Chapter 3. Cultivation method for higher grain yield under favourable water conditions

1. Introduction

In Northeast Thailand, the risk of drought and high cost of chemical fertilizer prevent farmers from intensive use of fertilizer. Fifty kg of chemical fertilizer ($N:P_2O_5:K_2O$ = 16:16:8%) and urea (N = 46%) cost 525 and 600 baht (1 baht is approx. 3.5 yen), respectively, in Khuang Nai District, Ubon Ratchathani, in August, 2006. The average amount of nitrogen application is only 25-41 kg ha^{-1} in southern part of Northeast Thailand (Lefroy and Konboon, 1998) or Khon Kaen province (Pandey et al., 2002). Although drought is recognized as a main production constraint, fields with favourable water conditions also exist in toposequentially lower positions in small watersheds (Oberthür and Kam, 2000; Homma et al., 2004; Haefele et al., 2006). Fertilizer can increase grain yield under favourable water conditions (Haefele et al., 2006).

Higher plant density in direct seeding results in higher grain yield than transplanting through higher biomass production and panicle number under favorable water conditions (Chapter 2; Naklang et al, 1996). In direct seeding under favourable water conditions, however, rice is often subjected to nitrogen deficit in later growth stage caused by too vigorous vegetative growth derived from its higher plant density (Dingkuhn et al., 1992a,b). If combined with the appropriate seeding rate and fertilizer management which can supply enough nitrogen in later growth period, direct seeding may be able to achieve high grain yield. In this chapter, it was hypothesized that the combination of lower seeding rate and more fertilizer application should supply enough nitrogen in later growth period and result in higher grain yield. The objective of this chapter was to evaluate the effectiveness of this cultivation method and propose the management to achieve higher grain yield in direct seeding in rainfed lowlands with favourable water conditions.

2. Materials and Methods

2.1. Experimental design and materials

Experiments were conducted from 2004 to 2006 at Ubon Rice Research Center, Ubon Ratchathani, Thailand (15°20′N, 104°41′E, 110 m elevation). According to the classification by Department of Agriculture of Thailand (1993), the soil type of the field was silty loam (sand:silt:clay = 2:86:12 %), and total nitrogen (calculated from the concentration of organic matter; 5% of the organic matter), available phosphorus (measured with the Bray P2 method), and exchangeable potassium (measured with the ammonium acetate method at pH 7.0) were 0.033%, 77.08 ppm, and 6.33 ppm, respectively. In every year, split-split design with 3 replicates was used. Three genotypes, KDML105, IR57514-PMI-5-B-1-2 (hereafter referred to as IR57514) and HY71 were used. IR57514 is an intermediate maturing genotype with intermediate photoperiod sensitivity. HY71 is an early maturing genotype with strong photoperiod sensitivity. These 2 genotypes were selected because they showed higher grain yield in direct seeding in the lower field in Chapter 2. All sub-subplots were bunded.

In 2004, topdressing (with topdressing, +TD and without topdressing, –TD) as main-plot, 2 genotypes, KDML105 and IR57514 as subplot and 3 seeding rates (high, middle and low seeding rates were 500, 250 and 125 seeds m^{-2}, respectively) as sub-subplot were examined. Size of each sub-subplot was 4 × 4 m.

In 2005 and 2006, 2 cultivation methods, CM1 (the combination of higher seeding rate and lower fertilizer application) and CM2 (the combination of lower seeding rate and higher fertilizer application) as main-plot, 2 seeding times, May and June as subplot and 3 genotypes, KDML105, IR57514 and HY71 as sub-subplotwere examined. In CM1, 500 seeds m^{-2} were sown and low rate of fertilizer ($N:P_2O_5:K_2O$ = 50:30:15 kg ha^{-1}) was applied. In CM2, 125 seeds m^{-2} were sown and higher rate of fertilizer ($N:P_2O_5:K_2O$ = 90-100:60:30 kg ha^{-1}) was applied. Size of each sub-subplot was 4 × 4.5 m.

