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Agronomic Research on Direct Seeded Rice Production in Rainfed Lowland in Northeast Thailand
(東北タイ天水田におけるイネ直播栽培に関する作物栽培学的研究)

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Introduction

Increasing the production of staple cereals such as rice is the important issue to feed the increasing population. As the expansion of cultivation area is difficult (IRRI, 2002), rice production have to be increased mainly through enhancing productivity (production per area). Recently, two factors are regarded as the major concerns in rice productivity in Asia. The one is the shortage of irrigation water, and the other is the shortage of labour for transplanting (TP).

Green Revolution has increased the grain yield in irrigated lowland rice systems (Khush, 1999; IRRI, 2002), but irrigation system requires a lot of fresh water. Shortage of water resource for irrigated lowland rice is supposed to be a big problem in near future (Bouman and Tuong, 2001; Pimentel et al., 2004; Rijsberman, 2006; Sahrawat 2006; ; Bouman et al., 2007; Belder et al., 2007; IRRI, 2002). Hence it is important to increase the productivity in rainfed lowlands, which occupy 35% of the rice cultivation area in Asia (IRRI, 2002), without much relying on irrigation systems. Northeast Thailand is one of the major rainfed lowland rice producing areas. Percentage of rainfed lowland is 92% (4.66 million ha) of the total rice cultivation area in this region and more than 50% of that in the whole country (OAE, 1994). Average grain yield in Northeast Thailand is low (1.92 t ha^{-1}) (OAE, 2007), mainly due to late season drought around flowering (Fukai et al., 1995) and low soil fertility (Bell et al., 2001; Bell and Seng, 2004).

In tropical Asian countries, TP has been rapidly replaced by direct seeding with less labour-requirement, owing to shortage of agricultural labour and increasing labour cost for TP (Pandey and Velasco, 2002; Dawe, 2005). In rainfed lowlands such as Northeast Thailand, dry seeding (referred to as DS) is the major direct seeding method, while wet seeding is mainly adopted in irrigated systems that can easily maintain soil saturation during seeding (Naklang, 1997; Miyagawa et al., 1999; Watanabe et al., 1999; Pandey and Velasco, 2002; Pandey et al., 2002). The percentage of DS in Northeast Thailand was about 25% in 1996 (Pandey et al., 2002), and DS is expected to be more widely adopted in future. The seeding methods in DS are mainly classified into three, broadcasting, row seeding and dibbling. In Northeast Thailand, manual broadcasting is widely adopted (Naklang, 1997). Although it was reported that mean grain yield in DS was lower than TP (1.37 vs. 1.80 t ha^{-1}) (OAE, 1994), DS can start cropping with less water in early season than TP and increase the opportunity of harvesting rice even when TP is not possible due to lack of soil moisture to transplant seedlings (Miyagawa, 1997; Naklang, 1997; Fukai, 1999; Mazid et al., 2002; Sipaseuth et al., 2002). Considering the increasing proportion of DS and its low grain yield, it is urgent to conduct researches to enhance the productivity of DS.

Previous studies to increase productivity of rainfed lowlands in Northeast Thailand have mainly three directions. The first is related with genotypic improvement, aiming to improve potential grain yield or enhance drought and disease (mainly blast) resistance (Romyen et al., 1998; Cooper et al, 1999a; 1999b; Jongdee, 2001; Pantuwan et al., 2002). The second is to increase productivity through fertilizer application or soil improvement (Herrera et al., 1997; Ohnishi et al., 1999; Naklang et al., 1999; Whitbread et al., 1999; Wade et al., 1999a; Haefele et al., 2006; Mochizuki et al., 2006). The third is to characterize environmental and managemental conditions for rainfed lowland rice production over the target geographical regions (Miyagawa and Kuroda, 1988; Kono et al., 1999; Supapoj et al., 1999; Oberthür and Kam, 2000; Homma et al., 2001; 2003; 2004). However, the number of studies on DS is limited compared with TP

Seeding rate is one of the important cultivation managements in DS which resource-poor farmers can easily adjust, but the relationship between seeding rate and grain yield under various rainfed lowland fields has not been well understood. Seeding rate affects grain yield through established seedling number, stem number and panicle number per area. In irrigated direct seeding (including both dry and wet seeding) in Japan, wide range of plant number (approx. 30 to 480 m^{-2}) or seeding rate (50 to 160 kg seeds ha^{-1}) was examined and it was reported that grain yield increased with increasing seedling number (or seeding rate) up to a certain value (which is regarded as an "optimum seeding rate"), and then got constant (Akamatsu, 1968a; Kobayashi and Washio, 1975; Kobayashi and Wada, 1979; 1980; Sekiyama and Shigenaga, 1980). If there was a problem such as nutrient deficit, overluxuriant growth and lodging, grain yield decreased over the optimum seeding rate (Akamatsu, 1966; 1968a; 1968b; Kobayashi and Wada, 1979). This relationship between plant number or seeding rate and grain yield could be partly applicable also for DS in rainfed lowlands in Northeast Thailand, but it is likely that the relationship and optimum seeding rate will be varied depending on wide range of growing conditions (i.e. water availability, soil fertility, weed infestation and fertilizer application) in rainfed lowlands. Under unfavourable growing conditions, increase of tiller number or percentage of fertile stems should be suppressed, and optimum seeding rate could get higher, compared with favourable conditions.

In DS, within-field variations in rice growth can be large (Lantican et al., 1999; Rickman et al., 2001), and this could cause substantial production losses. The main cause of this within-field variation should be limited land levelling technique, which results in unsmooth and heterogeneous soil surface in one field, and causes the uneven distribution of standing water and spatial variability in soil water content. In addition, manual broadcasting of seeds results in within-field variation in seedling establishment (seedling number per area). The intensity of weed infestation should also have spatial variability. However, these within-field variations in a DS field have not been quantified, and relationships among those variations have not been well understood.

The objectives of this thesis were

1) to clarify the relationship between seeding rate or plant number and grain yield and the effect of growing conditions on that relationship,
2) to quantify the spatial variability in soil water status, weed infestation and rice growth within one DS field and clarify the relationships among these within-field variations and
3) to propose suitable cultivation managements for DS in rainfed lowlands in Northeast Thailand.

In chapter 1, investigation of the growth of DS rice in farmers' fields was conducted, together with the interview to the farmers, to recognise the present situation and production constraints in DS. In chapter 2, productivity of DS and TP was compared using 3 plant densities to assess the effect of plant density on grain yield and using 14 genotypes to propose cultivar requirements for each cultivation method under favourable water condition and late season drought. It was reported that DS rice under favourable water conditions was often subjected to nitrogen deficit in later growth stage derived from its high plant density (Dingkuhn et al., 1992a,b). In chapter 3, cultivation method to avoid nitrogen deficit and achieve higher grain yield under favourable water conditions was investigated. In chapter 4, spatial variability in standing water distribution, soil water content, growth of rice and weed infestation and relationships among them in broadcast-seeding method was analysed using geostatistics. In addition, the effectiveness of row seeding as the method to reduce the within-field variation in rice growth and to control weeds was assessed in this chapter. In Chapter 5, relationships among seeding rate, emerged plant number, yield components and grain yield were analyzed, using the results in Chapters 1 to 4. In addition, genotypic performance and requirements were also analyzed in this chapter. Finally, cultivation managements to achieve higher grain yield under the wide range of growth conditions were discussed.

Chapter 1. Variation in grain yield of direct seeded rice among farmers' fields in Ubon Ratchathani Province

1. Introduction

Mean grain yield of direct seeding (DS) is lower than transplanting (OAE, 1994). Survey of TP and DS fields in Northeast Thailand also showed lower grain yield in DS, especially under water deficit conditions (Miyagawa et al., 1998; Tomita et al., 2003) and farmers often replied DS is lower-yielding than TP at their fields in farmer interviews (Kamoshita et al., 2006). This could be because farmers choose DS in fields with less water availability to avoid the risk for TP with less intensive management and resource input (Pandey et al., 2002). Drought is one of the major production constraints in Northeast Thailand. Drought in Northeast Thailand is generally divided into 2 patterns; early and late season droughts (Chang et al., 1979). Early drought occurs due to intermittence of rainfall in the beginning of early season (Polthanee, 1997). Drought or non flooded conditions in early season would suppress rice growth in early season and result in weed infestation in DS (Romyen et al., 2002). In this study, investigation in farmers' fields with contrasting growth conditions was conducted in 2003, 2005 and 2006 to recognise the present productivity and production constraints in farmers' fields. Although the number of investigated fields was small (n = 6), investigation was continued for multiple years at the 3 same fields.

2. Materials and methods

2.1. Investigation sites

Investigation in farmers' fields was conducted in 3, 5 and 3 sites in 2003, 2005 and 2006, respectively, around Ubon Rice Research Center (URRC), Ubon Ratchathani, Thailand (15°20′N, 104°41′E, 110 m elevation). In 2003, 3 sites were chosen from Don Chi (Don Chi 1), Nong Khaen (Nong Khaen 1) and Khu Khat (Khu Khat 1) villages; these villages are about 1 km east, 8 km south and 15 km northwest from URRC, respectively. In 2005, investigation was continued in Don Chi 1 and Nong Khaen 1 and 2 more sites in Don Chi village (Don Chi 2 and 3) and one field in Koei (Koei 1) village, about 12 km northwest from URRC, were added. Khu Khat 1 was excluded because the owner changed from broadcasting to dibbling. In 2006, investigation was conducted in the same sites as 2005 except for in Don Chi 2 and Koei 1 where DS was replaced by TP. Don Chi 1, Don Chi 2, Koei 1 and Nong Khaen 1 were located in toposequentially lower position in a small watershed. The toposequential position of Don Chi 3 and Khu Khat 1 was middle and upper part, respectively. Interview to the owners of investigated fields was conducted (about 30 minutes, with interpretation by a Thai researcher) to collect the information on their cultivation management for their direct seeded fields.

2.2. Measurements

Air temperature and rainfall were recorded at weather station in Ubon Rice Research Center (Table 1.1.). Soil sample was taken from plough layer (0-15 cm depth) from every site except for Khu Khat 1 to investigate pH, cation exchange capacity (CEC), organic matter, total nitrogen (N), available phosphorus (P), exchangeable potassium (K) and texture. Soil type was determined by the classification of Department of Agriculture of Thailand (1993). In 2003, 1 m^2 of rice was harvested to determine shoot dry matter, grain yield and panicle number. In 2005 and 2006, field water conditions (presence of standing water, depth of standing water or soil volumetric water content when standing water was absent), stem number, plant length and SPAD value, an index of plant nitrogen status (Peng et al., 2002), of rice were measured in about a month interval. Weed growth was scored visually using the visual weed score (Table 1.2.). At the maturity of rice, 0.75 m^2 of rice and weeds (only in 2005) were harvested to determine their shoot dry matter, grain yield and yield components of rice. In all the years, interview to the owners of the fields was also conducted to collect the information on their cultivation practice.

Table 1.1. Mean air temperature, rainfall and dry spell from April to November in 2003, 2005 and 2006.

	2003			2005			2006		
	Mean air temperature (°C)	Rainfall (mm)	Dry spell[1] (days)	Mean air temperature (°C)	Rainfall (mm)	Dry spell (days)	Mean air temperature (°C)	Rainfall (mm)	Dry spell (days)
Apr	30.3	34	20	30.0	45	17	29.5	187	0
May	30.1	240	15	29.9	86	10	29.0	85	17
Jun	29.0	195	8	28.7	256	8	29.5	189	8
Jul	28.8	221	8	27.9	256	8	26.0	322	0
Aug	28.3	214	5[2]	27.4	72	13	27.4	217	11
Sept	27.5	169	14	27.4	172	11	27.7	262	0
Oct	27.3	35	25	27.5	31	22	27.4	173	19
Nov	26.4	0	30	26.3	0	30	27.5	42	26

[1]Continuous days with rainfall less than 1 mm for more than 7 days.

[2]Dry spell continued until September.

Air temperature in 2005 and 2006 and rainfall in April and May in 2006 were measured in Ubon Ratchathani city, 22 km apart from Ubon Rice Research Center.

Table 1.2. Visual weed score used in this experiment.

Visual weed score	Plant height	Coverage (%)
0	No weed	
1	Lower than 10 cm	0 - 50
2		50 - 100
3	Lower than the half of rice	0 - 50
4		50 - 100
5	Lower than rice	0 - 50
6		50 - 100
7	Higher than rice	0 - 50
8		50 - 100

2.3. Statistical analysis

In all the years, phenotypic observation was analysed with analysis of variance (ANOVA), using the method of Gomez and Gomez (1984), to assess the difference between sites. In Don Chi 1, Don Chi 3 and Nong Khaen 1, difference among years was also analysed.

3. Results

3.1. Soil property

Soil type was loamy sand in Don Chi 1 and sandy loam in other 4 sites (Table 1.3). In Don Chi 2 and Don Chi 3, CEC and percentage of silt or clay was higher than other sites, but available P was lower. In Koei 1 and Nong Khaen 1, CEC was lower and the percentage of sand was higher than Don Chi 2 and Don Chi 3.

Table 1.3. Soil pH, CEC, organic matter, total N, avail. P, exch. K and texture in each site.

