CHAPTER 3

RESPONSES OF RICE TO NITROGEN AND PHOSPHORUS SUPPLY IN CHANGING SOIL WATER CONDITIONS

3.1 Introduction

Rainfed lowland rice systems are mainly characterized by changing drying and wetting periods of the soil within crop season (Saleh and Bhuiyan, 1995; Zeigler and Puckridge, 1995; Bell *et al.,* 2001). In fact, throughout the rainfed lowland area, there is often a period in early crop growth without standing water and growth is affected by aerobic environment. However, following such condition the rice plants are usually submerged by water, which comes from rainfall when rainy season is coming, and soil of the rainfed lowland now becoming waterlogged. This means that rice grown in rainfed lowlands often experiences by changing between aerobic and waterlogged soils.

Moreover, in rainfed lowland conditions rice growth, and nutrients uptake are limited not only by changing aerobic and waterlogged soils but also by nitrogen and phosphorus deficiency, which are also related to the soil water status (Wade *et al.,* 1998; Bell *et al.,* 2001). The lack of soil fertility is exacerbated by the effects of a changing soil-water regime on nutrient forms and their availability in the soil (Bell *et al.,* 2001). Previous studies have shown that rice grown in rainfed lowlands is often low yields, which as a result of lack of irrigation water and low nutrient availability in soil (Wonprasaid *et al.,* 1996; Wade *et al.,* 1999b). However, there is limited information on how rice plants respond to changes in water and O_2 content of the soil.

Specifically, how growth, nutrient uptake, and yield of rice when grown in such condition are not fully understood. Therefore, in this chapter it will be examined responses of rice plants to N and P supply in changing aerobic and waterlogged conditions.

3.2 Materials and Methods

Rice (*Oryza sativa* L.), Chainat 1 cultivar (a high yielding Thai rice) was used in this study. The experiment was conducted in pots in the glasshouses at the Experimental Station of the Multiple Cropping Center and Department of Agronomy, Faculty of Agriculture, Chiang Mai University, Thailand. The trial was commenced in June 2004 and ended in November 2004.

This experiment was conducted to evaluate growth, yield and nutrients (N, P) content of rice plants. The experiment was arranged as a randomized complete block (RCB) design with factorial combinations of two soil-water regimes (W0, W+), two levels of P fertilizer (10 and 50 kg P/ha, designated LP and HP, respectively), and four levels of N fertilizer (20, 60, 120, and 160 kg N/ha) with four replicates. There were a total of 64 pots for each of the 4 harvests.

Phosphate fertilizer was supplied as potassium dihydrogen orthophosphate (KH_2PO_4). Nitrogen was applied as urea content 46% of N. In addition to P and N fertilizers, potassium was applied as dipotassium sulfate (K_2SO_4). All fertilizers were diluted as stock solutions and supply to the soil each time by using graduated injectors. Fertilizers were applied with split as follows: basal P (100%), N (25%); at mid-tillering N (30%), and at panicle initiation N (45%). At mid-tillering and panicle initiation, N was supplied after each harvest one day. From one week after transplanting, 0.03 g K/pot was supplied weekly to ensure that plants did not experience K deficiency at any stage (shown in Table 3.1).

The soil (San Sai series, Table 3.2) was mixed thoroughly before 6 kg portions were placed in a plastic lined bag into undrained PVC pots. The soil was supplied by two regimes of waters. One regime was aerobic (soil moisture content at field capacity, W0). This soil was wetted with fresh water to field capacity one week before germinated rice seeds were transplanted. This water regime of each pot was checked daily by weighing and maintained at this level until at panicle initiation, and thereafter these pots were flooded to a depth of 8-10 cm and maintained at this level until maturity by daily watering (W0+). The other regime was waterlogged throughout. All pots of this water regime were flooded to a depth of 8-10 cm from transplanting to PI (W+), and this level of water was continually maintained until maturity by daily watering (W++).

Rice seeds were germinated for 48 h in Petri-dishes on moist filter papers. Four seedlings of uniform size, healthy plants were selected from four days old after emergence to transplant into each pot.

The plants of this experiment were harvested at four growth stages: mid-tillering (MT), panicle initiation (PI), flowering (FL), and maturity (MTR) to determine number of tillers per plant, plant dry weight, root:shoot ratio, and nutrient content (N, P). At MT, PI and FL the chlorophyll concentration of the youngest emerged blade (YEB) of plants in each pot were measured by a chlorophyll meter, SPAD-502 (Soil-Plant Analysis Development Section). Grain yield and yield components were also measured at maturity. At each harvest shoot, and root samples were separated for N and P analysis. Shoots were cut at ground level, and roots gently washed by hand to remove soil. Both shoots and roots were oven-dried at 75 ^{0}C for 48 h until reaching constant weight. After oven drying, plant materials were chopped and fined milled by an electrical grinder, then a sub-sample of about 15 g/sample package in a sealed plastic bag and stored at 4 ^{0}C prior to utilization. Shoot, root and grain samples were analyzed for N concentration (Kjeldahl method) and P concentration (molybdovanado-phosphoric acid method).

Statistical analysis

For each harvest, an analysis of variance (ANOVA) for all parameters measured was carried out to determine the treatment effects using Commercial software (Statistix V.7.1, analytical Software, Inc.). When treatment effects were significant, the least significant difference (LSD) and/or standard errors (SE) were used for mean comparisons.

Table 3.1 Nitrogen and phosphorus applications in each treatment of the experiment in Chapter 3.

Treatment (N:P kg/ha)	N and P application (g/pot)			
	Basal		Mid-tillering	PI
	P (100%)[†]	N (25%)	N (30%)	N (45%)
20:10	0.036[††]	0.02	0.02	0.03
20:50	0.180	0.02	0.02	0.03
60:10	0.036	0.05	0.06	0.10
60:50	0.180	0.05	0.06	0.10
120:10	0.036	0.11	0.13	0.20
120:50	0.180	0.11	0.13	0.20
160:10	0.036	0.14	0.17	0.26
160:50	0.180	0.14	0.17	0.26

[†] Percent of total N or P supply

[††] N and P applications were converted as kg/ha into g/pot

Table 3.2 General characteristics of San Sai soil series used for all experiments.

Soil characteristics	
Texture	Sand
pH (KCl)	4.5 – 5.5
CEC	Low
Slope	0 – 3%
Other characteristics	Low humus, low available phosphorus Low organic matter, poor irrigation, poor fertility Land use for rice growing and some soybeans, peanut, corn, garlic, tomato.

Source: Land Development Department, Bangkok, Thailand (2002)

3.3 Results

Soil-water conditions strongly affected leaf chlorophyll concentration, measured as SPAD value at each growth stage (Figure 3.1). W0 plants generally had higher SPAD values than W+ plants. At MT, the SPAD value increased throughout the whole range of N rates from N20 to N160 in both W0 and W+, but these increases were about the same between W0 and W+. At PI the effect of N on SPAD value was significantly different between W0 and W+ (WxN significant at $P < 0.01$). In W+ the SPAD value did not change with increasing N rate. The SPAD value in W0, which was two units higher than in W+, increased with increasing N rate to N120, but with no further effect to N160. Similarly, at FL the SPAD value was significantly higher in W0+ than in W++ ($P < 0.01$). However, the SPAD value in W0+ at this stage did not much increase with increasing N rate compared with plants in W0 at PI. In W++ the SPAD value did not change with increasing N rates.

Nitrogen concentration in rice shoots decline with age (Figure 3.2). Soil-water regimes strongly affected %N in shoot at each harvest, %N was always significantly higher in W0 than in W+ ($P < 0.01$), but magnitude of the difference lessened in the later stage of growth. At all three growth stages, MT, PI and FL, the effect of N on %N in shoot was significantly different between W0 and W+ (WxN significant at $P < 0.01$). At MT and PI the %N in shoot increased with increasing N rate to but changed little in W+. However, at FL %N in shoot increased with increasing N rate in both W0+ and W++, but %N was still higher in W0+, with the greater different at the higher N rates of N120 and N160.

The effect of P on P concentration in shoot was significantly different between W0 and W+ at all three growth stages, MT, PI and FL (WxP significant at *P*

< 0.01 at MT; $P < 0.05$ at PI and FL). At MT and PI, the %P in shoot was about 1-1.5 units greater in W+ than those in W0 (Figure 3.3). At these stages in both W0 and W+, the %P in shoot was increased by P application. At MT the %P in shoot was increased more by P application in W+ than that in W0, while at PI the effect of P application on %P in shoot in W+ was less than that in W0. By contrast, at FL the %P in shoot was increased by P more strongly in W0+ than in W++ (WxP significant at $P < 0.01$).