2.2. Cultural management

In each year, dry-seed broadcasting method was used. Field was irrigated to maintain standing water. In 2004, seeds were sown on 18 June and 185 kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 16:16:8%) was applied on 23 July in all the plots. In +TD plots, 45 kg ha^{-1} of urea (N = 46%) was topdressed at panicle initiation stage (Table 3.1).

Seeding date in 2005 was 10 May for May-sowing and 9 June for June-sowing. In

2006, seeding date for May-sowing was 18 May and for June-sowing was 16 June. Fertilizer application rates were 185 kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 16:16:8%) for both CM1 and CM2 around 30 days after seeding, 45 to 67.5 kg ha^{-1} of urea (N = 46%) for CM2 at tillering stage, 45 kg ha^{-1} of urea for CM1 or 185 kg ha^{-1} of chemical fertilizer for CM2 at panicle initiation stage and 22.5 kg ha^{-1} of urea for CM2 at heading stage (Table 3.1).

Table 3.1. Fertilizer application rate and date across year, cultivation method, seeding month and genotype in 2004, 2005 and 2006.

	$N:P_2O_5:K_2O$ (kg ha^{-1})	KDML105	IR57514
2004			
–TD	30:30:15	23 Jul	23 Jul
+TD	30:30:15	23 Jul	23 Jul
	20:0:0	21 Sep	2 Sep

	$N:P_2O_5:K_2O$ (kg ha^{-1})	May-sowing KDML105	May-sowing IR57514	May-sowing HY71	June-sowing KDML105	June-sowing IR57514	June-sowing HY71
2005							
CM1	30:30:15	15 Jun	15 Jun	15 Jun	6 Jul	6 Jul	6 Jul
	20:0:0	20 Sep	30 Aug	25 Aug	20 Sep	5 Sep	25 Aug
CM2	30:30:15	15 Jun	15 Jun	15 Jun	6 Jul	6 Jul	6 Jul
	20:0:0	27 Jul	27 Jul	27 Jul	27 Jul	27 Jul	27 Jul
	10:0:0[a]	–	–	–	22 Aug	22 Aug	–
	30:30:15	20 Sep	30 Aug	25 Aug	20 Sep	5 Sep	25 Aug
	10:0:0	21 Oct	23 Sep	27 Sep	23 Oct	30 Sep	2 Oct
2006							
CM1	30:30:15	20 Jun	20 Jun	20 Jun	12 Jul	12 Jul	12 Jul
	20:0:0	20 Sep	21 Aug	21 Aug	20 Sep	28 Aug	28 Aug
CM2	30:30:15	20 Jun	20 Jun	20 Jun	12 Jul	12 Jul	12 Jul
	20:0:0	17 Jul	17 Jul	17 Jul	4 Aug	4 Aug	4 Aug
	10:0:0[a]	11 Aug	11 Aug	11 Aug	29 Aug	–	–
	30:30:15	20 Sep	21 Aug	21 Aug	20 Sep	28 Aug	28 Aug
	10:0:0	21 Oct	6 Sep	26 Sep	25 Oct	2 Oct	2 Oct

[a]Additional urea of 22.5 kg ha^{-1} was applied to supply nitrigen because the reading value of SPAD was low (less than 30).

2.3. Measurements

In each year, mean air temperature and rainfall were recorded at a weather station in Ubon Ratchathani city. Monthly mean air temperature during crop growth season fluctuated from 26.0 to 29.9 °C, and it was generally high in May and decreased to November. In 2005, soil water potential was measured in the depth of 20 cm.