	Soil type	pH	CEC	Organic matter	Total N	Avail. P	Exch. K	Texture		
								Sand	Silt	Clay
			(c mole kg^{-1})	(%)	(%)	(ppm)	(ppm)	(%)	(%)	(%)
Don Chi 1	Loamy sand	5.1	19.5	1.48	0.07	6.7	16	76	18	6
Don Chi 2	Sandy loam	4.9	35.2	1.18	0.06	3.9	22	65	26	9
Don Chi 3	Sandy loam	5.2	23.3	1.50	0.08	3.9	21	62	30	8
Koei 1	Sandy loam	5.3	17.3	1.53	0.08	5.9	43	70	24	6
Nong Khaen 1	Sandy loam	5.2	11.5	1.37	0.07	9.5	28	70	26	4

pH; 1:1 H_2O, CEC; ammonium saturation and distillation, organic matter; Walkley-Black method, P; Bray II, K; ammonium acetate extraction at pH = 7, texture; hydrometer method.

3.2. Cultivation methods by farmers

Seeding date ranged from March to May (Table 1.4). In Don Chi 1 (late April to early May) and Don Chi 3 (early to mid May), seeding time was relatively consistent across years. In Nong Khaen 1, however, seeding date in 2006 (20 May) was later than in 2003 (mid April) and 2005 (late March). This was because the owner of Nong Khaen 1 at first intended transplanting in later month (e.g. June or July) but changed his mind in May to conduct direct seeding following the advice by his family members (that the grain yield in direct seeding and transplanting should be similar).

Seeding method varied among years even in a same site. In 2003, all investigated fields were ploughed once or twice followed by broadcasting and harrowing. In 2005, seeding method in Don Chi 1 and Nong Khaen 1 was changed from 2003. In those fields, ploughing was conducted after broadcasting and harrowing was not conducted in Nong Khaen 1. In Koei 1, harrowing was not conducted. In 2006, seeding method in Don Chi 1 and Nong Khaen 1 was changed again from 2005, and broadcasting was conducted after ploughing. Seeding method in Don Chi 3 was same as in 2005.

Genotypes were KDML105 or its glutinous mutant RD6 except for RD15 in Don Chi 3 in 2005. Wide variation was observed in seeding rate, ranging from 23 to 188 kg seeds ha^{-1}. Seeding rate in Don Chi 1 and Don Chi 3 was consistent among years, but that in Nong Khaen 1 varied greatly among years.

In Nong Khaen 1 in 2005 and 2006, neither manure nor chemical fertilizer was applied, but in other fields or year, some manure (cattle manure or rice straw) and/or chemical fertilizer (16-16-8, 15-15-15 or urea) was applied. Weed control by herbicide (c.f. 2,4-D is most popular in Northeast Thailand because of its low cost) and hand weeding was conducted in Don Chi 1 in 2003 and Koei 1 in 2005, respectively, but in other fields, no weeding was conducted.

Table 1.4. Information of cultivation management, year of adopting direct seeding, reasons for direct seeding (DS) and problems of direct seeding obtained from interview or observation.

	Seeding time	Seeding method	Genotype	Seeding rate (kg ha^{-1})	fertilizer	Weeding	Year of adopting DS	Reasons for DS	Problems of DS
2003									
Don Chi 1	Late April	Plough-broadcast-harrow	RD6	47	Organic matter as basal and 52 kg ha^{-1} of urea[1] at booting	Post-emergence herbicide	2002	Labour shortage, avoiding the risk of flood	Weed
Khu Khat 1	Early May	Plough in April and May-broadcast-harrow	KDML105	81	110 kg ha^{-1} of 16-16-8[2] at tillering	No weeding	Since 1999 (transplanted in 2001 and 2002)	Labour shortage, efficiency in cost	Weed
Nong Khaen 1	Mid April	Plough-broadcast-harrow	KDML105	31	15-15-15[3] (rate not available) at seeding and 81 kg ha^{-1} of urea at tillering	No herbicide	2002	Labour cost, higher yield in DS, avoiding the risk of flood	No problem
2005									
Don Chi 1	Early May	Burn residues-broadcast-plough-harrow	KDML105	47	1600 kg ha^{-1} of organic matter	No weeding	2002	Labour shortage, avoiding the risk of flood	Weed
Don Chi 2	Early May	Broadcast-plough-harrow	KDML105	23	47 kg ha^{-1} of 16-16-8	No weeding	na[4]	na	Weeds, difficulty in harvesting
Don Chi 3	Mid May	Broadcast-plough-harrow	RD15	31	44 kg ha^{-1} of 16-16-8	No weeding	2002	Avoiding the risk of flood	Uneven seedling establishment, weed
Koei 1	12 May	Burn residues-broadcast-plough	KDML105	na	156 kg ha^{-1} of 16-16-8 at panicle initiation	Hand weeding before fertilier application	na	na	na
Nong Khaen 1	Late March	Broadcast-plough	RD6	172	No fertilizer	No weeding	2002	Labour cost, higher yield in DS, avoiding the risk of flood	No problem
2006									
Don Chi 1	10 May	Plough twice (2 weeks interval)-broadcast-harrow	RD6	50	2813 kg ha^{-1} of organic matter	No weeding	2002	Labour shortage, avoiding the risk of flood	Weed
Don Chi 3	Early May	Broadcast-plough-harrow	RD6	30	A little of chemical fertilizer	No weeding	2002	Avoiding the risk of flood	Uneven seedling establishment, weed
Nong Khaen 1	20 May	Plough-harrow-broadcast	RD6	63	No fertilizer	No weeding	2002	Labour cost, higher yield in DS, avoiding the risk of flood	No problem

[1]Urea: N = 46 %

[2]16-16-8: N: P_2O_5: K_2O = 16: 16: 8 %

[3]15-15-15: N: P_2O_5: K_2O = 15: 15: 15 %

[4]Not available

3.3. Field water condition and rice growth

In 2005, standing water was observed since 17 June in Don Chi 1, Don Chi 2 and Nong Khaen 1 (Fig. 1.1). In Don Chi 3 and Koei 1, standing water was absent until the measurement on 22 July and it was observed since 23 August. In Don Chi 1 and Nong Khaen 1, standing water was deeper than other sites (25 and 30 cm, respectively, on 22 September). Depth of standing water on 22 September in Don Chi 2, Don Chi 3 and Koei 1 was 20, 18 and 13 cm, respectively. In 2006, standing water was observed since 4 July in Don Chi 1 and Don Chi 3, and since 25 July in Nong Khaen 1. In Don Chi 1, standing water deeper than 20 cm was observed at every measurement occasion from 4 July to 16 October. In Don Chi 3, depth of standing water was shallower than 18 cm until 22 September and it increased to 45 cm on 16 October. In Nong Khaen 1, standing water deeper than 28 cm was observed from 22 August to 16 October.

Large variation in stem number was observed among sites on 17 June (approx. 45, 45, 35, 36 and 85 days after seeding in Don Chi 1, Don Chi 2, Don Chi 3, Koei 1 and Nong Khaen 1, respectively) in 2005, reflecting the wide range of seeding rate (Fig. 1.2a). Stem number in Nong Khaen 1 with the highest seeding rate had the largest value (453 m^{-2}) on 22 July and decreased sharply until 22 September. Stem number in Koei 1 also decreased sharply until 23 August. In 2006, stem number on 6 June (approx. 27, 30 and 17 days after seeding in Don Chi 1, Don Chi 3 and Nong Khaen 1, respectively) was almost similar among sites (Fig. 1.2b). Stem number in Don Chi 1 and Nong Khaen 1 increased to 4 July and then decreased. Stem number in Don Chi 1 was larger than Nong Khaen 1 since 25 July until maturity. Different from other 2 sites, stem number in Don Chi 3 was almost constant or decreased slowly during growth period.

Plant length in Don Chi 1 and Nong Khaen 1 with deeper standing water was higher than other sites in 2005 (Fig. 1.2c).. Lodging was observed in these 2 sites at maturity (data not shown). Plant length in Don Chi 1 was the highest throughout measurement occasions in 2006 (Fig. 1.2d). Plant length in Nong Khaen 1 was lower than Don Chi 3 until 25 July, but was higher since 22 August until maturity. Also in 2006, rice lodged in Don Chi 1 and Nong Khaen 1 (data not shown).

In Nong Khaen 1 in 2005, no weed was observed throughout growth period (Fig. 1.3). Visual weed score in Don Chi 1 with deeper standing water was lower than 1 since 23 August. In other sites, visual weed score was higher than 3 (except for the measurements on 22 July in Don Chi 3 and on 10 November in Don Chi 2). Also in 2006, visual weed score in Don Chi 1 with deeper standing water was lower than 1. Visual weed score in Nong Khaen 1 fluctuated between 1 and 3. Low weed score was recorded in August, when depth of standing water increased sharply. Visual weed score in Don Chi 3 increased up to 5 on 22 August and decreased sharply. Sharp decrease after August was because sedges in the field died. No weed was observed on 16 October in Don Chi 3.

There was a large variation in shoot dry matter and grain yield across sites and years (Table 1.4). In Khu Khat 1 in 2003, both shoot dry matter and grain yield were the lowest. The highest grain yield was achieved in Don Chi 1 in 2005. Grain yield in Don Chi 1 and Nong Khaen 1 was higher than other 3 sites in 2005, because of larger panicle number and spikelet number. Don Chi 1 in 2006 had the highest shoot dry matter. Grain yield in Don Chi 1 was higher than other 2 sites in 2006. Although it was not significant, panicle number and spikelet number in Don Chi 1 tended to be larger than Don Chi 3 and Nong Khaen 1.

There was a clear relationship between spikelet number per area and grain yield (R^2 = 0.917, using 8 datasets in 2005 and 2006) (data not shown). Panicle number was associated with spikelet number per area and spikelet number per area increased with panicle number (R^2 = 0.814), but the relationship between spikelet number per panicle and per area was not clear (data not shown).

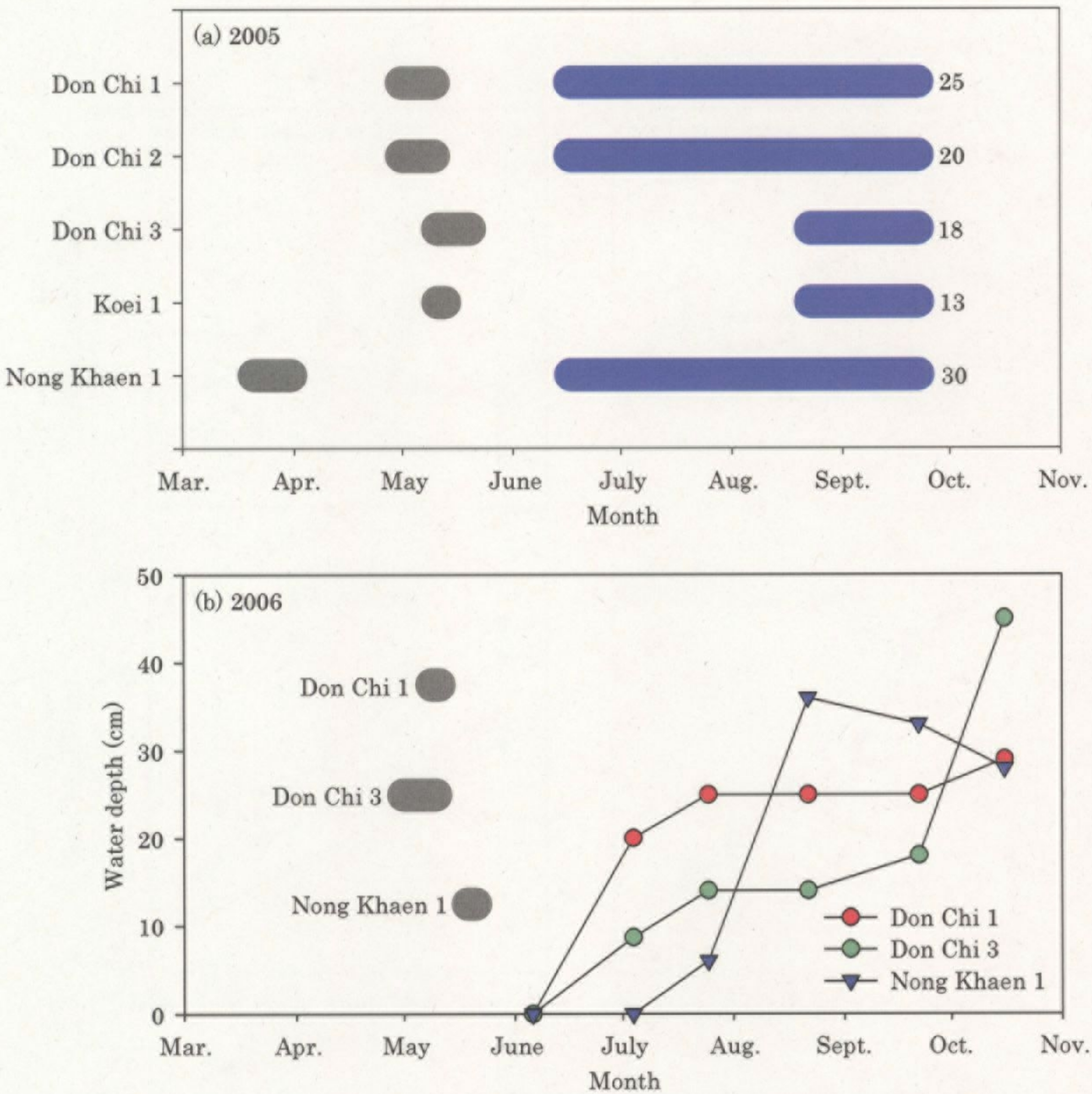

Fig. 1.1. Seeding time (grey marks) and flooded period (blue marks, only for 2005) in 2005 (a) and 2006 (b). Depth of standing water is shown for 2006 instead of flooded period.