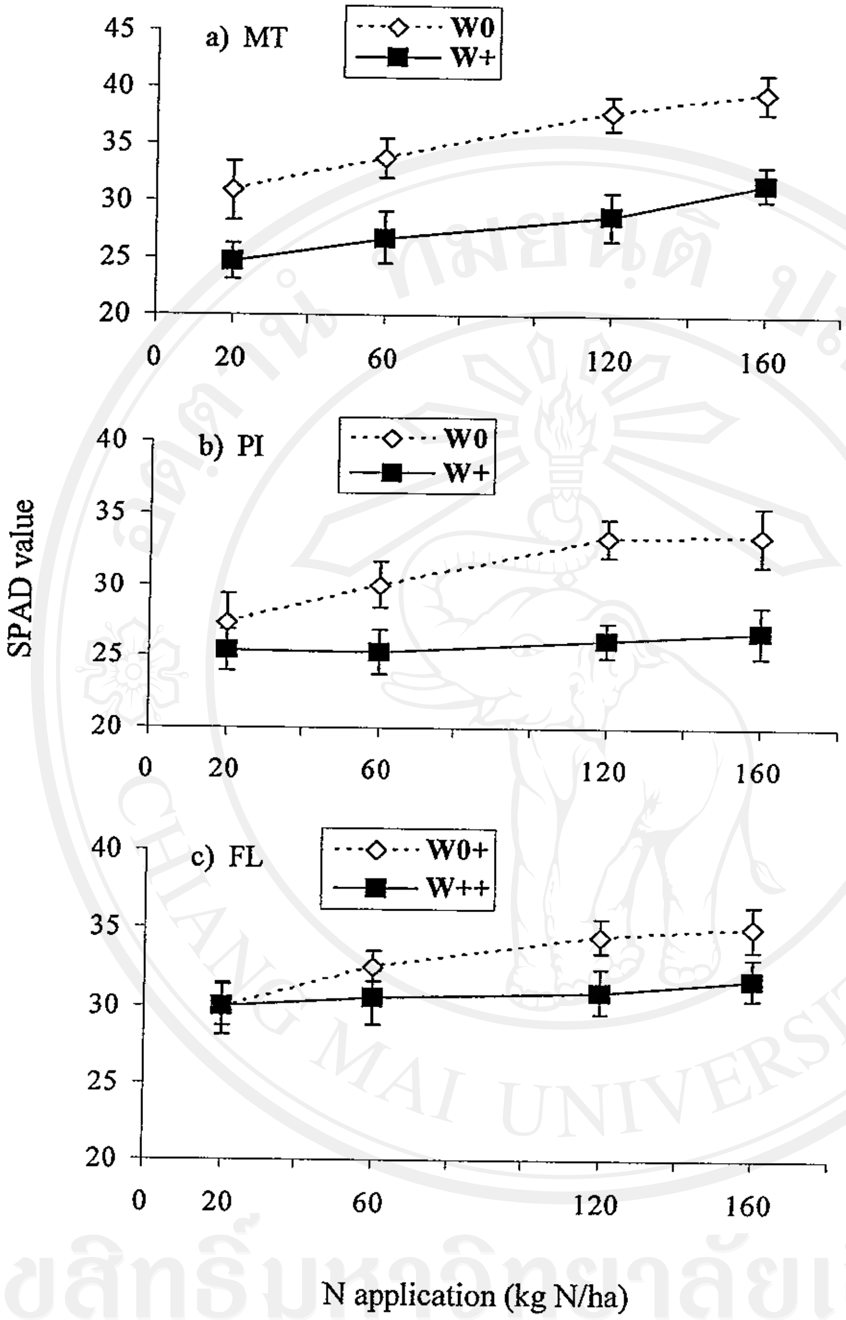

Figure 3.1 Effect of N applications on SPAD values of YEB at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); and flowering (c) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.

Analysis of variance	LSD $_{0.05}$	W	N	WxN
	MT	0.98**	1.39**	ns
	PI	0.93**	1.32**	1.87**
	FL	0.86**	1.22**	1.72**

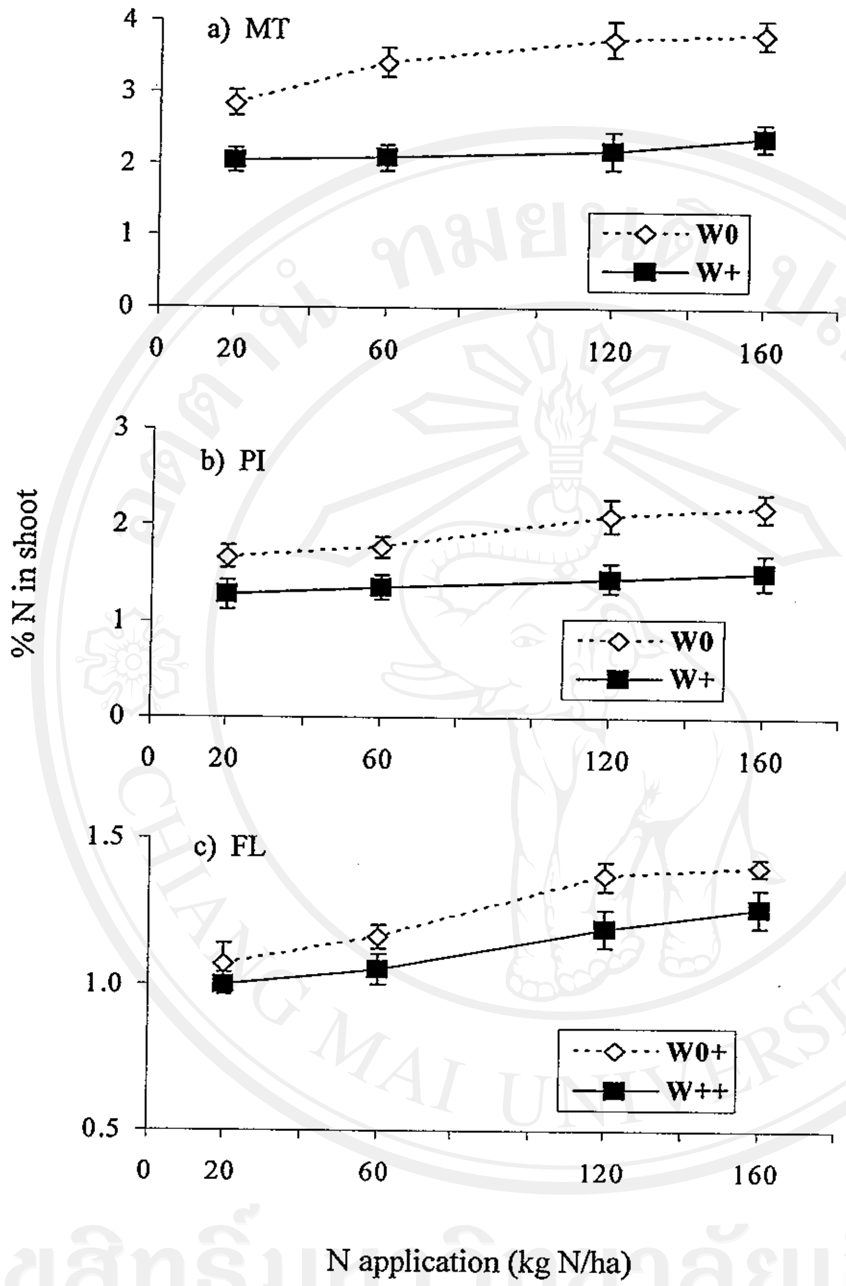

Figure 3.2 Effect of N applications on shoot N concentration (%) at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); and flowering (c) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.

Analysis of variance	LSD $_{0.05}$	W	N	WxN
	MT	0.09**	1.13**	0.19**
	PI	0.07**	0.10**	0.14**
	FL	0.03**	0.04**	ns

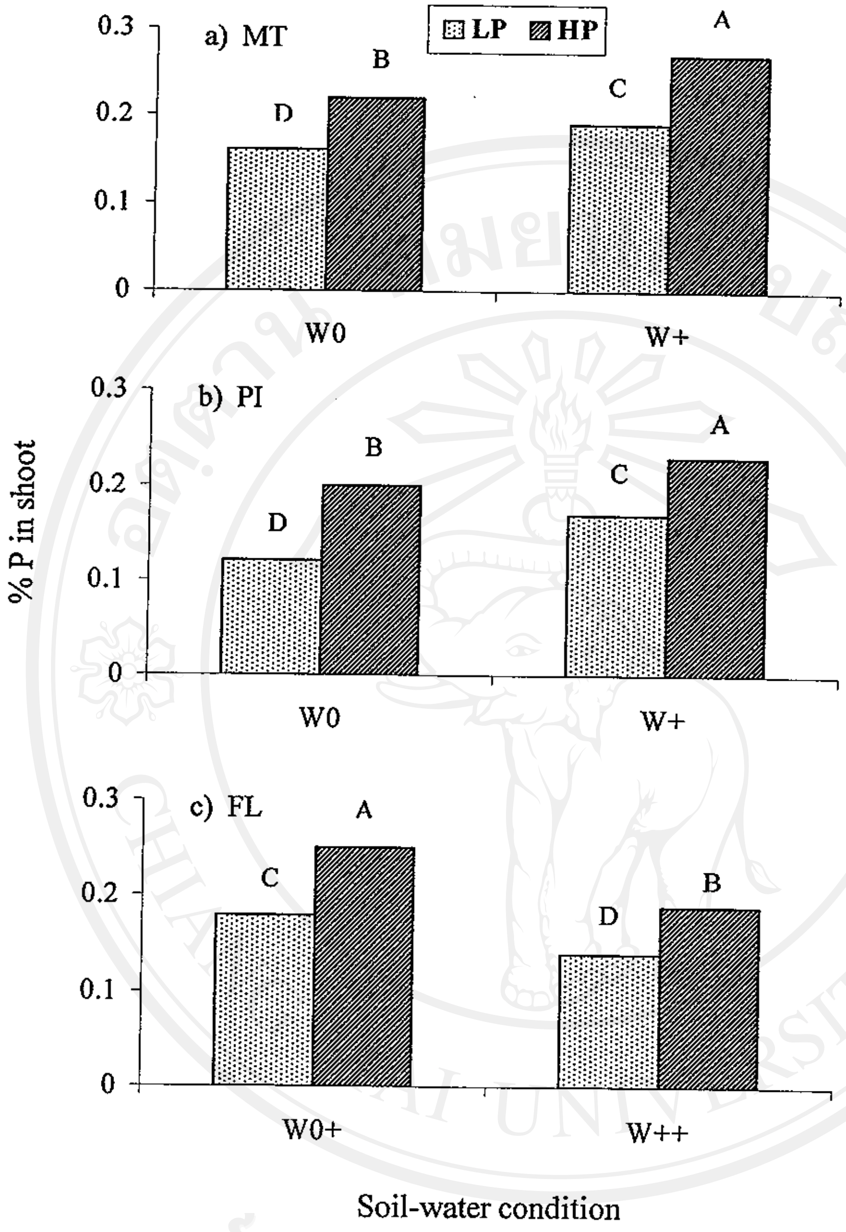

Figure 3.3 Effect of P applications (low P: LP or high P: HP) on % P in shoot at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); and flowering (c) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P < 0.05)}$.