Plant number in 0.5 m² was measured on 29 July in 2004, on 13 June for May-sowing and on 13 July for June-sowing in 2005 and 15 June for May-sowing and 14 July for June-sowing in 2006 (referred to as seedling number). SPAD (SPAD 502, Minolta Co., Japan) reading value, an index of plant nitrogen status (Peng et al., 2002), was measured from 19 August to 3 October in 2005 and from 2 August to 26 October in 2006 in about 2-weeks interval. In each year, heading date was recorded. Shoot dry matter at heading and maturity, grain yield and yield components were determined from samples from 0.5 m² for 2004 and 2005 and 1 m² for 2006. Dry matter was measured after drying at 80 °C of forced-air oven for 3 days. In 2004, length of all the panicles in samples taken at heading was measured and mean panicle length was determined. Fifteen panicles which had moderate panicle length (mean panicle length ± 1 cm) were sampled to investigate panicle structure. Spikelets on sampled panicles were divided into spikelets on primary rachis branches, secondary pedicels, secondary rachis branches and tertiary pedicels (Fig. 3.1), according to the method of Matsuba (1991).

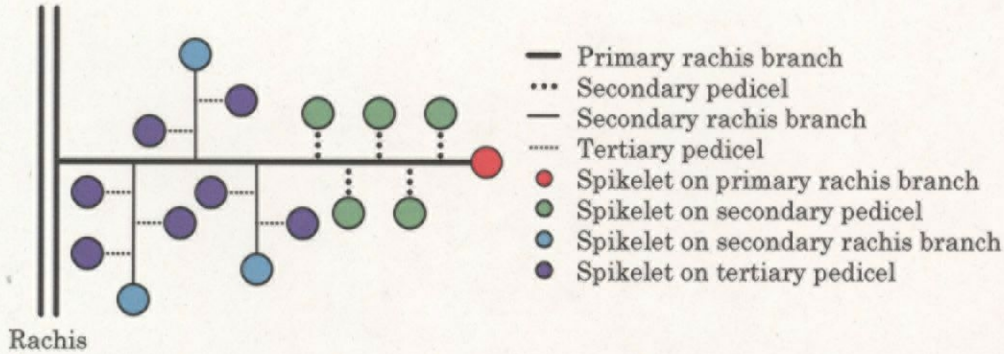

Fig. 3.1. Classification of rachis branches, pedicels and spikelets in one panicle. (From Matsuba, 1991)

2.4. Statistical analysis

Analysis of variance (ANOVA) was conducted with the method of Gomez and Gomez (1984). In each year, phenotypic observation was modelled with split-split design to assess the effects of topdressing, genotypic difference, seeding rate, cultivation method and seeding time, or their interactions. For the results in 2005 and 2006, combined analysis over years was also conducted.

3. Results

Rainfall pattern and period with standing water is shown in Fig. 3.2. There was standing water from late or mid July in 2004 and 2006, but standing water was absent until 17 August in 2005. In 2005, soil water potential measured in the depth of 20 cm fluctuated from –42 to –1 kPa until 23 July. Since 24 July, soil water potential was 0. In every year, standing water was maintained until maturity of KDML105 (latest genotype used in this study).