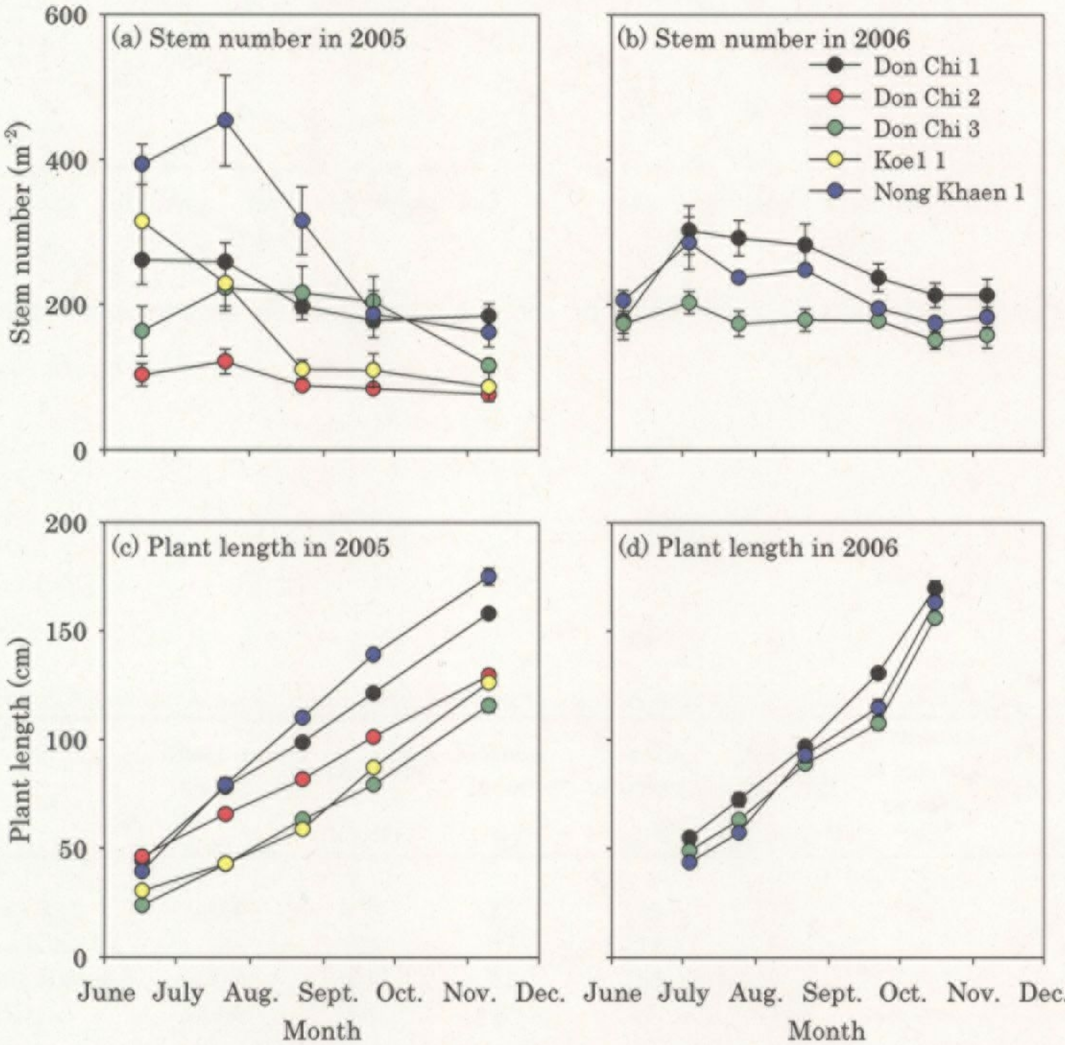

Fig. 1.2. Time course of stem number in 2005 (a) and 2006 (b) and plant length in 2005 (c) and 2006 (d). Vertical bars indicate standard errors.

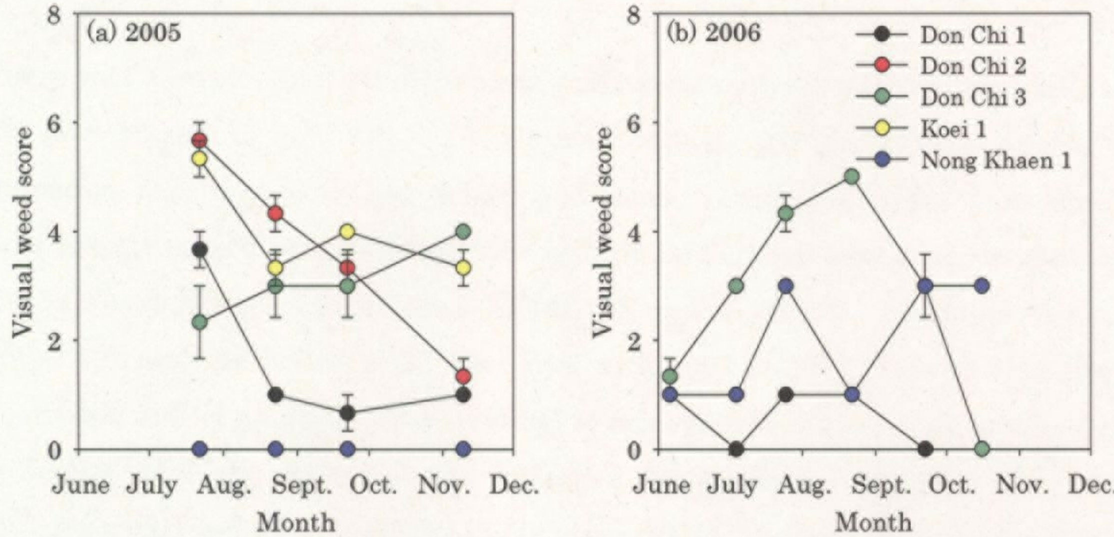

Fig. 1.3. Time course of visual weed score in 2005 (a) and 2006 (b). Vertical bars indicate standard errors.

Table 1.5. Shoot dry matter, grain yield, harvest index and yield components in investigated sites.

	Shoot dry matter ($g\ m^{-2}$)	Grain yield ($g\ m^{-2}$)	Harvest index (%)	Panicle number (m^{-2})	Spikelet number ($panicle^{-1}$)	Percentage of ripened grains (%)	Grain weight (mg)
2003							
Don Chi 1	1059	283	27	140	–	–	–
Khu Khat 1	340	128	37	114	–	–	–
Nong Khaen 1	1117	236	21	154	–	–	–
$LSD_{0.05}$	187	60	6	*31*	–	–	–
2005							
Don Chi 1	1295	514	35	184	101	95	29.0
Don Chi 2*	530	200	33	76	105	89	28.5
Don Chi 3	414	165	35	116	66	76	28.9
Koei 1	404	155	33	87	72	85	28.0
Nong Khaen 1	1375	401	26	161	103	86	28.6
$LSD_{0.05}$	352	115	*5*	49	25	6	ns
2006							
Don Chi 1	1600	436	24	213	97	78	27.5
Don Chi 3	902	256	25	157	71	81	28.3
Nong Khaen 1	1015	284	24	183	75	72	29.3
$LSD_{0.05}$	293	88	ns	ns	ns	4	1.0

$LSD_{0.05}$ indicates least significant difference at $P = 0.05$. *Italic* values indicate LSD at $P = 0.10$.
*Data was collected from panicles harvested by the owner and straw left in the field.

4. Discussion

There was a large variation in farmers' management methods. Seeding time ranged from late March to mid May. Genotypes used in the investigated fields were photoperiod sensitive (Jongdee, 2001), and hence heading and maturity time was almost similar regardless of seeding time (except for RD15 in Don Chi 3 in 2005, which matured about a week earlier than KDML105 and RD6). The farmer in Don Chi 1 adopted different method in 2005 compared with 2003 or 2006. This was because the farmer tried to find an appropriate method to achieve a better seedling establishment. The farmer in Nong Khaen 1 also changed his method every year (he omitted harrowing after seeding to save cost in 2005 and 2006). The lowest and highest seeding rate was 23 in Don Chi 2 in 2005 and 156 to 172 kg ha^{-1} in Nong Khaen 1 in 2005, respectively. Although seeding rates were almost constant among years in Don Chi 1 and Don Chi 3, seeding rate in Nong Khaen 1 varied greatly (31 in 2003 and 172 kg ha^{-1} in 2005). Seeding rate in investigated fields was generally lower than the recommended 50 to 100 kg ha^{-1} (Naklang, 1997). This result was different from the survey in Khon Kaen Province by Pandey et al. (2002). Pandey et al. (2002) reported farmers generally use higher seeding rate (97 kg ha^{-1} in average) to secure the seedling establishment. Although harrowing after broadcasting is recommended (Naklang, 1997), no harrowing was conducted in Koei 1 in 2005 and Nong Khaen 1 in 2005 and 2006. If harrowing is not conducted, it would increase the infestation of weeds (Naklang, 1997) and undulating soil surface should increase the within-field variability in the distribution of standing water. In Nong Khaen 1 in 2005, however, less weed was observed (visual weed score lower than 1). This could be owing to deeper standing water (Bhagat et al., 1996). Consequently, the variation in farmers' cultivation methods across years even in a same field could indicate that suitable direct seeding method has not been established and farmers were trying various methods to find an appropriate management.

Grain yield ranged from 128 to 514 g m^{-2}. Grain yield in Don Chi 1 and Nong Khaen 1 in 2005 and Don Chi 1 in 2006 (higher than 400 g m^{-2}) should be near the highest grain yield of KDML105 or RD6 (glutinous mutant of KDML105), judging from the previous studies (Romyen et al., 1998; Ohnishi et al., 1999). This indicated the high potential productivity of DS under favourable conditions, which is also supported by

Naklang et al. (1996). Average grain yield in the investigation in this Chapter was 278 g m^{-2}. This average was higher than the average grain yield in Northeast Thailand reported by OAE (1994). A survey of 179 paddy fields in Northeast Thailand showed a low average grain yield (approx. 150 g m^{-2}) (Tomita et al., 2003). Higher grain yield in the investigation in this Chapter should be due to the better water availability (longer flooded period). Miyagawa et al. (1998) investigated 178 fields in 9 provinces in the southern and central parts of Northeast Thailand and reported DS was conducted in the fields with less favourable water availability. This would be to avoid the risk of early season water shortage which makes it difficult to transplant seedlings to paddy fields (Naklang, 1997; Fukai, 1999). Contrary, most of the investigated fields in this study had relatively favourable water availability. The farmers in these fields replied to the interview that they direct seeded in order to avoid the risk of flooding. However, in the field with less water availability (e.g. Khu Khat 1 in 2003) and the fields with later presence of standing water (e.g. Don Chi 3 and Koei 1 in 2005), grain yield was lower due to smaller panicle number and spikelet number (not investigated in Khu Khat 1 in 2003). Clear relationships were observed between panicle number and spikelet number per area, and spikelet number per area and grain yield. Panicle number in these sites was small (The largest panicle number was 213 m^{-2} in Don Chi 1 in 2006). Improvement of cultivation method to enhance the productivity through increasing panicle number (i.e. appropriate land preparation, seeding time, seeding rate, etc) should be required.

5. Conclusions

A large variation was observed in rice growth. Average grain yield in this investigation was higher than the average of DS in Northeast Thailand, which was owing to better water availability. In the fields with better water availability (i.e. Don Chi 1 and Nong Khaen 1 in 2005 and Don Chi 1 in 2006), grain yield was higher than 400 g m^{-2} and should be near the potential of KDML105 and RD6. Contrary, grain yield was lower due to smaller panicle number and spikelet number in toposequentially upper field (e.g. Khu Khat 1 in 2003) and the fields with later presence of standing water (e.g. Don Chi 3 and Koei 1 in 2005). Improvement of cultivation method to achieve larger spikelet number per area should be required for such fields.

Summary: The investigation of DS rice growth was conducted in farmers' fields together with the interview to the owners of the fields. There was a wide range of variation in seeding time and seeding rate. Generally harrowing was conducted after broadcasting, but not in several fields to save the cost (Koei 1 in 2005 and Nong Khaen 1 in 2005 and 2006). These results suggested that suitable cultivation managements for DS have not been established yet. In fields with better water availability, grain yield higher than 400 g m^{-2} was achieved and this indicated the high potential productivity of DS under favourable conditions. In contrast, grain yield in toposequentially upper field (Khu Khat 1 in 2003) and fields with later flooding (Don Chi 3 and Koei 1 in 2005) was lower. Grain yield was correlated with panicle number, and it was suggested that cultivation method to achieve larger panicle number (i.e. appropriate land preparation, seeding time, seeding rate, etc) should be required.