Analysis of variance	LSD $_{0.05}$	W	P	WxP
	MT	0.007**	0.008**	0.01**
	PI	0.006**	0.006**	0.02*
	FL	0.006**	0.005**	0.01*

Aerobic followed by waterlogged rice produced greater tillers than waterlogged rice throughout the entire experimental period (Figure 3.4). At MT the effect of P on tiller numbers was significantly different between W0 and W+ (WxP significant at $P < 0.05$). In LP application, there was about the same number of tillers in W0 and W+. Applying HP slightly increased tillering in W+, but much more strongly in W0. These same effects of P on tiller numbers that was significantly different between W0 and W+ (WxP significant at $P < 0.01$) were observed at PI. At this stage tiller numbers was still increased by HP application in W0 but only slightly in W+. Applying LP, W0 plant had significantly higher number of tillers than W+ plant. At FL and MTR the effect of P on the tiller numbers was no longer different between W0+ and W++.

Total plant dry weight of W0 plants was less than those of W+ plants at MT and PI. However, at FL and MTR the plant dry weight of W0+ plants was greater than those of W++ plants. Applying N increased plant dry weight but did not change about these between W0 and W+ at MT; W0+ and W++ at FL and MTR (Figure 3.5). At PI the effect of N on plant dry weight was significantly different between W0 and W+ (WxN significant at $P < 0.01$). At this stage, the plant dry weight did not change with increasing N rate in W0. The plant dry weight in W+, which was about 2 to 4 units greater than those in W0, increased with increasing N rate and was greatest in W+N160. Furthermore, the effect of P on plant dry weight was significantly different between W0 and W+ at MT (WxP significant at $P < 0.05$); W0+ and W++ at FL and MTR ($P < 0.05$ and 0.01, respectively) but not evident about these at PI (Figure 3.6). At MTR, applying HP increased dry weight of both W0 plants and W+ plants but much more strongly in W+HP than in W0HP. At PI, the dry weight of W+ plants was still greater than those of W0 plants. Applying HP increased plant dry weight in both W0HP and W+HP with the same extent compared to W0LP and W+LP, respectively. At FL and MTR, W0+ plants had higher dry weight than those W++ plants. At these stages, applying HP increased plant dry weight but much more strongly in W0+ than in W++. Lowest plant dry weight was in W++LP and greatest in W0+HP.

Generally, LP plants had greater root:shoot ratio than HP plants. The interaction between W and P effected on root:shoot ratio was significant only at PI ($P < 0.05$) but not at the other stages, MT, FL and MTR (Figure 3.7). At PI the root:shoot ratio was higher in W0 than in W+. This difference was more strongly increasing about root:shoot ratio in W0LP than in W0HP while root:shoot ratio was about the same in W+LP and W+HP.

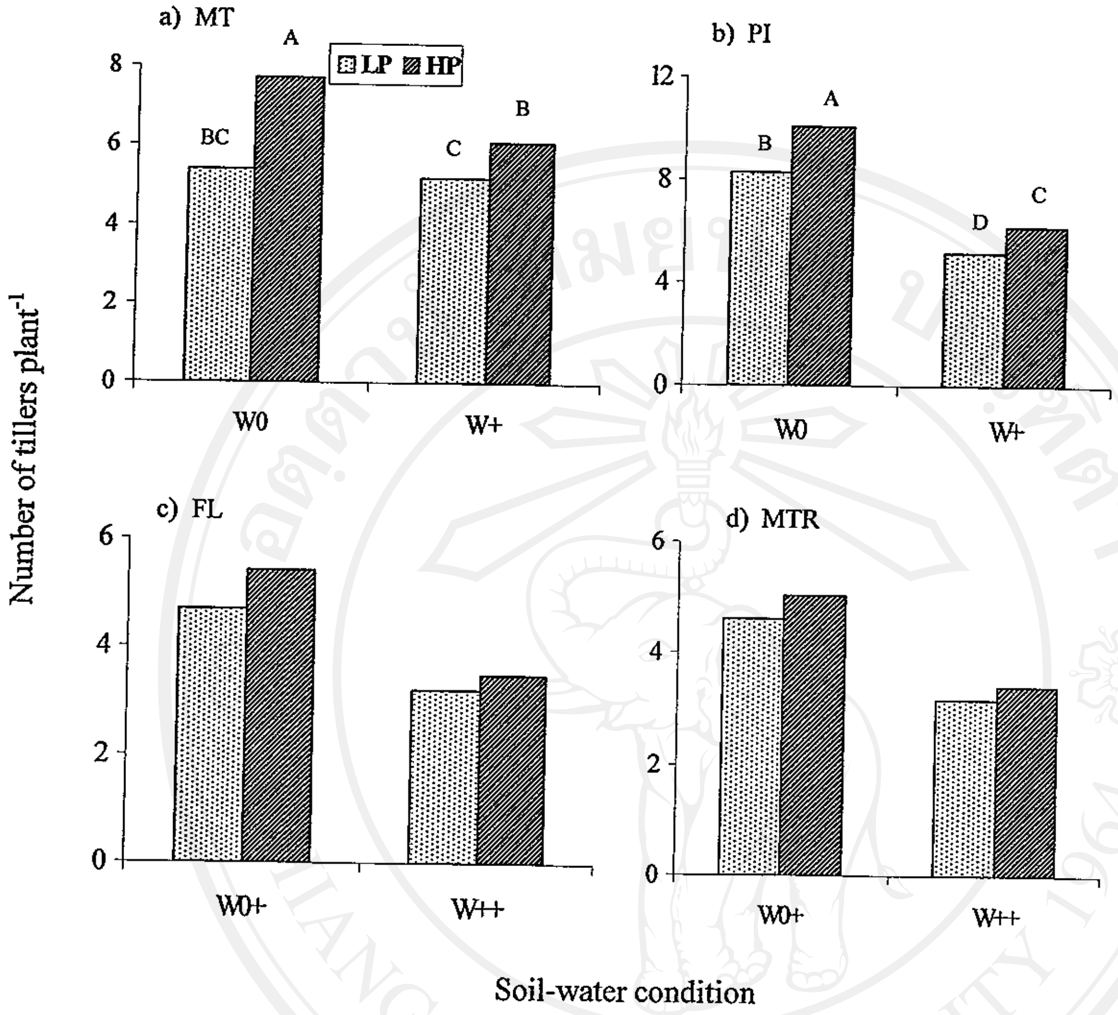

Figure 3.4 Effect of P applications (low P: LP or high P: HP) on number of tillers per plant at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); flowering (c); and maturity (d) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P<0.05)}$.

Analysis of variance	LSD $_{0.05}$	W	P	WxP
	MT	0.52**	0.53**	0.74**
	PI	0.36**	0.37**	0.49**
	FL	0.26**	0.26*	ns
	MTR	0.27**	ns	ns

