrogen (N) concentration has increased with increasing P rates under waterlogging (Griffin and Brandom, 1983). Research has shown that the transpiration rate of soybean plants was reduced by 52% when the plants were waterlogged, because of decreased water uptake and stomatal aperture (Araki, 2006) and decreased N_2 fixation (Do Amarante et al., 2006). In our work, stomatal resistance tended to increase when soybeans received P fertilizer compared with no P application under waterlogging. This was probably due to partial stomatal closure of the soybeans to keep water from leaving the plant and thereby maintaining plant water status. In our experiments, under waterlogged conditions, high P fertilizer application rates increased grain yield, number of pods per plant, 100-seed weight, shoot dry weight, LAI, and RLD when compared to the values obtained when no P was applied. This indicates that P could increase yield of soybeans and mitigate the effect of waterlogging. In the present experiment, yield of soybeans grown after rice ranged from 549 to 757 kg ha^{-1}, which is more than the yield (229 to 409 kg ha^{-1}) of soybeans grown after rice in our previous experiment in 2007 (Jaidee et al., 2012). This was due to the fact that the soybeans were not subjected to water deficit during their entire growing season. At planting, the ground water level was maintained at the 40 cm depth from soil surface due to the intensity of rainfall at the end of rainy season. In 2008, the ground water level was maintained at the 80 cm depth from soil surface due to a low intensity of rainfall at the end of rainy season, which resulted in plants being subjected to drought at the reproductive stage. This indicated that ground water level at the planting date and the receding rate of the ground water level determine yield of a crop grown after rice.

Materials and Methods

Locations and soil properties

The soybean grown before a rice crop (Experiment 1) was conducted from 27 April to 9 August 2007 in a farmer's field in the village of Maung Yai , Mueang District, Khon Kaen Province. The soil was a Typic Kandiaquults in the order Ultisols. The texture of the soil was a sandy loam. It had a pH of 5.5 and 0.028% total N, 2 ppm available P (Bray II test), 26 ppm exchangeable K, 0.82% organic matter content. Field capacity (FC) was 12.41%, and permanent wilting point (PWP) was 4.21%. The soybean grown after a rice crop (Experiment 2) was conducted from 14 December 2007 to 17 March 2008 in a farmer's field in the village of Kok Yai, Ban Fang District, Khon Kaen Province. The soil was a Typic Hapludalf in the order Alfisols. The texture of soil was a sandy loam. It had a pH of 5.9 and 0.036% total N, 11 ppm available P (Bray II test), 29 ppm exchangeable K, 0.63% organic matter content. Field capacity was 12.36%, and permanent wilting point was 3.22%.

Experimental design and plant culture

A split plot design with three replications was used in this study. Three soybean cultivars (high yield, widely-used cultivar in northeast of Thailand and recommended by Department of Agirculture), Chiangmai 60 (CM60), Khon Kaen University 74 (KKU74), and Sorjor 5 (SJ5), were assigned to the main plots, and three levels of P application (0, 29, and 58 kg P_2O_5 ha^{-1}) were assigned to the sub-plots. Plot size was 5 m x 4 m with plant spacing of 50 cm between rows and 20 cm between plants in rows. 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 broadcasted and incorporated into the soil before seeding in all treatments. The three rates of P were also broadcasted and incorporated 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 at about 5 cm depth made by a hand-pushed seeder or Planet Junior (Hunt, NY, USA), and then they were covered with soil. Soybean seedlings were thinned to 2 plants per hill at 10 days after emergence (DAE). Plants were not irrigated throughout growing season. Hand weeding was done at 15, 30, and 45 DAE. 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.

Soil moisture content and weather observation

The moisture content of soil samples from the 0-15 and 15-30 cm depths were determined using the gravimetric procedure at 7 DAE and at weekly intervals thereafter until harvest. Ground water depth was measured at 7 DAE and at weekly intervals thereafter until harvest using an observation well of perforated PVC tube 2 m long installed to a 1.50 m depth in each replication. Data on weekly rainfall were obtained from the nearest weather stations of the Thai Meteorological Service.

Recorded data

Four plants from each plot were taken for shoot dry weight and leaf area measurements. Leaf area was measured at 30, 45, and 60 days after emergence (DAE) using a Li-COR 3100 leaf area meter (Lincoln, NE, USA). Shoot dry weight was determined by weighing the shoots after drying at 80 °C for 48 hrs. Root length density was measured at 30, 45, and 60 DAE. Roots were taken using soil cores at 0-15, 15-30, and 30-45 cm soil depths. 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

Table 6. Leaf area index and stomatal resistance of three soybean cultivars grown after a rice crop (Experiment 2) with different phosphorus fertilizer rates at 30, 45, and 60 days after emergence (DAE).