Chapter 2. Comparison between direct seeding and transplanting, using different plant densities or genotypes

1. Introduction

The mean grain yield of direct seeding (DS) (1.37 t ha^{-1}) is lower than that of transplanting (TP) (1.80 t ha^{-1}) in Northeast Thailand (OAE, 1994). The lower grain yield could be because farmers choose to use DS with less intensive management and resource input in fields that have less water availability to avoid the risks associated with TP (Pandey et al., 2002). A better comparison of the productivity of TP and DS would include similar conditions of water availability and other inputs (i.e. fertilizer use and weed management). In DS, plant density gets much higher compared with TP. It was hypothesized that DS can have a higher yield than TP under favourable water availability conditions, because the higher plant density of DS could be advantageous for greater biomass production. In this chapter, the grain yield of DS and TP was compared systematically under favourable and late season drought conditions.

Adjusting plant density (i.e. hill density in TP and seed rate in DS) is easy for resource-poor farmers, but there are surprisingly few reports on the effects of plant density on the yield of rainfed lowland rice. It is well known that rice cultivars with low tillering ability or paddies with low soil fertility require higher plant density to achieve maximum yield using TP under irrigated lowland conditions (De Datta, 1981). Under favourable rainfed lowland conditions, yield response to plant density may be similar to that under irrigated lowland conditions. Under drought or weedy conditions, however, the yield might decrease and alter the relevance of plant density. In DS, seeding rates do not have a great effect on the yield of wet seeded rice under irrigated conditions with weed control (Phuong et al., 2005), but there is limited information on the effects of seeding rates in DS rice under rainfed conditions. DS with higher plant density than TP might exhaust the available soil water more quickly under late season drought conditions, which could be disadvantageous. Appropriate plant density and cultivation methods would be different under different water conditions with either TP or DS.

Efforts to improve grain yield under drought conditions through breeding are continuing in Northeast Thailand (Cooper et al., 1999b; Jongdee, 2001), but progress is limited, mainly because of the large genotype by environment (G $\times$ E) interaction

(Cooper and Somrith, 1997; Wade et al., 1997; Cooper et al., 1999a; Wade et al., 1999b). In multi-environment trials in breeding programs, fields a long way apart—in different provinces or countries with different rainfall patterns or soil types—are often chosen, but in Northeast Thailand toposequential position is aassociated with large differences in water availability, even between quite close fields (Homma et al., 2004). In toposequentially lower fields, water availability is generally favorable throughout rice growth, but in upper fields a water deficit frequently occurs. There have been no systematic studies of genotype by toposequence interaction. The most popular genotypes in Northeast Thailand—KDML105 and its glutinous mutant RD6—are late maturing and easily affected by late-season drought (Jongdee, 2001). These genotypes generally flower before the onset of water deficit in lower fields, but in upper fields, drought often occurs before their flowering time. Hence, earlier genotypes that flower before the onset of drought are required in upper fields (Fukai, 1999; Fukai and Cooper, 1995; Pantuwan et al., 2002), but the yield potential of early genotypes is often low because of their shorter growth duration (Pantuwan et al., 2002). Genotypes with larger panicle number could have a larger sink size (spikelet number per area) and higher grain yield, especially in TP.

The genotypic requirements for DS are not well known in Northeast Thailand. Higher plant density in DS could be advantageous for early genotypes because it would compensate for their potentially low biomass production caused by the shorter growth duration. In addition, DS with higher plant density might not need genotypes with larger panicle number, and there could be a genotype by cultivation method interaction between TP and DS. The yield performance of 14 genotypes (13 genotypes bred for rainfed lowlands in northeastern Thailand and 1 semi-dwarf genotype bred for irrigated lowlands) with different phenology was evaluated in TP and DS on toposequentially lower (favorable water conditions) and upper (late-season drought conditions) fields.

Objectives of this chapter were to assess the effects of plant density on grain yield and to propose some general cultivar requirements in DS and TP under different water conditions (favourable water or late-season drought).

2. Materials and Methods

2.1. Experimental design and materials

The experiment was conducted in 2003 in two fields that have different water availability at Ubon Rice Research Center, Ubon Ratchathani, Thailand (15°20′N, 104°41′E, 110 m elevation). One field (referred as the lower field, 32 × 53 m) was toposequentially lower than the other (the upper field, 32 × 59 m), about 200 m apart. According to the classification by the Department of Agriculture of Thailand (1993), the soil type in both fields is silt loam (the ratios of sand:silt:clay were 2:86:12 in the lower field and 6:74:20 in the upper field). Each field was divided in half; one-half for TP and the other for DS. Hereafter, TP and DS in the lower field are referred to as L-TP and L-DS trials, and TP and DS in the upper field are referred to as U-TP and U-DS trials. The 4 trials were conducted under rainfed conditions in both fields except for supplementary irrigation during puddling and transplanting time in the TP plots. Two experiments were conducted in these fields; the one for plant density (Exp. 1) and the other for genotypic difference (Exp. 2). For both experiments, the experimental design was a randomized complete block design with 3 replicates.

In Exp. 1, 2 *indica* cultivars, KDML105 and IR24, were used for TP, but only KDML105 was used in DS. KDML105 is an improved traditional cultivar with strong photoperiod sensitivity. It is widely grown in Northeast Thailand owing to its high grain quality and its adaptation to low soil fertility (Jongdee, 2001). However, it often suffers from late-season drought because of its late maturity and it has low yield potential, which drought exacerbates (Jongdee, 2001). IR24 is a non-photosensitive (about 120 days to maturity), semi-dwarf, high-yielding cultivar suited to irrigated lowlands. This cultivar was chosen because of its earlier maturity and higher yield potential, but its adaptability to low soil fertility is not well understood. In both TP and DS, three plant densities (high, middle, and low): 44, 25, and 16 hills m^{-2} with hill spacings of 15 cm × 15 cm, 20 cm × 20 cm, and 25 cm × 25 cm, respectively, in TP; and 125, 62.5, and 31.3 kg seeds ha^{-1} (approx. 500, 250 and 125 seeds m^{-2}, respectively) in DS, were examined. The recommended plant density in Northeast Thailand is 25 hills m^{-2} in TP and 50–100 kg seeds ha^{-1} in DS (Naklang, 1997). Each plot for each cultivar under each density and each planting method was 3 × 4 m in the lower field and 3 × 4.5 m in the upper field.

In Exp. 2, 14 *indica* cultivars were grown. When sown in mid-June, HY71, KKNLR84149-SRN-35-1-1-1-6 (KKNLR84149), Low Taek, Sakhon Nakhon, Siw Mae

Jan, and IR24 were early-maturing genotypes; IR57514-PMI-5-B-1-2 (IR57514), NUBN2, RD15, and UBN92110-NKI-B5-30-1 (UBN92110) were intermediate; and KDML105, Niaw Meaung Pai, RD6, and RD8 were late-maturing. Only IR24 was a semi-dwarf genotype for irrigated lowlands; the other 13 had been bred for the rainfed lowlands of Northeast Thailand. These 13 genotypes had been used in a farmer-participatory breeding program in Northeast Thailand in 2002 (Pantuwan and Jongdee, 2005). These were cultivars or breeding lines with promising characteristics and different times of maturity. The size of each plot was 3 × 4 m in the lower field; this was also the size of the plots for 12 of the genotypes other than IR24 and KDML105 in the upper field. For IR24 and KDML105 in the upper field the plot size was 3 × 4.5 m.

2.2. Cultural management

For each experiment, sowing dates were 12 June for TP and 19 June for DS. In TP, seedlings were transplanted on 18 July at a rate of three plants per hill in both the lower and upper fields. The planting density in TP was 16 hills m^{-2} (25 × 25 cm spacing) and the seeding rate in DS was 62.5 kg ha^{-1} in DS in Exp. 2. Leaf age of seedlings ranged from 5.9 to 7.5 (mature seedlings). One hundred and eighty-eight kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 16:16:8%) was applied to TP plots before transplanting and to DS plots on 17 July. A further 14.4 kg ha^{-1} of urea on 15 August and 12 September in all plots was applied. Weeds were removed by hand in all plots.

2.3. Measurements

Air temperature and rainfall were recorded at the weather station at Ubon Rice Research Center. Mean air temperature in June was 29.0 °C and it gradually decreased to 26.4 °C in November. Soil sample was taken from plough layer (0-15 cm depth) from each site to investigate total nitrogen and texture. In both the lower and upper fields, ground water level was measured from 25 July to the end of harvest at 6 h intervals by installing a PVC tube to a depth of 60 cm below the soil surface and using a water-level datalogger (DIK 610A, Daiki Rika Kogyo Co. Ltd., Tokyo, Japan). The percentage of each plot covered in standing water was observed visually and was scored (0% to 100%, in 10% increments) from 11 September to the end of the harvest at 3- or 4-day intervals. The soil volumetric water content in the upper field was measured to a depth of 12 cm using time domain reflectometry (HydroSense, Campbell Scientific Inc., Logan, Utah, USA) on 17 October (just before heading of KDML105).

In DS in both Exp. 1 and Exp. 2, the number of plants per 0.5 m^2 was measured on 19 July. The above-ground parts of rice were harvested from a part of each plot at heading (0.25 m^2) and maturity (0.25 m^2 of subsample and 0.75 m^2 of bulk sample) to measure shoot dry matter. Grain yield and yield components were determined with mature samples. The number of spikelets per panicle, percentage of ripened grains, and grain weight were measured from subsample. Dry matter was weighed after it was dried at 70 °C in a forced-air oven for 3 days.

2.4. Statistical analysis

An analysis of variance (ANOVA) was conducted using the method of Gomez and Gomez (1984). In all of the growing conditions in Exp. 1, phenotypic observation was modelled with a randomized block design to assess the effects of plant density, cultivar (only in TP), or their interaction (only in TP). The effect of field location and the interactions between location, plant density, and cultivar (only in TP) were assessed by a combined analysis of the 2 trials of the same planting method (International Rice Research Institute, 1999). For KDML105, the effect of cultivation method and the interaction between cultivation method and plant density were assessed by a combined analysis of the 4 trials.

In all the growing conditions in Exp. 2, phenotypic observation was modeled by a randomized block design to assess genotypic differences. The effect of field location, cultivation method, and the interaction between them and genotype were assessed by combined analysis. Correlation and multiple regression analysis of the data in each growing condition was conducted using Systat Version 11 for Windows (Systat Software Inc., San Jose, Calif., USA).

3. Results

3.1. Rainfall pattern, standing water and ground water level

Total rainfall from May to November was 1009 mm (Fig. 2.1). There was a period with less rainfall from mid July to early August. There was no rainfall since 15 October (before the heading of late maturing genotypes). Almost 100% of the lower field had standing water until early October, but the area covered in standing water started to decrease in mid October, and standing water completely disappeared in early November (Table 2.1). In the upper field, standing water was observed only for the first several days after rain until mid October; from then on, there was almost no visible standing water. In the lower field, the groundwater level was near the soil surface from the end of August to early October (Fig. 2.2). It decreased gradually from then on, and no groundwater was observed in early November. In the upper field, groundwater was observed only after heavy rain. In the upper field, the soil volumetric water content of the top 12 cm on 17 October (just before the heading of KDML105) was 7.0%, whereas it was 40% to 45% both in the lower and upper fields under flooded or saturated conditions.

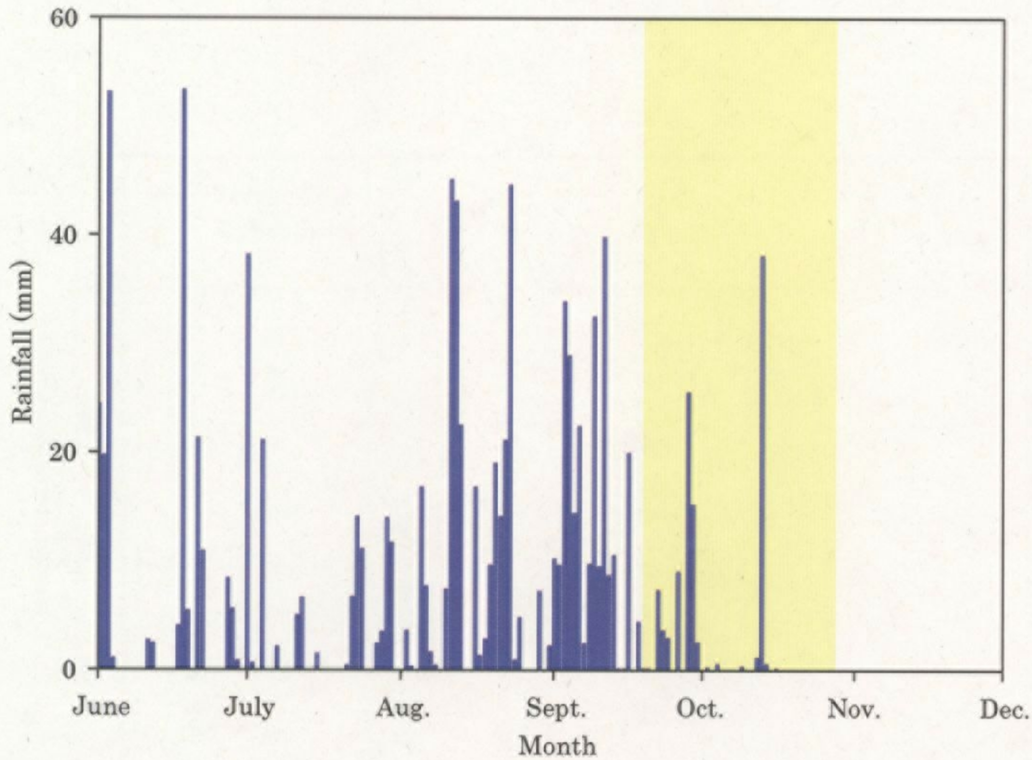

Fig. 2.1. Rainfall from June to December in 2003 (blue bar) and the heading period of 14 genotypes grown in the experiments (yellow bar).