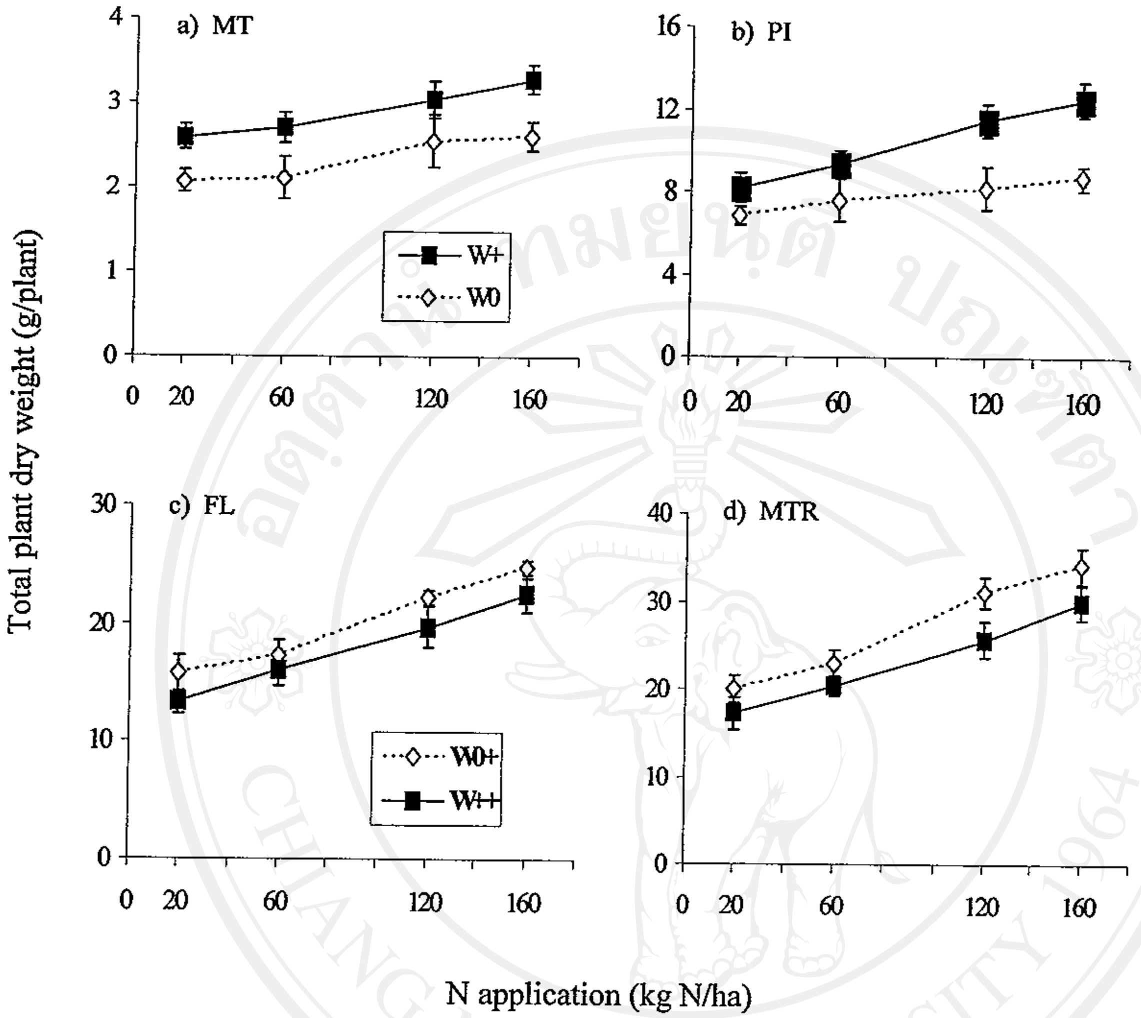

Figure 3.5 Effect of N applications on total plant dry weight (g/plant) at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); flowering (c); and maturity (d) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.

Analysis of variance	LSD $_{0.05}$	W	N	WxN
	MT	0.10**	1.16*	ns
	PI	0.41**	0.58*	0.82**
	FL	0.91**	1.28**	ns
	MTR	1.00**	1.41**	ns

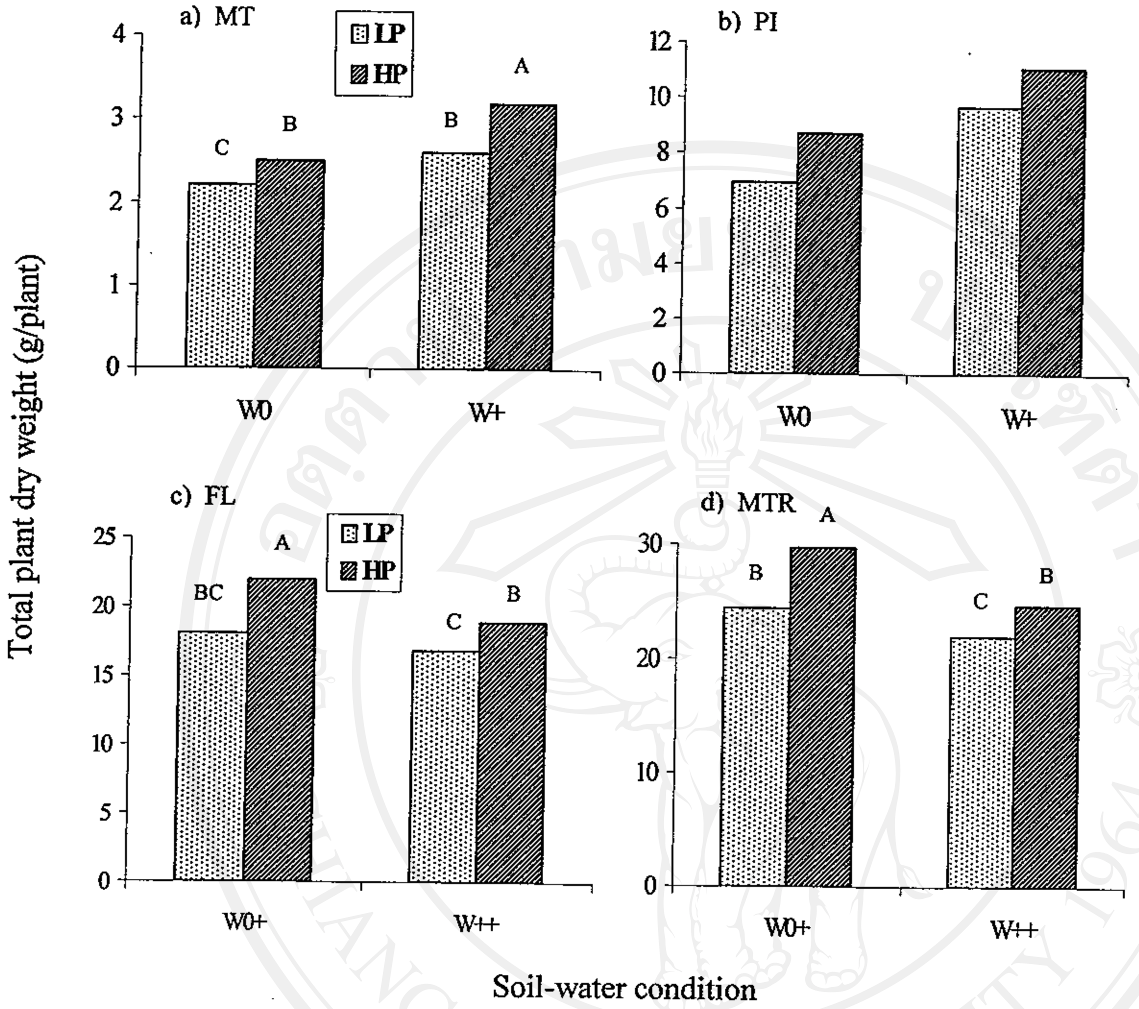

Figure 3.6 Effect of P applications (low P: LP or high P: HP) on total plant dry weight (g/plant) at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); flowering (c) and maturity (d) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P < 0.05)}$.

Analysis of variance

LSD $_{0.05}$	W	P	WxP
MT	0.10**	0.11**	0.16*
PI	0.41**	0.42**	ns
FL	0.91**	0.93**	1.28**
MTR	1.00**	1.01**	1.41**

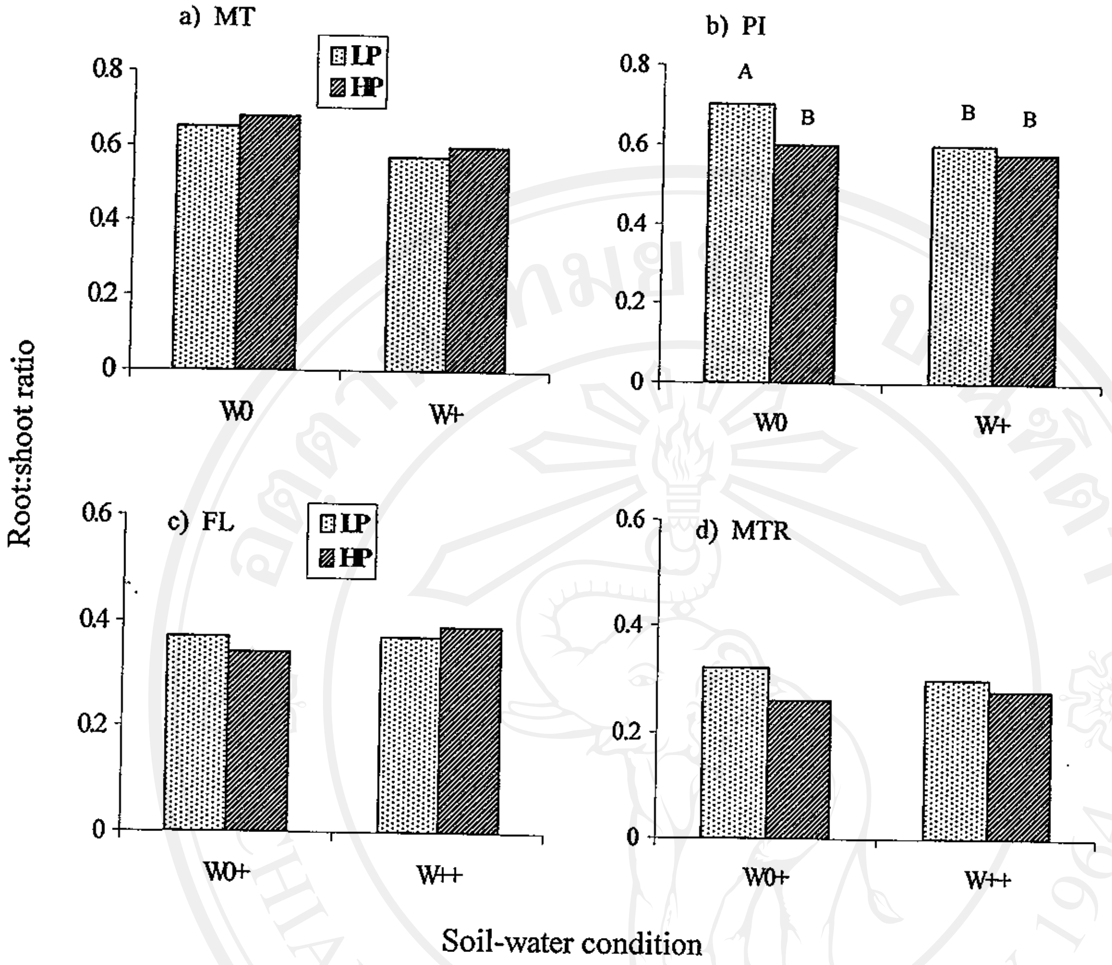

Figure 3.7 Effect of P applications (low P: LP or high P: HP) on root:shoot ratio at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); flowering (c) and maturity (d) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P < 0.05)}$.