Treatments	Leaf area index (LAI)			Stomatal resistance (s/cm)		
	30 DAE	45 DAE	60 DAE	30 DAE	45 DAE	60 DAE
P rates (P)						
0 kg P_2O_5/ha	0.40	0.84	0.94 b	0.57	0.52	1.02
29 kg P_2O_5/ha	0.42	0.84	1.10 ab	0.41	0.51	1.08
58 kg P_2O_5/ha	0.40	0.98	1.33 a	0.57	0.71	1.19
Soybean cultivars (C)						
CM60	0.41	0.93	1.09	0.50	0.49	1.08
KKU74	0.44	0.98	1.29	0.53	0.63	1.12
SJ5	0.38	0.77	0.99	0.51	0.62	1.09
F-test						
P fertilizer rates (P)	**	**	*	ns	ns	ns
Soybean cultivars (C)	ns	ns	ns	ns	ns	ns
C x P	ns	ns	ns	ns	ns	ns
CV (a) %	17.30	20.82	21.22	51.86	41.18	31.42
CV (b) %	17.30	19.04	19.95	38.49	36.12	20.98

ns, *, and **= Not significant, significant at <0.05 and <0.01, respectively. Means followed by the same letter in the same column were not significantly different based on the Duncan's Multiple Range Test.

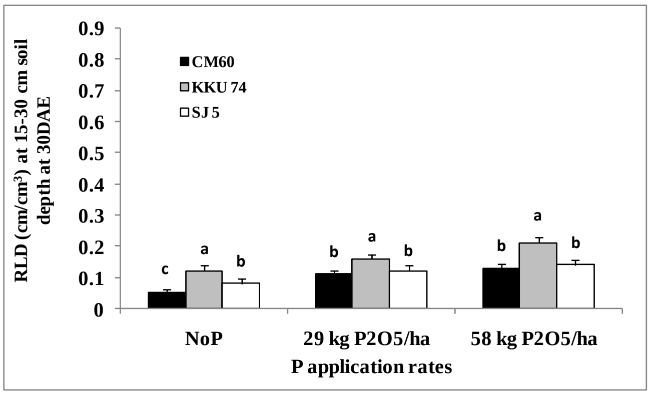

Fig 6. Root length density (RLD) at the 15-30 cm depth of three soybean cultivars grown with different P fertilizer rates on 30 DAE. Soybean was grown after a rice crop.

was used to recover fine roots. Roots were scanned, and total root length was measured by analyzing pictures taken by a WinRHIZO pro V2004a scanner (Reagent Instruments Inc., Quebec, Canada). Root length density was calculated by dividing total root length (cm) by soil core volume (cm^3). Four plants labeled from each plot were used to determine plant height at 30, 45, and 60 DAE. Stomatal resistance was measured on the second fully expanded leaf from the top of the main stem at 30, 45, and 60 DAE between 12:00 and 13:30 hr using a porometer (Delta-T Devices, Cambridge, U.K.). Leaf area index (LAI) was computed as the ratio between leaf area and the corresponding ground surface area. Soybean seed yield and 100-seed weight were determined from 3 m^2 harvested areas in each experimental plot. The number of pods per plant and seeds per pod were determined from subsamples collected from ten plants selected randomly from each plot. Harvest index (HI) was computed as the ratio between seed dry weight and total top dry weight at the harvest stage.

Data analysis

Analysis of variance (ANOVA) for all data was performed using MSTAT-C software (Analytical Software, Tallahassee, Florida, USA). The significances of mean differences were determined at the 0.05 and 0.01 probability levels. Duncan's Multiple Range Test (DMRT) was used to compare treatment means when the F-test was significant.

Conclusion

Phosphorus fertilizer application rates had a significant effect on grain yield of soybean grown before and after rice. Plants grown with P applied at the highest rate (58 kg P_2O_5 ha^{-1}) had the highest grain yield. This was due to P improving root and shoot growth. Soybean yield was highly responsive to P. There was a significant difference among soybean cultivars on grain yield. The cultivar KKU74 had a higher grain yield compared to the cultivars CM60 and SJ5. This was due to the fact that the cultivar KKU74 had the highest RLD, shoot growth, number of pods per plant, and 100-seed weight. The results indicated that the cultivar KKU74 was better adapted to waterlogging stress (pre-rice crop) and drought stress (post-rice crop) compared to the other cultivars.

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