Table 2.1.Percentage of area with standing water in the lower and upper fields from 11 September to 19 November in 2003.

	Percentage of area with standing water (%)	
	Lower field	Upper field
11 Sep - 17 Sep	96 ± 11	51 ± 36
18 Sep - 24 Sep	95 ± 13	26 ± 35
25 Sep - 1 Oct	100 ± 0	69 ± 24
2 Oct - 8 Oct	90 ± 18	30 ± 28
9 Oct - 15 Oct	51 ± 35	10 ± 15
16 Oct - 22 Oct	50 ± 40	4 ± 6
23 Oct - 29 Oct	28 ± 22	0 ± 0
30 Oct - 5 Nov	0 ± 0	0 ± 0
6 Nov - 12 Nov	0 ± 0	0 ± 0
13 Nov - 19 Nov	0 ± 0	0 ± 0

The results are indicated as mean ± standard deviation.

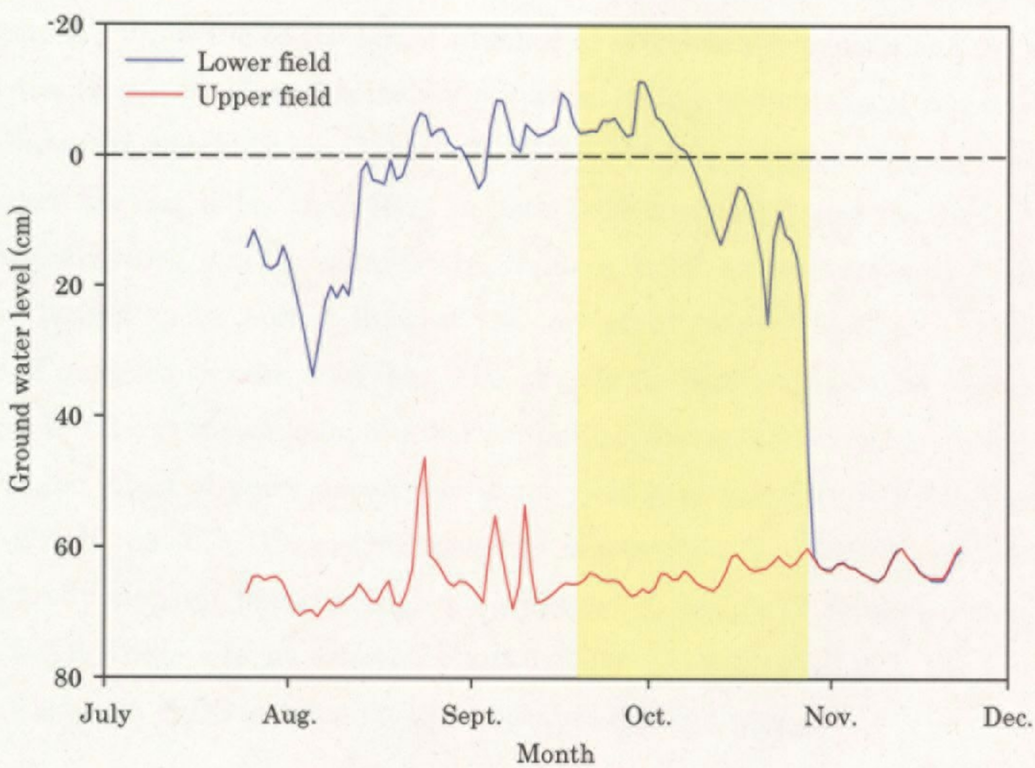

Fig. 2.2. Ground water level in the lower (blue line) and upper (red line) fields in 2003 and the heading period of 14 genotypes grown in the experiments (yellow bar).

3.2. Growth of rice in Exp. 1

Plant number of direct seeded KDML105 on 19 July in high, middle and low plant density was 563, 216 and 123 m^{-2} in the lower field and 401, 225 and 148 m^{-2} in the upper field, respectively.

IR24 headed about 30 days earlier than KDML105 (data not shown). On average, heading occurred 3 days later in U-TP than in L-TP.

The amount of shoot dry matter was lower in the upper field than in the lower field, although the difference was not significant in TP (Table 2.2). KDML105 produced more shoot dry matter than IR24 in both L-TP and U-TP, although the difference was not significant at maturity in U-TP (experimental error caused by uneven distribution of standing water (i.e. the standard deviation in the percentage of area with standing water) was large in the upper field). Shoot dry matter in L-TP and U-TP (KDML105) at high and medium plant densities was higher than at low density. There was no significant effect of plant density on the shoot dry matter of DS (KDML105), but the shoot dry matter in U-DS plots at low plant density tended to be lower than at higher plant densities. The shoot dry matter was significantly higher in L-DS than in L-TP.

Grain yield was higher in the lower field than in the upper field (although not significant in TP), owing to the larger number of spikelets per panicle and per area in TP and the larger number of spikelets per area, higher percentage of ripened grains and higher grain weight in DS (Table 2.3). KDML105 had a higher biomass production but a lower harvest index than IR24 in both L-TP and U-TP, and the grain yield of these two cultivars was similar. Grain yield in L-TP at medium and high plant densities tended to be higher than at the low plant density because of the larger number of panicles in both cultivars. The panicle number increased at higher plant density in U-TP, but the spikelet number per panicle decreased at higher plant density. Therefore, no effect of plant density on grain yield was detected in U-TP. The grain yield of KDML105 in L-DS was significantly higher than in L-TP because of higher biomass production and panicle number, but the grain yield in U-DS tended to be lower than in U-TP. There was no effect of plant density on grain yield in L-DS, but grain yield was lower in U-DS low-density plots because of fewer panicles.

Table 2.2. Shoot dry matter at heading and maturity in the lower and upper fields, across cultivation method, cultivar and plant density.

Cultivation method	Cultivar	Plant density	Shoot dry matter ($g\ m^{-2}$) Heading Lower field	Heading Upper field	Maturity Lower field	Maturity Upper field
Transplanting	KDML105	High	1013	1003	1069	882
		Middle	1023	894	1088	784
		Low	846	472	804	598
	IR24	High	448	455	630	673
		Middle	474	373	656	378
		Low	362	495	486	538
$LSD_{0.05}$						
Cultivar (C)			201	160	138	n.s.
Plant density (PD)			n.s.	*159*	169	n.s.
C × PD			n.s.	277	n.s.	n.s.
Location of field (LF)			n.s.		n.s.	
LF × C			n.s.		n.s.	
LF × PD			n.s.		n.s.	
LF × C × PD			n.s.		n.s.	
Direct seeding	KDML105	High	1276	921	1409	807
		Middle	1109	928	1251	801
		Low	1226	724	1382	585
$LSD_{0.05}$						
Plant density (PD)			n.s.	n.s.	n.s.	n.s.
Location of field (LF)			n.s.		265	
LF × PD			n.s.		n.s.	
$LSD_{0.05}$						
Cultivation method (CM)			n.s.	n.s.	182	n.s.
CM × PD			n.s.	n.s.	n.s.	n.s.

$LSD_{0.05}$ means least significant difference at 5 % level, values indicated in italic mean least significant difference at 10 % level and n.s. means there was no significant difference at 10 % level. LF, C, PD and CM mean location of field, cultivar, plant density and cultivation method, respectively.

Table 2.3. Grain yield, harvest index and yield components in the lower and upper fields, across cultivation method, cultivar and plant density.

Cultivation method	Cultivar	Plant density	Grain yield ($g\ m^{-2}$)		Harvest index (%)		Panicle number (m^{-2})		Spikelet number ($panicle^{-1}$)		Spikelet number (m^{-2})		Percentage of ripened grains (%)		Ripened grain number (m^{-2})		Grain weight (mg)	
			L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U
Transplanting	KDML105	High	316	222	26	22	168	170	90	68	15098	11887	76	66	11487	7802	27.4	25.3
		Middle	355	243	29	27	150	120	112	91	16824	11193	78	80	13202	8936	26.9	26.2
		Low	261	186	28	27	111	103	111	90	12346	9434	77	75	9526	7107	27.2	25.3
	IR24	High	297	305	41	40	210	236	88	70	18414	16961	69	74	12769	12475	23.4	24.6
		Middle	320	175	43	41	178	149	104	68	18564	10212	71	69	13243	7095	24.1	24.5
		Low	250	255	45	42	133	165	105	78	13849	13224	75	78	10373	10335	24.4	24.6
$LSD_{0.05}$																		
Cultivar (C)			n.s.	n.s.	3	5	7	32	n.s.	11	n.s.	n.s.	5	n.s.	n.s.	n.s.	1.1	n.s.
Plant density (PD)			*57*	n.s.	n.s.	n.s.	9	39	n.s.	*11*	3518	n.s.	n.s.	n.s.	*2248*	n.s.	n.s.	n.s.
C × PD			n.s.	n.s.	n.s.	n.s.	*10*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Location of field (LF)			n.s.		n.s.		n.s.		13		*3654*		n.s.		n.s.		n.s.	
LF × C			n.s.		n.s.		n.s.		n.s.		n.s.		n.s.		n.s.		1.3	
LF × PD			n.s.		n.s.		27		n.s.		n.s.		n.s.		n.s.		n.s.	
LF × C × PD			n.s.		n.s.		n.s.		n.s.		n.s.		n.s.		n.s.		n.s.	
Direct seeding	KDML105	High	385	179	24	19	363	275	51	40	18522	10680	83	74	15460	7923	25.0	22.6
		Middle	325	199	23	22	224	190	67	66	14990	12604	81	71	12112	8916	26.6	23.1
		Low	394	98	25	15	187	133	101	56	19064	7123	78	63	14907	4506	26.0	21.2
$LSD_{0.05}$																		
Plant density (PD)			n.s.	n.s.	n.s.	n.s.	76	*87*	27	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Location of field (LF)			90		n.s.		n.s.		n.s.		3498		8		3300		2.2	
LF × PD			n.s.		n.s.		n.s.		*22*		n.s.		n.s.		n.s.		n.s.	
$LSD_{0.05}$																		
Cultivation method (CM)			55	n.s.	3	n.s.	25	*67*	10	*26*	1465	n.s.	n.s.	n.s.	1107	n.s.	n.s.	2.4
CM × PD			n.s.	n.s.	n.s.	n.s.	45	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

L and U mean the lower and upper fields, respectively.

$LSD_{0.05}$ means least significant difference at 5 % level, values indicated in italic mean least significant difference at 10 % level and n.s. means there was no signidicant difference at 10 % level.

LF, C, PD and CM mean location of field, cultivar, plant density and cultivation method, respectively.

3.3. Growth of rice in Exp. 2

Plant number on 19 July in DS ranged from 151 (Siw Mae Jan) to 275 (RD6) m^{-2} in the lower field and from 157 (IR57514) to 243 (RD15) m^{-2} in the upper field.

Wide variation was observed in heading date, ranging from 19 September to 28 October (Table 2.4). For TP and DS, heading date in the upper field was an average of 3 and 2 days later, respectively, than in the lower field. In L-TP and U-TP, heading of Siw Mae Jan was the earliest. For DS, the heading dates of IR24 and Low Taek were the earliest in the lower and upper fields, respectively. The heading date of RD8 was the latest, regardless of the field or cultivation method. The greatest delay in heading (comparison of upper field with lower field) was observed in HY71, Sakhon Nakhon, and KDML105 in TP. In DS, the delay in heading was greatest in KKNLR84149.

The level of shoot dry matter production among the 14 genotypes ranged widely, and there were significant genotypic differences in the combined analysis of all the growing conditions (Table 2.4). Under all growing conditions, KKNLR84149 had a relatively high level of shoot dry matter at maturity, and the shoot dry matter of IR24 was low. Significant interaction between cultivation method and genotype was observed for shoot dry matter at maturity in the lower field. In L-TP, late-maturing genotypes had high shoot dry matter. In L-DS, some of the early- and intermediate-maturing genotypes such as HY71 and IR57514 had shoot dry matter more than twice those in L-TP and comparable to those of the late-maturing genotypes. HY71 also achieved a high shoot dry matter level in U-DS. The shoot dry matter at maturity was significantly higher in DS than in TP in the lower field, but it tended to be higher in TP than DS in the upper field.