Analysis of variance	LSD $_{0.05}$	W	P	WxP
	MT	0.04**	ns	ns
	PI	0.04**	0.05**	0.07*
	FL	ns	ns	ns
	MTR	ns	ns	ns

Number of panicles per plants was increased by increasing N rate, but the effect was significantly different between W0+ and W++ (WxN significant at $P < 0.01$). The number of panicles increased slightly with each increase in N rate in W++ and much more strongly in W0+ (Figure 3.8). The effect of P, however, was not significantly different between W0+ and W++ (Figure 3.9).

Soil-water regime, N and P all were significantly effect on total number of grains per panicle ($P < 0.01$), but there was neither WxN nor WxP interaction effects on the total number of grains per panicle (Figure 3.10 and 3.11). Generally, the total number of grains per panicle increased with increasing applied N and P rates. The greater total number of grains per panicle was found in W0+ plants, which was 6% more than W++ plants.

The effects of N on number of filled grains per panicle were significantly different between W0+ and W++ (WxN significant at $P < 0.01$). Applying N20, the filled grains number per panicle did not change between W0+ and W++ (Figure 3.12). The filled grains number was increased by increasing N application up to N160. The increasing of filled grains number per panicle however was more strongly in W0+ than in W++. Moreover, the effect of P on filled grains number per panicle was also significantly different between W0+ and W++ (WxP significant at $P < 0.01$). The lowest number of filled grains per panicle was found in W++LP (Figure 3.13). Significantly more filled grains per panicle, 9%, was found in W0+LP than in W++LP. The highest number of filled grains per panicle was found with W0+HP, which was 15% more than W++HP and 23% more than W++LP.

1000-grains weight was significantly greater in W0+ than that in W++ ($P < 0.01$), but the interaction effect of soil-water and N on 1000-grain weight was not significant (Figure 3.14). In W++ the 1000-grains weight steady increased with increasing whole rang of N rates from N20 to N160. The 1000-grains weight in W0+, which was little more increased with applying N rate to N120 but slowed down with applying N160. The effect of P on 1000-grain weight also did not change between W0+ and W++ (Figure 3.15). W0+ plants had greater than W++ plants about 1000-grains weight, but applying P both W0+ plants and W++ plants increased 1000-grains weight.

Soil-water, N and P all had significant effects on grain yield, but the effect of both N and P were strongly dependent on soil water status (Table 3.3). The interaction effect of W and N on grain yield was also significantly different (WxN significant at $P < 0.01$). In W0+, increasing N rates increased strongly grain yield while in W++ grain yield increased less with increasing N rates. The relationship between grain yield and nitrogen application in W0+ and W++ are as follows:

$$Y_{W0+} = 0.04X + 4.24$$

$$Y_{W++} = 0.02X + 4.43$$

Where Y = grain yield (g/plant); X = kg N/ha

Moreover, the effect of P on grain yield was significantly different between W0+ and W++ (WxP significant at $P < 0.05$). The yield in LP was 15% higher in W0+ than in W++. In both W0+ and W++ the grain yield increased with HP, but the increase was 26% in W0+, and only 9% in W++.

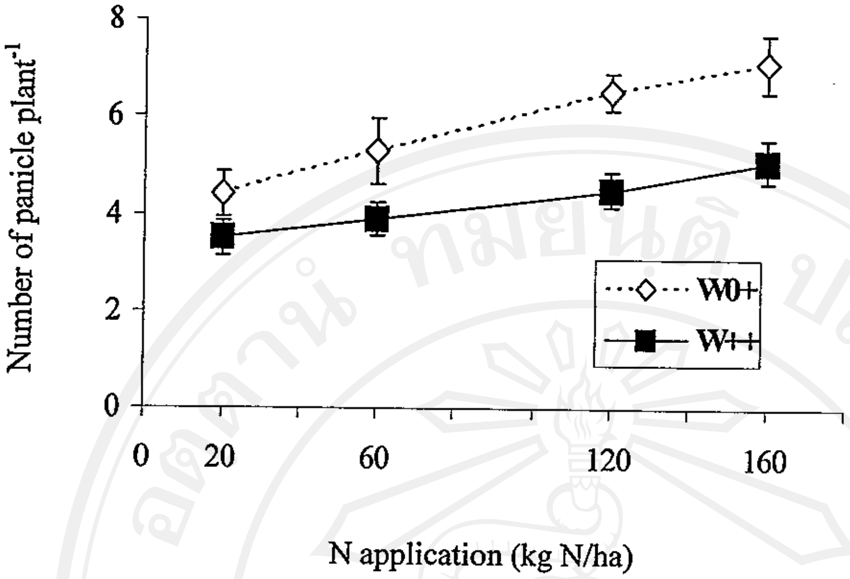

Figure 3.8 Effect of N applications on number of panicles per plant in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 0.26**, N = 0.37**, WxN = 0.52**

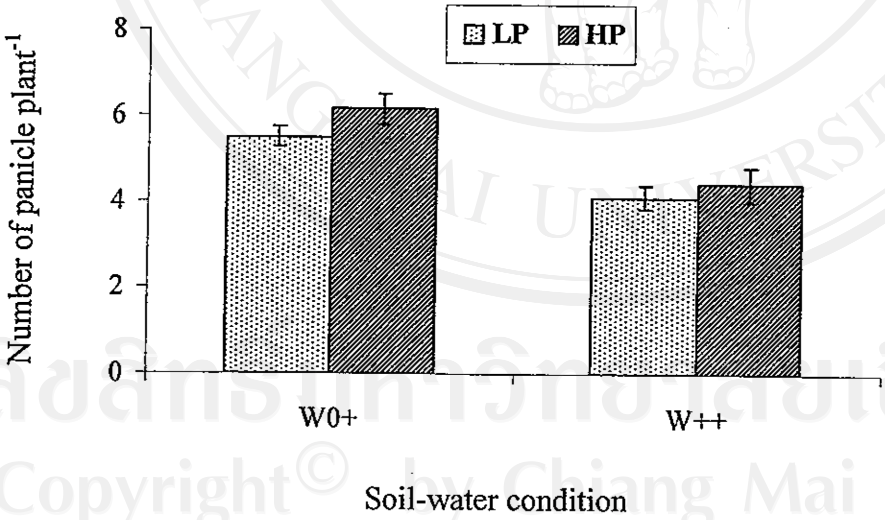

Figure 3.9 Effect of P applications (low P: LP or high P: HP) on number of panicles per plant in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 0.26**, P = 0.23**, WxP = ns

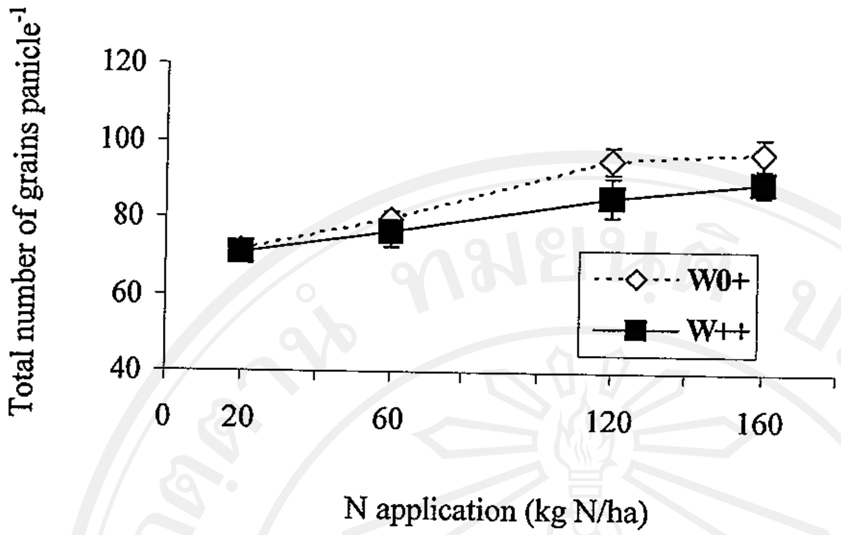

Figure 3.10 Effect of N applications on total number of grains per panicle in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 2.26**, N = 3.76**, WxN = ns