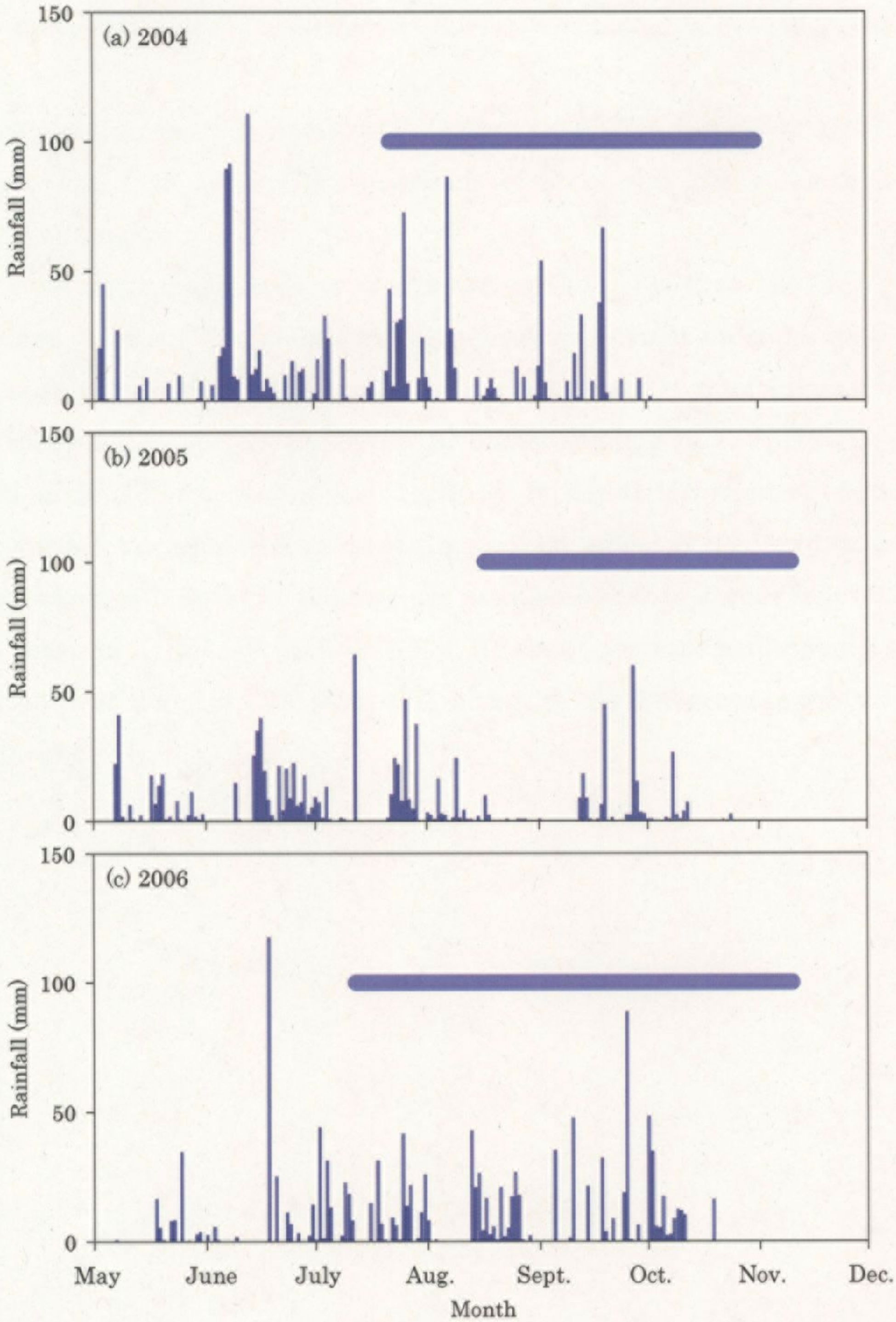

Fig. 3.2. Rainfall pattern from May to November in 2004 (a), 2005 (b) and 2006 (c). Horizontal bars indicate the period with standing water in the field.

3.1. Experiment in 2004

3.1.1. Heading date, shoot dry matter, grain yield and yield components

Heading date of KDML105 and IR57514 ranged from 21 to 26 October and 3 to 7 October, respectively (data not shown). Lower seeding rate headed earlier in each genotype.

Shoot dry matter in +TD tended to be higher than –TD, but the difference was not significant (Fig. 3.3). Generally, increment of shoot dry matter from heading to maturity was small.

Grain yield and harvest index were higher in KDML105 than IR57514 (Table 3.2). Seeding rate did not affect grain yield significantly. Harvest index in middle and low seeding rates was higher than high seeding rate. Panicle number was higher and spikelet number per panicle was lower in higher seeding rate. Spikelet number per panicle of KDML105 was larger than IR57514. In KDML105 effect of seeding rate on spikelet number per panicle was large. In contrast, effect of seeding rate in IR57514 was relatively small. Spikelet number per area tended to be larger in +TD than –TD and was larger in KDML105 than IR57514. However, percentage of ripened grains and grain weight was lower in +TD than –TD, although the difference in grain weight was not significant.