No significant differences in grain yield, harvest index, or yield components were observed between L-TP and U-TP, but the differences in grain yield, panicle number per area, spikelet number per unit area, and ripened grain number per area were significant between L-DS and U-DS (Table 2.5). Grain yield, panicle number, and spikelet and ripened grain number per unit area were significantly higher in L-DS than in L-TP, but the differences in these parameters between U-TP and U-DS were small.

Significant genotypic differences in grain yield, harvest index, and all the yield components were observed in combined analysis of all the growing conditions. KKNLR84149 had the highest grain yield in both L-TP and U-TP, owing to its high shoot dry matter production and large per-area panicle and spikelet numbers. In L-DS, the grain yields of HY71 and IR57514, which had high shoot dry matter and large spikelet number per area, were the highest and exceeded 400 g m^{-2}. Large spikelet number panicle resulted in large spikelet number per area in HY71, but in IR57514, large spikelet number per panicle was obtained from large panicle number. These genotypes did not perform as well in L-TP, leading to significant interactions between cultivation method and genotype for grain yield. HY71 also achieved a high grain yield in U-DS through its high shoot dry matter and large spikelet number per panicle. KKNLR84149 had the highest grain yield also in U-DS through its high shoot dry matter and large panicle number. IR24 had the highest harvest index in all the growing conditions, but grain yield was not high owing to poor shoot dry matter production.

In L-TP and U-TP, there was significant correlation between panicle number and grain yield (Table 2.6). Genotypes with higher grain yield (black symbol) had larger panicle number also in the scatter plot (Fig. 2.3a,b). Neither in L-DS nor U-DS, the correlation was significant at $P = 0.05$. A significant correlation between spikelet number per panicle and grain yield was observed only in L-DS. In L-DS, genotypes with higher grain yield had larger spikelet number per panicle also in the scatter plot (Fig. 2.3c). In all of the growing conditions, spikelet number per area, percentage of ripened grains and number of ripened grains per unit area were significantly correlated with grain yield. There was no significant correlation between grain weight and grain yield.

In the lower field, shoot dry matter increased with later heading date or longer days from seeding/transplanting to maturity (data not shown), but heading date or days to maturity did not affect grain yield (Fig. 2.4). In contrast, grain yield decreased with later heading in the upper field. In U-TP, the grain yield of 2 early genotypes, Sakhon Nakhon and Siw Mae Jan, was also low. Some early-maturing genotypes (KKNLR84149 under all growing conditions and HY71 in DS) had high grain yields. In L-DS, grain yield increased with increasing shoot dry matter at maturity (Fig. 2.5). Also, in U-TP and U-DS, grain yield increased higher with increasing shoot dry matter in 6 early and 4 intermediate genotypes. In U-TP, 2 early genotypes (Sakhon Nakhon and Siw Mae Jan) and 1 late genotype (RD6) had low percentages of ripened grains (Fig. 2.6). In U-DS, late genotypes generally had low ripened grain percentages. The percentage of ripened grains in RD8 was particularly low. Two early genotypes (Low Taek and Siw Mae Jan) also had relatively low percentages in U-TP. In L-TP and L-DS, genotypes with large numbers of ripened grains had low grain weights (data not shown).

Table 2.4. Heading date and shoot dry matter at heading and maturity of 14 genotypes in transplanting and direct seeding in the lower and upper fields.

Genotype	Heading date		Shoot dry matter (g m^{-2})			
			Heading		Maturity	
Trasnplanting	Lower	Upper	Lower	Upper	Lower	Upper
HY71	30 Sep	6 Oct	544	339	591	608
KKNLR84149	29 Sep	28 Sep	661	681	721	903
Low Taek	25 Sep	28 Sep	488	505	582	652
Sakhon Nakhon	22 Sep	28 Sep	445	432	568	402
Siw Mae Jan	20 Sep	20 Sep	387	377	461	460
IR24	24 Sep	26 Sep	362	495	486	538
IR57514	7 Oct	11 Oct	624	605	651	610
NUBN2	13 Oct	16 Oct	658	681	610	848
RD15	12 Oct	14 Oct	725	564	747	745
UBN92110	8 Oct	9 Oct	513	539	745	864
KDML105	20 Oct	26 Oct	846	472	804	598
Niaw Meaung Pai	21 Oct	22 Oct	971	872	836	743
RD6	24 Oct	25 Oct	912	1061	745	742
RD8	27 Oct	26 Oct	748	892	721	848
Mean	7 Oct	10 Oct	635	608	662	683
Probability						
Genotype (G)	0.000	0.000	0.000	0.000	0.031	0.165
Location of field (LF)	0.025		0.354		0.501	
LF × G	0.340		0.097		0.726	
Direct seeding	Lower	Upper	Lower	Upper	Lower	Upper
HY71	2 Oct	30 Sep	1080	864	1342	897
KKNLR84149	20 Sep	28 Sep	837	590	1150	963
Low Taek	20 Sep	21 Sep	579	519	762	685
Sakhon Nakhon	21 Sep	26 Sep	805	572	961	684
Siw Mae Jan	21 Sep	22 Sep	455	693	563	596
IR24	19 Sep	24 Sep	449	235	680	470
IR57514	1 Oct	7 Oct	674	979	1223	720
NUBN2	15 Oct	19 Oct	890	1037	910	772
RD15	13 Oct	12 Oct	1018	575	1137	670
UBN92110	8 Oct	9 Oct	641	549	1187	658
KDML105	25 Oct	25 Oct	1109	928	1251	801
Niaw Meaung Pai	26 Oct	20 Oct	1053	816	1404	755
RD6	26 Oct	27 Oct	1000	1098	1101	819
RD8	27 Oct	28 Oct	1225	1001	1228	931
Mean	6 Oct	8 Oct	844	747	1064	744
Probability						
Genotype (G)	0.000	0.000	0.019	0.023	0.000	0.801
Location of field (LF)	0.037		0.073		0.005	
LF × G	0.005		0.526		0.438	
Probability	Lower	Upper	Lower	Upper	Lower	Upper
Cultivation method (CM)	0.329	0.168	0.002	0.021	0.000	0.309
CM × G	0.000	0.269	0.614	0.105	0.028	0.941
Genotype (G)*	0.000		0.000		0.000	
LF × CM	0.502		0.175		0.001	
LF × CM × G	0.025		0.661		0.857	

LF, G and CM mean location of field, genotype and cultivation method, respectively.
*Combined analysis of L-TP, U-TP, L-DS and L-DS.

Table 2.5. Grain yield, harvest index and yield components of 14 genotypes in transplanting and direct seeding in the lower and upper fields.

Genotype	Grain yield ($g\ m^{-2}$)		Harvest index (%)		Panicle number (m^{-2})		Spikelet number ($panicle^{-1}$)		Spikelet number (m^{-2})		Percentage of ripened grains (%)		Ripened grain number (m^{-2})		Grain weight (mg)	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Trasnplanting																
HY71	205	241	32	34	107	104	88	100	9443	10361	80	82	7567	8547	27.1	26.5
KKNLR84149	279	291	34	28	148	167	94	93	13912	15600	79	72	11014	11293	25.4	25.6
Low Taek	245	295	37	39	125	116	110	120	13751	13875	70	76	9627	10501	25.4	27.7
Sakhon Nakhon	206	140	31	30	87	96	109	81	9537	7771	72	58	6829	4541	30.1	30.2
Siw Mae Jan	199	135	38	26	96	95	100	88	9591	8344	72	58	6865	4869	29.0	28.0
IR24	250	255	46	42	133	165	103	78	13698	12976	75	78	10261	10140	24.4	24.6
IR57514	241	221	33	31	142	127	77	73	10961	9279	80	78	8786	7210	27.5	28.3
NUBN2	218	278	31	28	116	129	85	87	9918	11253	73	80	7287	9032	29.9	30.4
RD15	252	227	30	27	119	107	100	103	11900	10940	75	74	8947	8084	28.2	27.3
UBN92110	216	280	26	28	131	127	93	103	12112	13108	74	80	8980	10442	24.1	25.1
KDML105	261	186	29	28	111	103	112	90	12417	9313	77	75	9581	7015	27.2	25.3
Niaw Meaung Pai	250	186	26	22	103	102	85	76	8718	7743	82	75	7130	5778	35.1	31.2
RD6	236	169	28	19	109	86	106	151	11499	12974	83	61	9522	7907	24.8	24.7
RD8	172	196	21	20	97	103	101	86	9793	8822	60	75	5902	6608	29.1	29.8
Mean	231	221	31	29	116	116	97	95	11232	10883	75	73	8450	7998	27.7	27.5
Probability																
Genotype (G)	0.403	0.510	0.000	0.001	0.000	0.003	0.098	0.152	0.061	0.157	0.303	0.186	0.035	0.225	0.000	0.000
Location of field (LF)	0.323		0.056		0.956		0.516		0.283		0.243		0.071		0.650	
LF × G	0.759		0.390		0.547		0.354		0.985		0.230		0.870		0.136	

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Table 2.5. Continued.

Genotype	Grain yield ($g\ m^{-2}$)		Harvest index (%)		Panicle number (m^{-2})		Spikelet number ($panicle^{-1}$)		Spikelet number (m^{-2})		Percentage of ripened grains (%)		Ripened grain number (m^{-2})		Grain weight (mg)	
Direct seeding	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
HY71	426	320	28	32	259	212	74	75	19266	15889	77	80	14921	12693	29.2	26.4
KKNLR84149	385	332	29	30	315	300	59	56	18554	16891	82	77	15182	12927	25.3	25.4
Low Taek	249	234	29	30	267	256	56	50	14941	12833	62	66	9195	8507	27.2	27.5
Sakhon Nakhon	305	241	28	30	243	193	58	44	14051	8513	72	79	10112	6766	30.5	34.1
Siw Mae Jan	202	211	31	26	185	153	57	62	10563	9534	67	69	7115	6551	29.2	29.5
IR24	321	188	41	36	301	328	51	33	15513	10693	83	74	12876	7913	24.8	24.3
IR57514	426	240	31	26	315	248	56	43	17770	10708	83	79	14801	8499	28.9	25.4
NUBN2	313	245	30	27	250	240	54	45	13549	10888	82	77	11138	8343	28.2	27.2
RD15	318	180	24	23	243	239	60	41	14558	9733	81	71	11770	6942	26.8	25.6
UBN92110	302	183	22	24	325	271	54	42	17456	11419	75	72	13051	8194	23.6	22.6
KDML105	325	199	23	21	224	190	67	66	14990	12604	81	71	12112	8916	26.6	23.1
Niaw Meaung Pai	366	189	23	16	212	134	65	46	13800	6191	83	68	11422	4187	33.0	29.1
RD6	231	157	18	17	241	186	50	57	12072	10689	76	65	9172	6913	24.8	23.0
RD8	280	141	20	12	217	162	60	63	13023	10271	73	46	9552	4735	29.0	25.7
Mean	318	219	27	25	257	222	59	52	15008	11204	77	71	11601	8006	27.7	26.4
Probability																
Genotype (G)	0.003	0.882	0.000	0.042	0.000	0.012	0.539	0.470	0.015	0.607	0.001	0.273	0.002	0.700	0.000	0.000
Location of field (LF)	0.014		0.230		0.007		0.076		0.007		0.240		0.011		0.065	
LF × G	0.932		0.858		0.841		0.933		0.977		0.343		0.969		0.057	
Probability	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Cultivation method (CM)	0.002	0.904	0.006	0.112	0.000	0.000	0.000	0.000	0.004	0.540	0.289	0.653	0.001	0.843	0.974	0.093
CM × G	0.036	0.953	0.782	0.976	0.004	0.414	0.101	0.369	0.134	0.983	0.516	0.287	0.061	0.967	0.134	0.107
Genotype (G)*	0.017		0.000		0.000		0.028		0.000		0.000		0.000		0.000	
LF × CM	0.007		0.714		0.002		0.381		0.003		0.423		0.004		0.118	
LF × CM × G	0.915		0.957		0.977		0.820		0.992		0.103		0.936		0.376	

LF, G and CM mean location of field, genotype and cultivation method, respectively.

*Combined analysys of L-TP, U-TP, L-DS and U-DS.

Table 2.6. Correlation coefficients between yield components and grain yield in transplanting and direct seeding in the lower and upper fields in Exp. 2.

	Panicle number	Spikelet number per panicle	Spikelet number per unit area	Percentage of ripened grains	Ripened grain number per unit area	grain weight
L-TP	0.648 *	0.014	0.656 *	0.625 *	0.830 **	–0.203
U-TP	0.720 **	0.085	0.763 **	0.747 **	0.930 **	–0.275
L-DS	0.473	0.540 *	0.814 **	0.676 **	0.910 **	0.209
U-DS	0.338	0.256	0.692 **	0.685 **	0.845 **	0.244

n = 14.