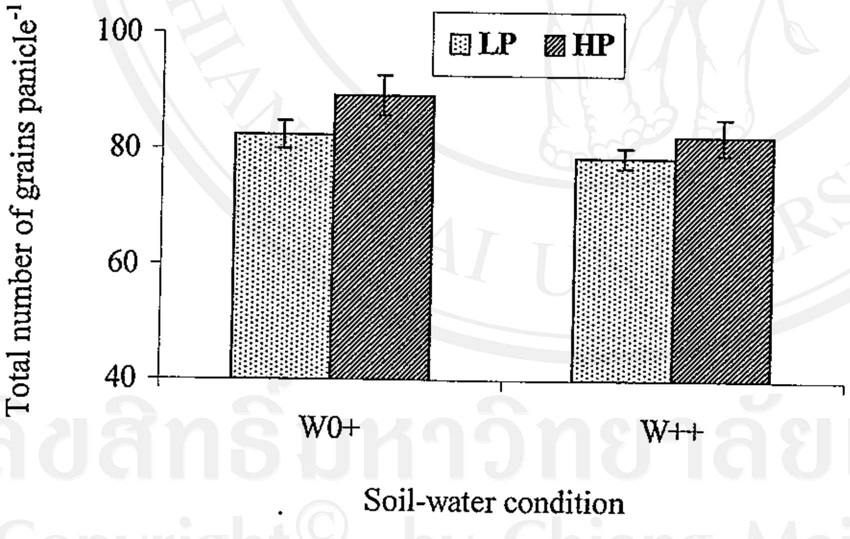

Figure 3.11 Effect of P applications (low P: LP or high P: HP) on total number of grains per panicle in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 2.26**, P = 2.66**, WxP = ns

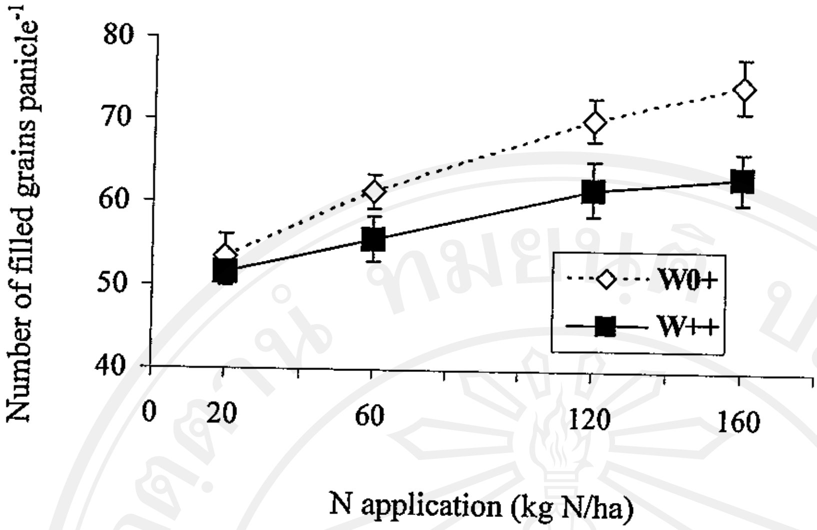

Figure 3.12 Effect of N applications on number of filled grains per panicle in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.

LSD $_{0.05}$: W = 2.10**, N = 2.97**, WxN = 4.20**

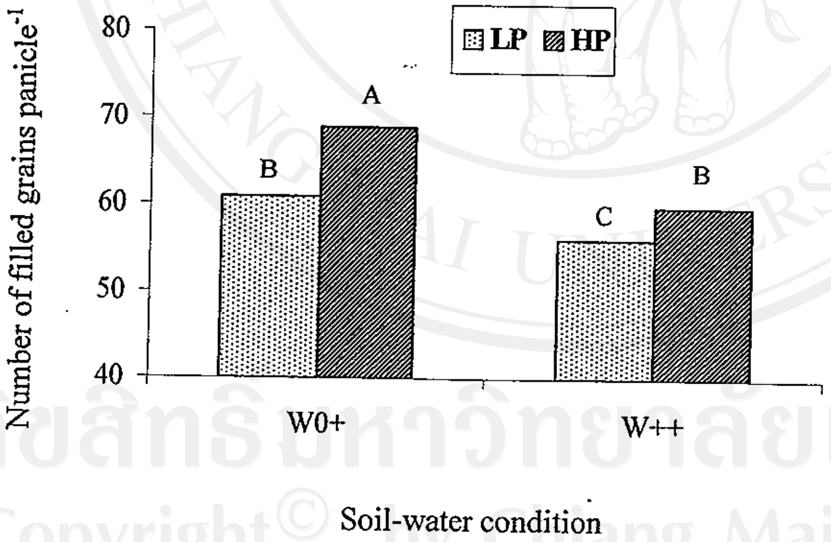

Figure 3.13 Effect of P applications (low P: LP or high P: HP) on number of filled grains per panicle in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P < 0.05)}$.

LSD $_{0.05}$: W = 2.10**, P = 2.12**, WxP = 2.97**

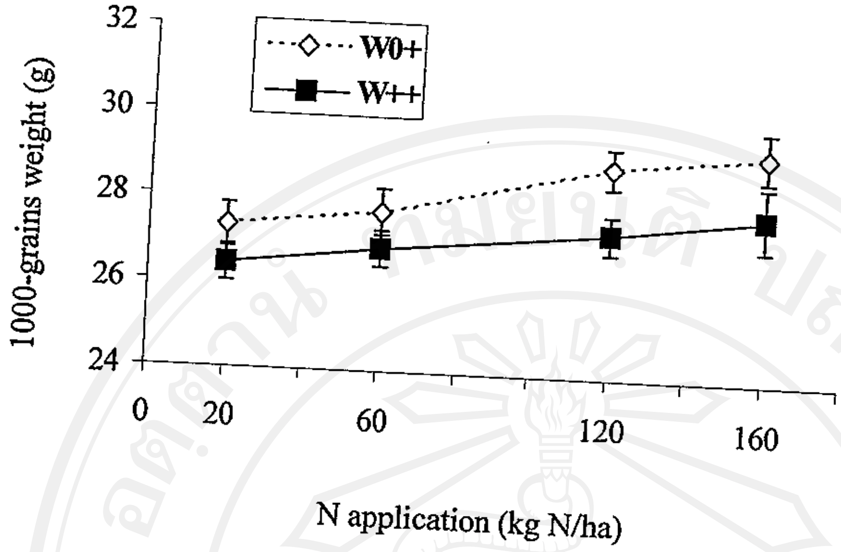

Figure 3.14 Effect of N applications on 1000-grains weight (g) of rice in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 0.32**, N = 0.45**, WxN = ns

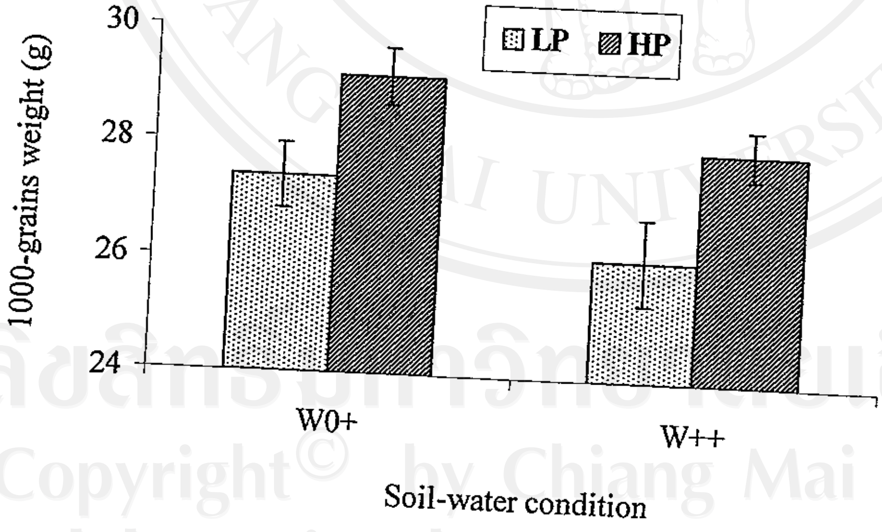

Figure 3.15 Effect of P applications (low P: LP or high P: HP) on 1000-grains weight (g) of rice in aerobic before PI followed by waterlogged soil to maturity (W0+), and waterlogged soil throughout (W++). Each vertical bar is mean ± standard error value of 4 replicates.
LSD $_{0.05}$: W = 0.32**, P = 0.33**, WxP = ns

Table 3.3 Effect of N and P applications on grain yield (g/plant) of rice grown in two soil-water conditions.

[††]Soil condition	P application	Nitrogen application (kg N ha^{-1})				Mean	
		20	60	120	160		
W0+	LP	4.47	5.37	8.75	9.59	7.05B	
	HP	5.97	7.13	10.82	11.49	8.85A	
	Mean	5.22dA	6.25cA	9.79bA	10.54aA[†]		7.95A
W++	LP	4.75	5.57	6.45	7.70	6.12C	
	HP	4.93	6.08	7.42	8.30	6.68B	
	Mean	4.84dA	5.83cA	6.94bB	8.00aB		6.40B
	W	N	P	WxN	WxP	NxP	WxNxP
F-test	**	**	**	**	*	ns	ns
LSD$_{0.05}$	0.36	0.51	0.36	0.73	0.51	-	-

[†] The lower cases and capital letters are used for comparison between rows and columns, respectively. The different letters are significantly different by LSD$_{(P<0.05)}$

LP: low P (10 kg P/ha), HP: high P (50 kg P/ha)

N application was 20, 60, 120 and 160 kg N/ha

[††] W0+: aerobic followed by waterlogged soil at PI to maturity;

W++: waterlogged soil throughout.