** and * mean significant correlation at 1 and 5 % level, respectively.

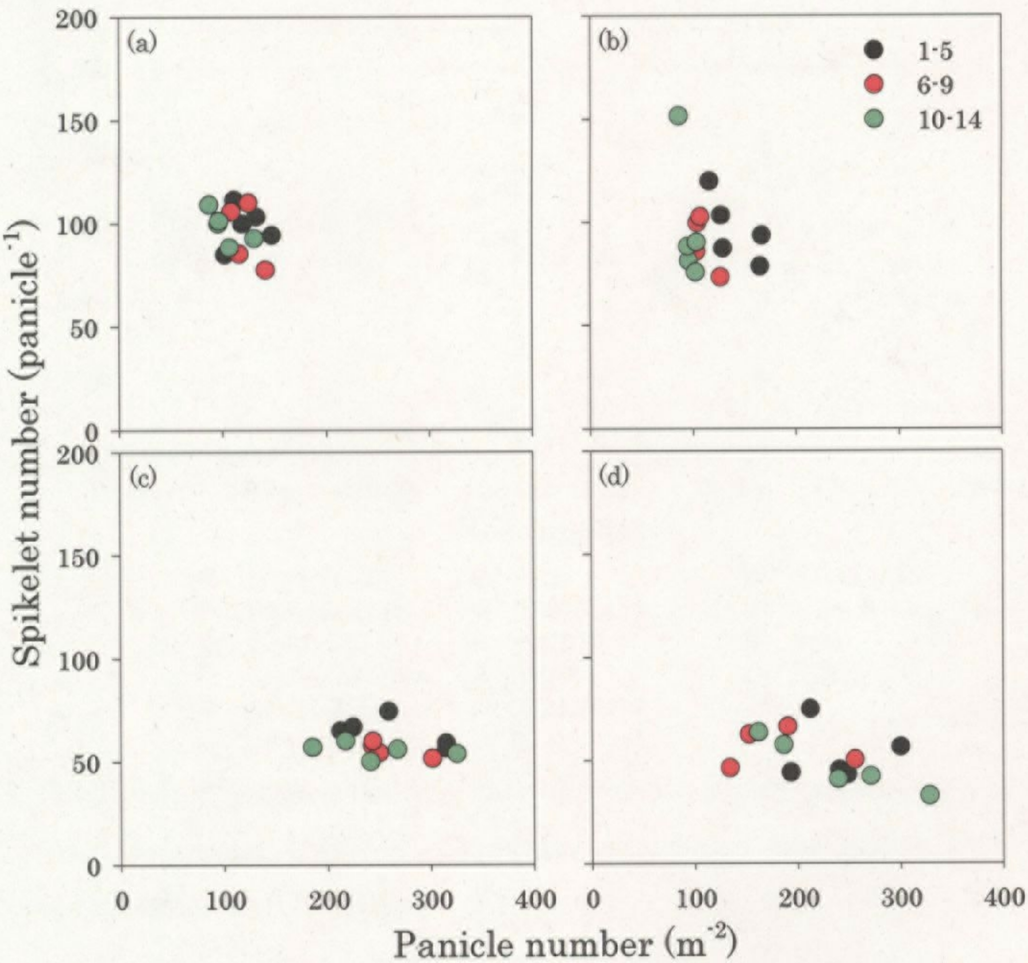

Fig. 2.3. Relationship between panicle number and spikelet number per panicle of 14 genotypes in L-TP (a), U-TP (b), L-DS (c) and U-DS (d). Black, red and green symbols indicate the genotypes with the highest to 5th highest, 6th highest to 9th highest and 10th to 14th highest grain yields in each growing condition, respectively.

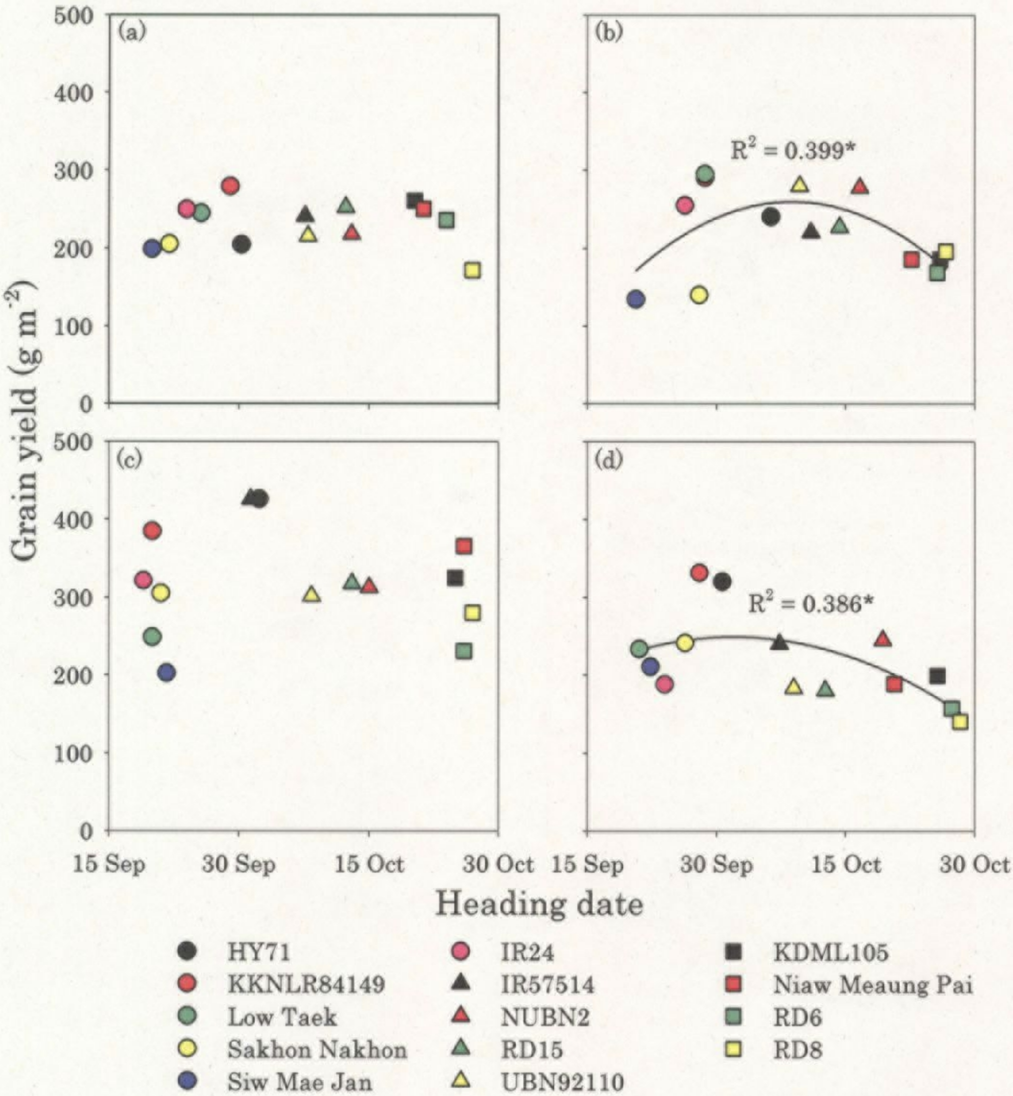

Fig. 2.4. Relationship between heading date and grain yield of 14 genotypes in L-TP (a), U-TP (b), L-DS (c) and U-DS (d). Quadratic regression was drawn and * means significant regression at 5 % level.

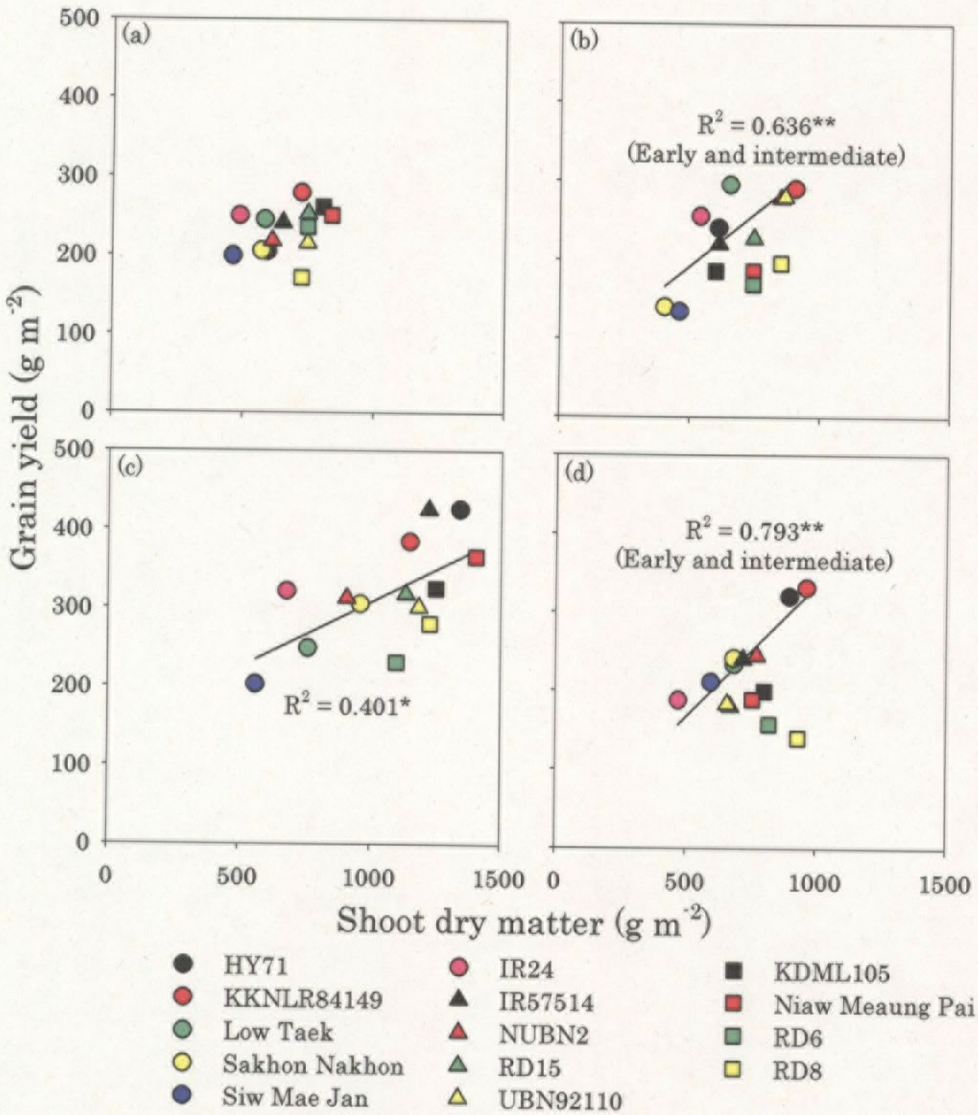

Fig. 2.5. Relationship between shoot dry matter at maturity and grain yield of 14 genotypes in L-TP (a), U-TP (b), L-DS (c) and U-DS (d). Linear regression was drawn and ** and * mean significant regression at 1 and 5 % level, respectively.

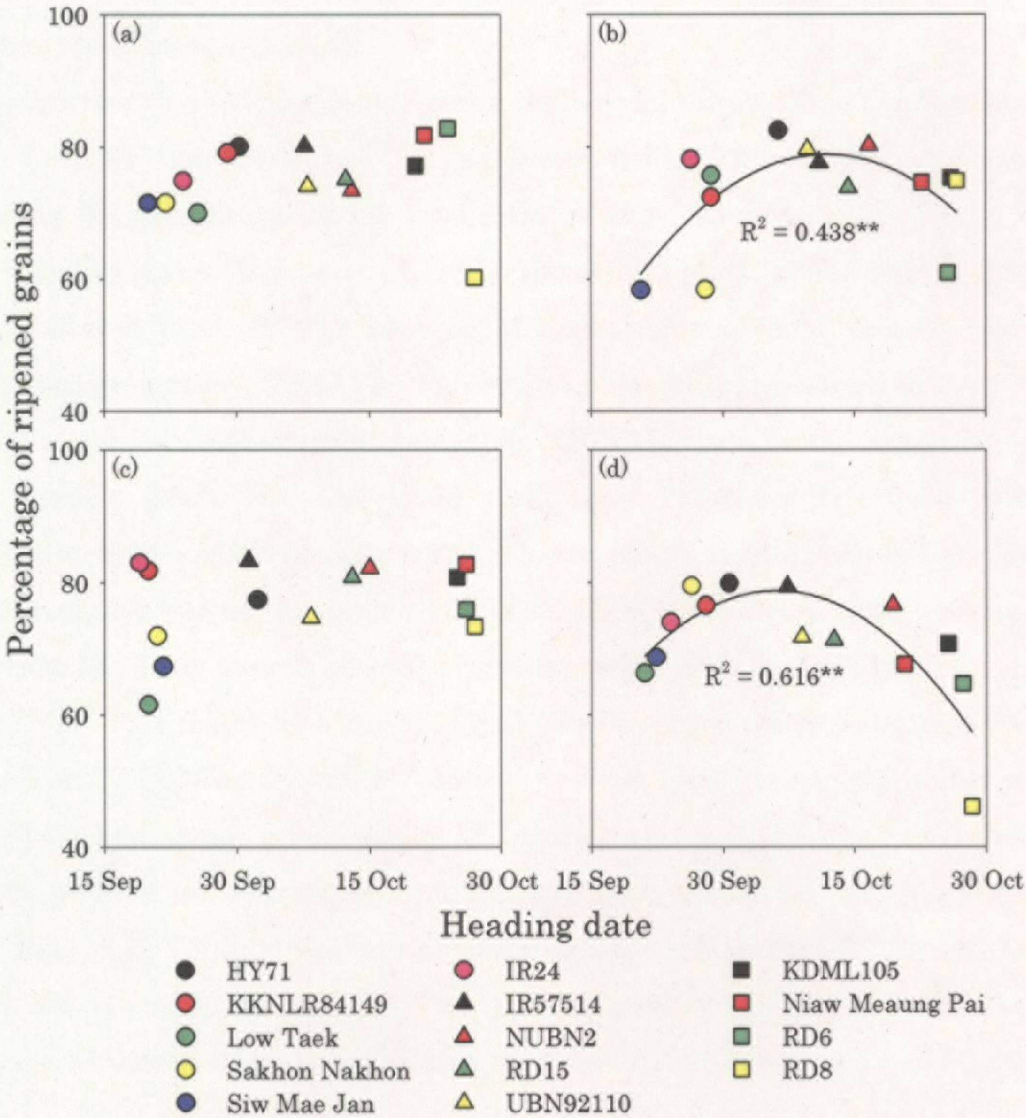

Fig. 2.6. Relationship between heading date and percentage of ripened grains of 14 genotypes in L-TP (a), U-TP (b), L-DS (c) and U-DS (d). Quadratic curve regression was drawn and ** means significant regression at 1 % level.