* significant at $P < 0.05$; ** significant at $P < 0.01$; ns: not significant

Soil-water and N interaction effects on plant N content was significantly different at three growth stages, MT ($P < 0.01$), FL and MTR ($P < 0.05$) but not at PI (Figure 3.16). At MT, applying N20 the W0 plants and W+ plants had about the same N content. In W0 the N content increased strongly with increasing N rate to N120, but with less effect to N160. In W+ the N content increased with increasing N rate to N160. At PI, plants increased N content with increasing N rates. At this stage the increase of N content was about the same between W0 plants and W+ plants. Similarly to MT, at FL and MTR the N content increased with increasing N rate in both W0+ and W++. Plant N content was significantly higher in W0+ than in W++ throughout the whole range of N rates from N20 to N160.

Generally, the interaction effects of soil-water and P on plant P content was significant throughout 4 growth stages, MT, PI, FL and MTR (Figure 3.17, 3.18). At MT and PI the plant P content was significantly less in W0 than in W+, but those was significantly greater in W0+ than in W++ at FL and MTR. At MT and PI, waterlogging and P application had about the same effect on plant P content. At two these stages, applying P to waterlogged soil had strongest effect on plant P content, increasing it by 60-70% over that in W0+HP and 66-84% over that in W++LP. By contrast, at FL the greatest plant P content was found in W0+HP and lowest in W++LP. The plant P content in LP was 18% higher in W0+ than in W++. In both W0+ and W++ the plant P content increased with HP, but the increase was 66% in W0+, and only 48% in W++. Furthermore, at MTR the effect of interaction between N and P on plant P content was significantly different between W0+ and W++ (WxNxP significant at $P < 0.05$). In LP plant P content was slightly higher though not significantly different in W0+ than W++ at each N rate from N20 to N160 (Figure

3.18). The application of P raised P contents in all N and water treatments. In HP the plant P content was significantly higher in W0+ than in W++, with the difference becoming greater at higher N rates of N120 and N160.

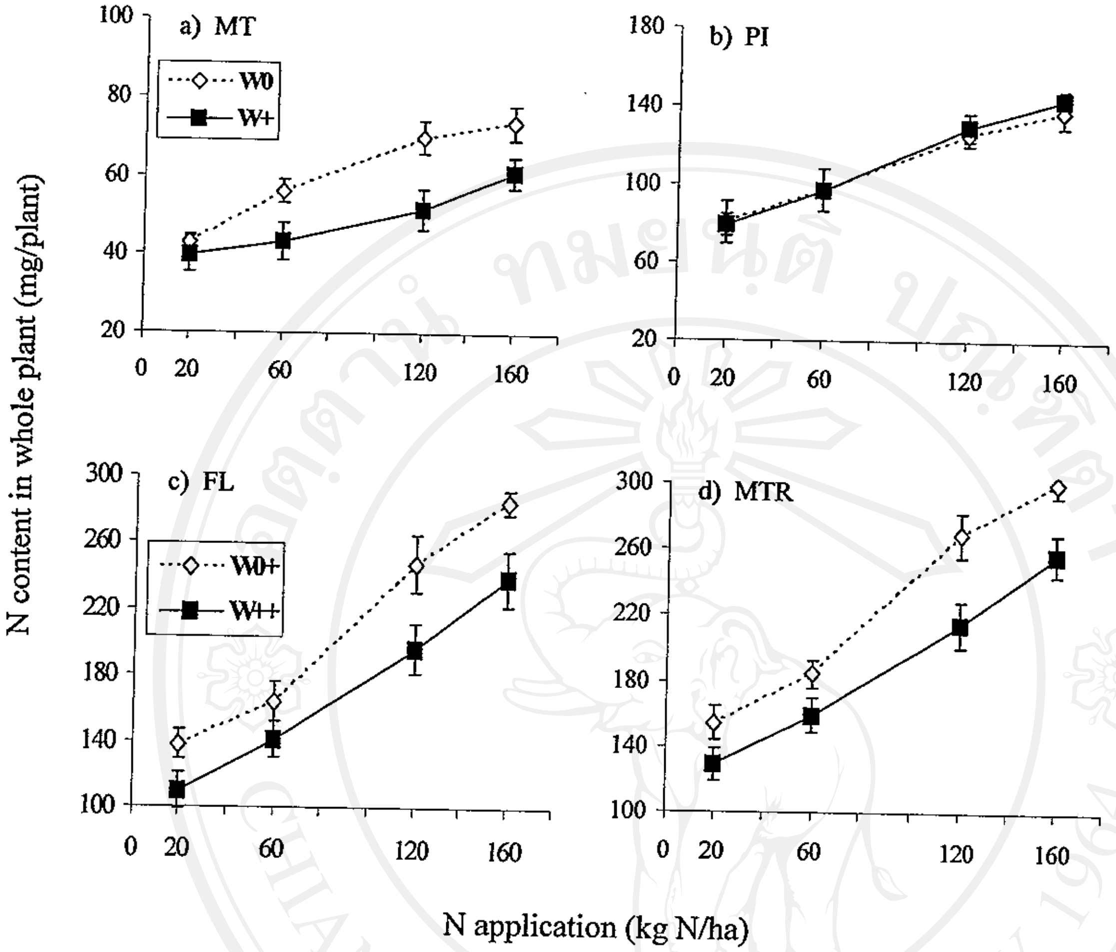

Figure 3.16 Effect of N applications on N content in whole plant (mg/plant) at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged soil (W+); flowering (c) and maturity (d) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each data point is mean ± standard error value of 4 replicates.

Analysis of variance	$LSD_{0.05}$	W	N	WxN
	MT	3.01**	4.26**	6.02**
	PI	ns	7.70**	ns
	FL	10.84**	15.33**	21.68*
	MTR	7.68**	10.86**	15.36**

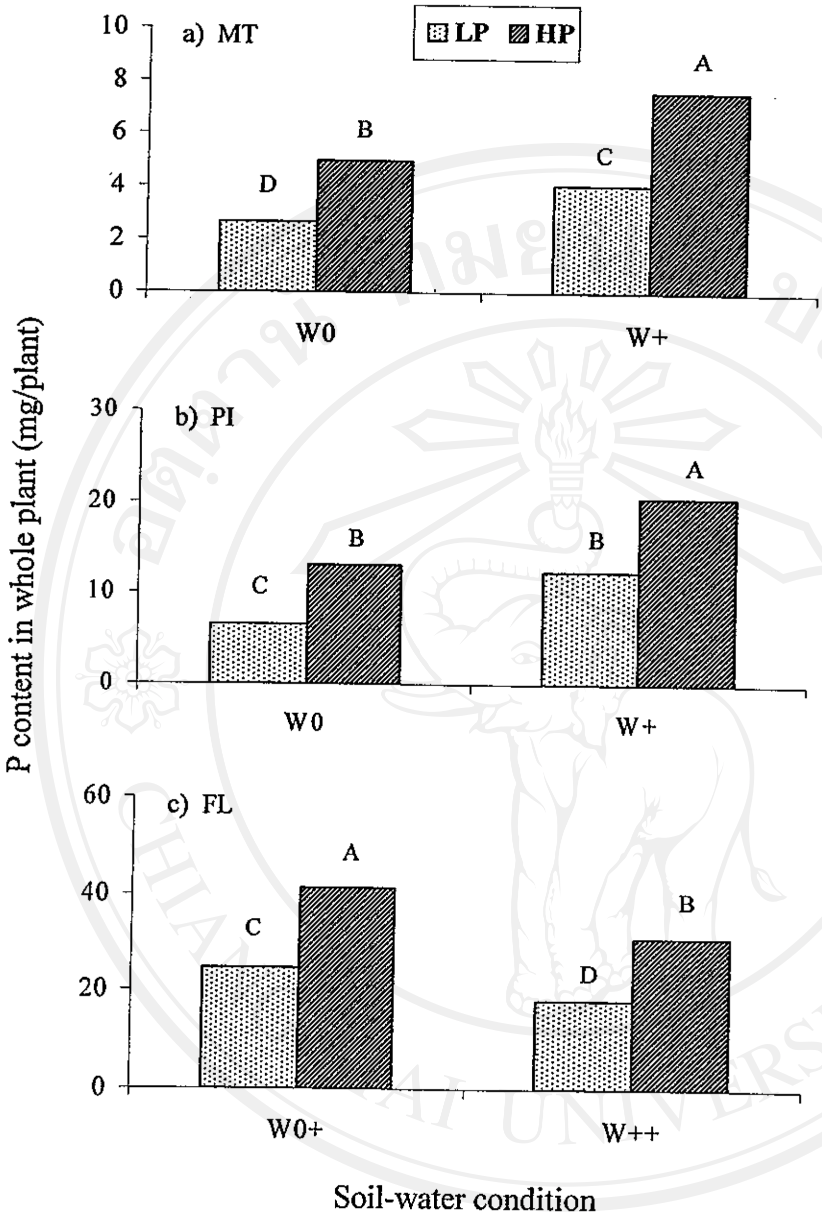

Figure 3.17 Effect of P applications (low P: LP or high P: HP) on P content in whole plant (mg/plant) at mid-tillering (a); panicle initiation (b) in aerobic (W0) or waterlogged (W+); flowering (c) in aerobic followed by waterlogged soil at PI to maturity (W0+) or waterlogged soil throughout (W++). Each vertical bar is mean value of 4 replicates. Different letters indicated significantly different of means by LSD $_{(P< 0.05)}$.

Analysis of variance	LSD $_{0.05}$	W	P	WxP
	MT	0.23**	0.24**	0.32**
	PI	0.81**	0.83**	1.14*
	FL	1.85**	1.86**	2.62**

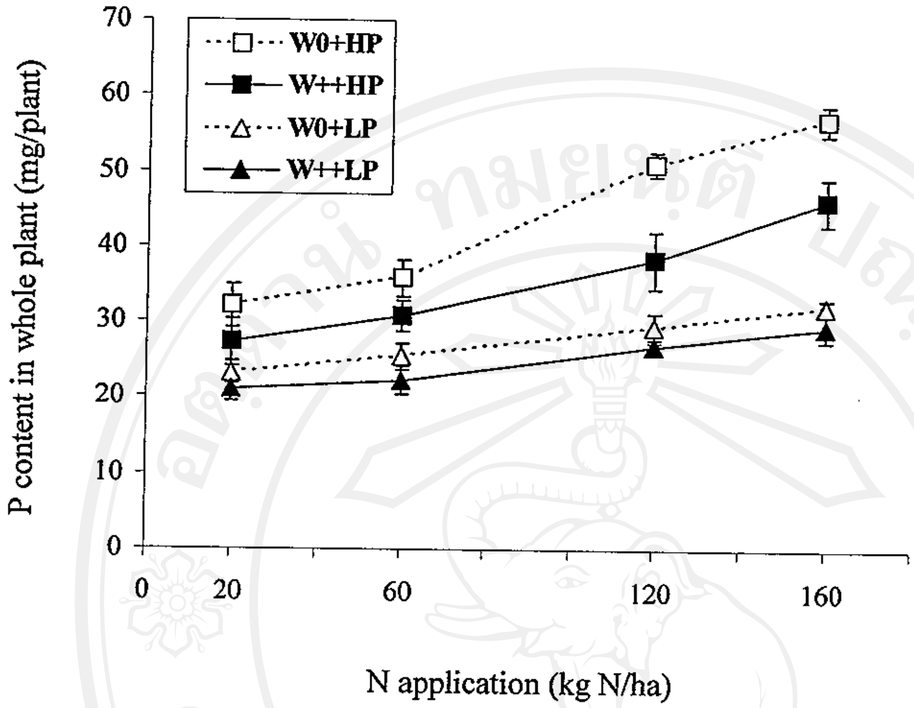

Figure 3.18 Effect of interaction between N and P on plant P content (mg/plant) at maturity in aerobic followed by waterlogged soil at PI to maturity, or waterlogged soil throughout. Each data point is mean ± standard error value of 4 replicates.

W0+HP: aerobic followed waterlogged soil-high P

W++HP: waterlogged soil throughout-high P

W0+LP: aerobic followed waterlogged soil-low P

W++LP: waterlogged soil throughout-low P

Analysis of variance

LSD $_{0.05}$	W	N	P	WxN	WxP	NxP	WxNxP
MTR	1.19**	1.68**	1.18**	2.38*	1.70**	2.37**	3.36*

3.4 Discussion

In many field studies under rainfed lowland condition have been reported that aerobic rice gave lower yields than those of continuously irrigated rice (Wade *et al.*, 1999a; Fukai *et al.*, 1999). Studies of soils in Cambodia, Laos and North-East Thailand suggested a complex combination of factors restrict rice yield and nutrient uptake in response to loss of soil-water saturation (*reviewed by* Bell *et al.*, 2001). Bell *et al.* (2001) discussed that intermittent flooding and drying of soils depresses availability of some nutrients. Moreover, extreme fluctuations in soil-water levels may impair root activity, further restricting nutrient uptake particularly N and P result in low yield of rainfed lowland rice compared with irrigated rice. By theory, the concentration of available P in submerged or anaerobic soil is greater than that in aerobic soil because of release of sorbed and co-precipitated P following the reduction of Fe^{3+} compounds. Furthermore, submergence enhances diffusion, easily-extractable soil P the main mechanism of P supply to rice roots (Ponnamperuma, 1972; Dobermann *et al.*, 2000; Kirk *et al.*, 1998). Therefore, growth of plants under submerged soil is often better than under aerobic soil by root nutrient supply. In this study, the results showed that at MT and PI, plant P content and plant dry weight of aerobic rice were less than those of waterlogged rice. Peng *et al.* (2005) also found aerobic rice produced less total dry weight than flooded rice in whole growing period. However, the result of this study has clearly shown at both FL and MTR, plant P content and plant dry weight of W0+ plants were greater than those of W++ plants. Particularly, the grain yield of W0+ rice was significantly by 12% over that of W++ rice (Table 3.3). These findings differed from the previous results which were discussed above.

However, there are reasonable evidences that submergence of a aerobic or dry soil first the reductive dissolution of ferric (Fe^{3+}) compounds is major factor causing increased post-flooding P availability. Flooding brings about the liberation of sorbed and co-precipitated P from surfaces of free Fe hydroxides; this process increases the levels of extractable P in acidic soils (Ponnamperuma, 1972; Willett, 1986). Secondly, desorption and dissolution reactions causes by pH changes. Hydrolysis due to increased soil pH results in higher solubility of iron-bound phosphate ($FePO_4.2H_2O$) and anuminum-bound phosphate ($AlPO_4.2H_2O$) in acid soils (Sanyal and De Datta, 1991). The soil-pH of this study was not measured during the experimental period; however, it was reported that the pH of this soil is low (Table 3.2). Finally, organic anions produced during anaerobic decomposition of organic matter under flooded soil conditions may increase the solubility of Ca-P compounds by complexing Ca^{2+} ions, and thereby disturbing the solubility equilibria of Ca-P (Willet, 1986). Therefore, after transfer from aerobic into waterlogged soil at PI, the rice plants grew better by favorable nutrient supply to roots compared with plants did in aerobic soil. Grigg *et al.* (2000) also found that delayed-flooded irrigation until panicle initiation stage reduced shoot dry weight but did not effect on grain and head-rice yield compared with continuously flooded rice (5-10 cm water depth).

In general, increasing N and P application increased plant N and P uptake of both W0+ and W++ rice. Clearly that P uptake of rice plant was more strongly depending on soil-water condition than N uptake. Although N uptake of rice under W0 was high; and the plant N content did not differ between W0 plants and W+ plants at PI. However, the plant dry weight in W0 was low by low plant P content compared with plants in W+. The results of this study indicate that the response of plants to N application depends on P status.

Furthermore, W0 plants were significantly less P uptake than those of W+ plants at MT and PI but it was significantly greater in W0+ plants than in W++ plant at FL and MTR. Previous studies reported that grown in low P, plants have higher root:shoot ratio compared with plants grown in high P (Gutschick, 1993; Nielsen *et al.*, 2001). In this chapter, the result has shown that in low P the rice plant had higher root:shoot ratio than in high P at PI. The difference about root:shoot ratio in low and high P only found in W0 but no evidence in W+. Bell *et al.* (2001) discussed that aerobic rice usually has longer maximum root length than irrigated or anaerobic rice to facilitate of water and nutrient capturing in the soil at deep layers, and therefore root is more developing than shoot under aerobic or dry condition. The difference of root:shoot ratio between low and high P application is well understood, but how rice responds to change between aerobic and waterlogged soils is still not clear.

In addition to the varying of soil-P chemistry in changing between aerobic and waterlogged conditions, the adaptive characteristics of rice plants to anaerobic condition also restrict plant growth and nutrient uptake. Previous study has shown that the dry weight and nutrient concentrations in the shoots of stagnant plants was lower than those of aerated plants (Wiengweera *et al.*, 1997). They also found cross-sectional area (aerenchyma) of the stagnant roots was nine-fold higher than that of aerated plants. In addition, Wiengweera *et al.* (2004) reported that net N and P uptake of stagnant plants was lower than those of aerated plants. The study in rice was reported stagnant plants had higher root porosity compared with aerated plants (Colmer *et al.*, 1998). They explained that the adaptation of plants to waterlogging is the production of adventitious roots which contain aerenchyma. The aerenchyma provide a low resistance internal pathway for movement of O_2 from the shoots to the roots. To reduce radial oxygen loss to the rhizosphere, roots induce barrier; however, one possible drawback of the barrier inhibit of nutrient absorption by anaerobic roots. These results support similar finding in tribe Triticeae when grown in aerated or stagnant condition by McDonald *et al.* (2001). Therefore, rice grown in anaerobic soils is affected by limitation nutrient uptake compared with rice grown in aerobic soils. Thus, the result of nutrient uptake by rice plants in this study is possible.

In conclusion, the aerobic rice is restricted by nutrient availability supply to the roots which relate to soil-water regime. Anaerobic rice, on the other hand, is restricted by adaptive characteristics to anaerobic environment on nutrient uptake. The result of this study is confirmed that the growth, nutrient uptake and grain yield of rice grown in aerobic followed by waterlogged soils at PI are better than those of rice in continuously waterlogged soil. In this chapter, however, the response of plant growth to P supply in pre-waterlogged and non-waterlogged soils; and the adaptation of root morphology and physiology to change between aerobic and anaerobic conditions are not examined. These will be explored in chapter 4.