4. Discussion

Because of the toposequential differences between the two fields, field water status differed greatly. In this chapter, TP and DS were compared under two contrasting rainfed lowland conditions in terms of water availability.

4.1. Effect of cultivation method

It was proved that DS rice could have a higher yield than TP rice under favourable rainfed lowland conditions (i.e. in the lower field). This result was surprising, considering the perceptions of the local farmers and researchers that TP yields were higher than DS yields (Tomita et al., 2003; Kamoshita et al., 2006). Higher grain yield in DS compared with TP was because of higher biomass and greater numbers of panicles. Naklang et al. (1996) also reported that large panicle number in DS had the potential to achieve higher grain yield than TP. These results indicated that DS had higher biomass production and grain yield than TP under favourable conditions because of its higher plant density, which allowed plants to utilize more light (although light interception was not measured in this study) and produce greater amounts of dry matter from the early growth stage. In contrast, grain yield in U-DS tended to be lower than in U-TP. This might be associated with the lower soil water content in the top 12 cm of soil on 17 October (5.3 vs. 8.7% v v^{-1}) and the more severe leaf rolling in U-DS. Rice in U-DS had higher plant density and more biomass at heading and it thus might have had greater transpirational demand and have exhausted the soil water more quickly than in U-TP. In U-DS, panicle number was smaller than L-DS, although that in U-TP did not differ from L-TP. This smaller panicle number in U-DS (i.e. lower percentage of fertile stems) should also owing to the water deficit and higher plant density.

4.2. Effect of plant density

KDML105 in TP yielded less at low plant density than at higher plant densities under both favourable and unfavourable water conditions because of the small panicle number. The reason of small panicle number in low plant density should be the combination of the low fertility of soils in Northeast Thailand (e.g. the total nitrogen in the soil in the experimental sites in this study was 0.033% in the lower field and 0.041% in the upper field), a low level of chemical fertilizer application, and the cultivar's low tillering ability. This revealed that low plant densities should be avoided and a density of 25 hills m^{-2} should be planted in general to have enough panicle number in rainfed lowland rice-growing regions with low soil fertility and low rates of fertilizer application. Under upland conditions in Nigeria, lowland rice cultivar ANDY11 achieved higher grain yield with closer spacing when there was no drought stress, but wider spacing performed better when drought occurred (De Datta, 1984). In the upper field with late season drought in this study, however, any advantage of lower plant density was not detected (no significant interaction between the location of field and plant density); the component of evaporation from the surface of paddy field may be larger than in the case of upland rice field, and lower plant density may not work as well as drought prone upland field.

The effect of plant density on grain yield in DS was different, depending on the water availability. In this study, plant density did not affect grain yield in L-DS under favourable water conditions with complete weeding. The favourable water conditions in the lower field allowed the vigorous growth of rice plants in the plots with the low seeding rate (31.3 kg ha^{-1}), with similar shoot dry matter production by heading to higher seeding rates and with greater grain number per panicle to compensate for the smaller number of panicles compared with higher seeding rates. This result indicated the optimum seeding rate under favourable water conditions should be around 31.3 kg seeds ha^{-1}. Naklang (1997) and Du and Tuong (2002) also reported the small effect of seeding rate on grain yield. These results were similar to that of wet direct seeding of irrigated rice under weed control, in which the seeding rate did not affect grain yield between 40 and 160 kg seeds ha^{-1} (Phuong et al., 2005). In contrast, the grain yield in low plant density in U-DS was almost half of that in high and middle plant densities (although not significant) owing to the smaller number of panicles. Low plant density had smaller panicle number than middle density, and there was little difference in spikelet number per panicle between these 2 densities in U-DS. This result indicated the optimum seeding rate under late season drought conditions should be around 62.5 kg seeds ha^{-1}. These results suggested that low seeding rate is sufficient under favourable water conditions (like L-DS), but middle seeding rate would be required for higher grain yield under a late-season water deficit, like U-DS.

4.3. Genotypic requirements for different toposequence position

In Northeast Thailand, environmental conditions, especially water availability, can be quite different even between very close sites owing to toposequential differences (Homma et al., 2004), and the adaptability of genotypes to each toposequence position should also differ. In this study, late season drought occurred in the upper field resulted in significantly lower grain yield in U-DS than in L-DS through lower biomass production and smaller panicle number and spikelet number per area in the former. Although the location of field (toposequence) by genotype interaction was not significant (partly owing to the small number of field locations and genotypes), in the upper field, the grain yield of late maturing genotypes was lower. The advantages of early or intermediate genotypes have been observed under severe late-season drought also in other studies (Fukai, 1999; Fukai and Cooper, 1995; Pantuwan et al., 2002).

4.4. Genotypic requirements for DS and TP

Coefficient of variation in panicle number (15 to 25%), spikelet number per panicle (11 to 23%) or spikelet number per area (16 to 25%) was larger than that in percentage of ripened grains (8 to 12%) or grain weight (8 to 12%), suggesting that larger genotypic variation existed in panicle number, spikelet number per panicle and spikelet number per area.

In TP, grain yield increased with increasing number of panicles. Because some of the early or intermediate genotypes, such as KKNLR84149, had large numbers of panicles and the late genotypes generally had small numbers of panicles, heading date and grain yield in L-TP were poorly correlated, despite the larger shoot dry weight in late-maturing genotypes.

Sipaseuth et al. (2002), Fukai et al. (2004) and Mitchell et al. (2004), using cultivars or breeding lines bred in Thailand, Laos, or Cambodia, reported a significant correlation between grain yields in TP and DS over a wide range of flowering times in irrigated or rainfed lowlands, and suggested that genotypes that were high-yielding under TP would generally also perform well under DS (Sipaseuth et al., 2002; Fukai et al., 2004). In contrast, correlation between grain yields in TP and DS was significant in neither the lower nor the upper field (data not shown), and the genotype by cultivation method interaction was significant in the lower field; the differences will be discussed later. These results suggest that TP and DS have different cultivar requirements. The effect of panicle number on grain yield was smaller in DS than in TP, because all of the genotypes in DS had greater numbers of panicles than TP. High tillering capacity is not required for DS rice (Fukai, 2002) because of its high planting density. In DS under favorable water conditions (e.g. L-DS), spikelet number per panicle should be more important than panicle number, judging from the higher correlation coefficient between the former and grain yield. In DS, spikelet number per panicle becomes smaller than in TP owing to a trade-off relationship with increasing panicle number. Hence, genotypes that can maintain large spikelet numbers per panicle under DS conditions may be required. This different cultivar requirement (larger panicle number in TP vs. larger spikelet number per panicle in DS) resulted in a significant cultivation method by genotype interaction for grain yield in the lower field.

In both L-TP and L-DS, late maturing genotypes had higher biomass at maturity, but in L-DS some early or intermediate genotypes (e.g. HY71 and IR57514) also had high biomass. This is presumably because higher plant density and longer growth duration in the paddy field in DS compared with TP benefited early or intermediate genotypes. Genotypes with shorter growth duration have lower biomass production and lower potential grain yield in TP (Romyen et al., 1998; Pantuwan et al., 2002). However, the disadvantages of earlier maturing genotypes as well as of genotypes with small panicle number could be reduced by DS under favourable growing conditions. The absence of genotype by cultivation method interaction in the studies of Sipaseuth et al. (2002), Fukai et al. (2004) and Mitchell et al. (2004) might have derived from their environmental and managemental conditions that resulted lower or at best similar yield levels of DS compared with TP, unlike this study. Although lodging did not cause yield reduction in this study (data not shown), lodging could be a problem in DS (Fukai, 2002; Fukai et al., 2004). Intermediate plant height, large stem diameter, thick stem walls, and high lignin content are lodging tolerance characteristics (Mackill et al., 1996). In addition, competitiveness against weeds is an important characteristic in DS (Bastiaans et al., 1997; Fukai, 2002; Caton et al., 2003). Greater plant height at the seedling stage and faster leaf area expansion to cover the ground quickly are important for competitiveness (Bastiaans et al., 1997; Fukai, 2002; Caton et al., 2003). These aspects may well be important cultivar requirements for DS.

5. Conclusions

Both in Exp. 1 and 2, DS rice had higher yields than TP rice because of its larger panicle number and higher biomass production under favourable conditions with complete weed control. In Exp. 1, low seeding rate (31.3 kg ha^{-1}) gave grain yield as good as higher seeding rates under the favourable conditions. In contrast, grain yield in DS tended to be lower than that in TP in the upper field, and yield was increased by changing seeding rate from low to middle density. For TP under rainfed lowland conditions with infertile soils and a low rate of application of chemical fertilizers, this suggested that low plant density (16 hills m^{-2}) could not produce enough panicles to achieve high grain yield in KDML105, irrespective of the availability of water. In Exp. 2, significant genotypic differences in grain yield were observed in the combined analysis of all growing conditions. In the lower field there was a significant cultivation method by genotype interaction. In TP, grain yield was increased in genotypes with larger panicle numbers, but in DS with larger panicle numbers compared with TP, not panicle number but spikelet number per panicle affected grain yield. Because in DS there was higher plant population density and longer period of growth in the paddy field, some early to intermediate maturing genotypes gave higher yields in DS compared with TP. The interaction between location of field and genotype was not significant, but in the upper field, late maturing genotypes yielded less and early or intermediate maturing genotypes with higher biomass production yielded better. These results thus showed the importance of phenology, biomass production, panicle number, and spikelet number per panicle in achieving high yields for different toposequential locations and for different cultivation methods.

Summary: The effect of plant density on grain yield (Exp. 1) and the genotypic differences in grain yield (Exp. 2) of rainfed lowland rice grown with TP and DS was evaluated. These experiments were conducted with complete weeding in toposequential lower and upper fields that had different levels of water availability. In Exp. 1, one cultivar (KDML105) was grown in both TP and DS sections, while another cultivar (IR24) was grown only in TP sections. Three levels of plant density in TP (16, 25, and 44 hills m^{-2}) and DS (31.3, 62.5, and 125 kg seeds ha^{-1}, approx. 125, 250 and 500 seeds m^{-2}) were tested. In Exp. 2, 14 genotypes were grown. Thirteen of the genotypes—5 early-maturing, 4 intermediate, and 4 late—had been bred for rainfed lowlands in Northeast and North Thailand. IR24, a semi-dwarf, high-yielding, and early-maturing

genotype bred for irrigated lowlands, was included for comparison. Noticeable water limitation was not observed in the lower field, but standing water became scarce in the upper field after mid October (before the heading of late maturing genotypes). In the upper field, grain yield tended to be lower in DS than in TP, as is often reported. In the lower field, however, grain yield was higher in DS than in TP because of higher biomass production and a larger number of panicles. In Exp. 1, DS plots in the lower field with the lowest sowing rate showed vigorous vegetative growth and equally high grain yield as plots with higher sowing rates. In contrast, DS in the upper field produced lower yields at low sowing rates. In both the lower and upper fields, grain yield of TP tended to be lower at low plant densities (e.g. 16 hills m^{-2}) than at higher plant densities, irrespective of water availability. In Exp. 2, genotypic difference in grain yield was significant in a combined analysis of all 4 growing conditions, and both high sink size (spikelet number per area) and high ripened grain percentage were associated with high yield. IR24 did not out-yield the rainfed-lowland genotypes, and its yield was particularly low in DS, owing to poor shoot dry matter production and low spikelet number per panicle. In the lower field, the interaction between cultivation method and genotype was also significant. In the lower field, late maturity was more strongly related to high shoot dry weight at maturity in TP than in DS; some of the early- to intermediate-maturing genotypes in DS produced shoot dry matter at maturity that were comparable to those of the late-maturing genotypes. High shoot dry matter production and large spikelet number per panicle were associated with high grain yield in DS in the lower field, whereas in TP genotypes with large numbers of panicles were required for high grain yield. Although the field location by genotype interaction was not significant, regression analysis showed that late-maturing genotypes yielded less than earlier maturing genotypes, owing to the smaller ripened grain percentage resulting from late-season drought, in the upper field but not in the lower field.