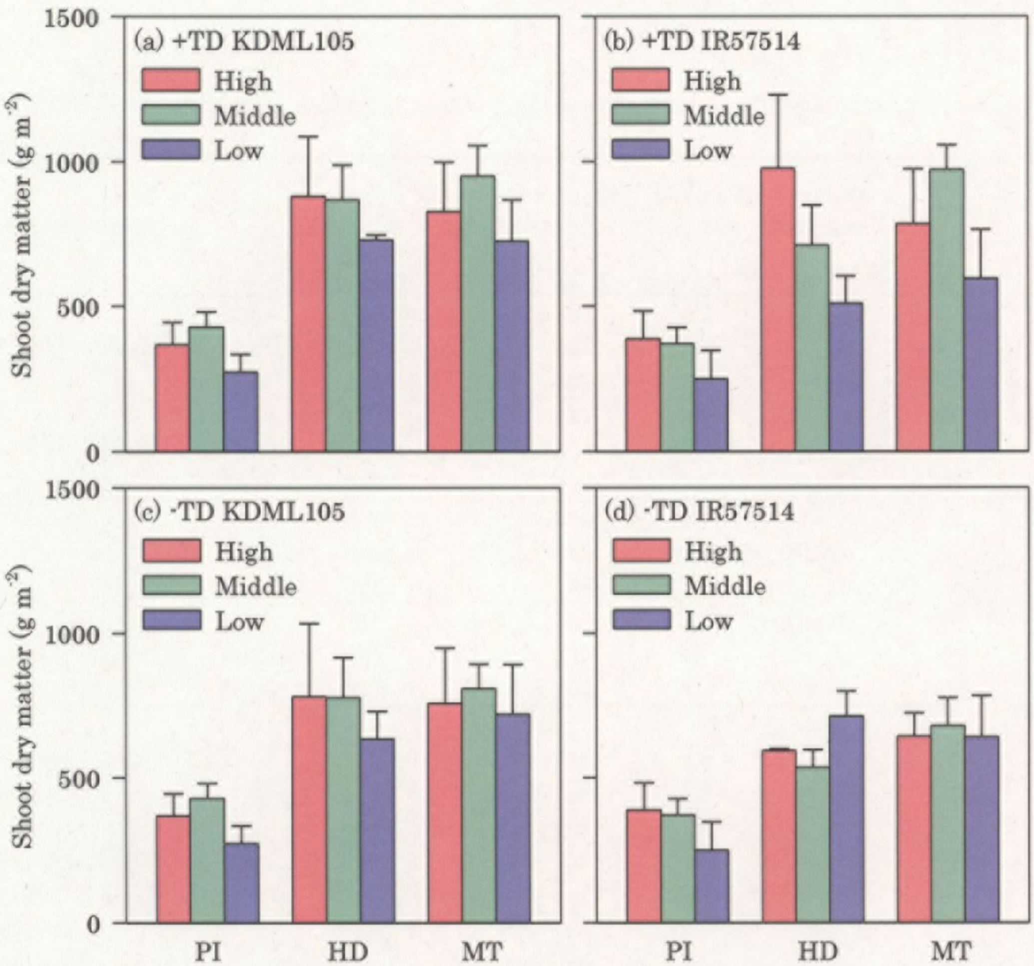

Fig. 3.3. Shoot dry matter at panicle initiation (PI), heading (HD) and maturity (MT) stages across seeding rate in +TD KDML105 (a), +TD IR57514 (b), –TD KDML105 (c) and –TD IR57514 (d) in 2004. Vertical bars indicate standard errors.

Table 3.2. Grain yield, harvest index and yield components across fertiliser application, genotype and seeding rate in 2004.

Topdressing	Genotype	Seeding rate	Grain yield ($g\ m^{-2}$)	Harvest index (%)	Panicle number (m^{-2})	Spikelet number ($panicle^{-1}$)	Spikelet number (m^{-2})	Percentage of ripened grains (%)	Grain weight (mg)
+TD	KDML105	High	323	34	301	47	14066	84	28.0
		Middle	382	36	297	58	17228	81	28.2
		Low	313	39	163	93	15067	74	28.2
	IR57514	High	237	26	317	38	11905	70	30.1
		Middle	384	35	267	58	15511	84	29.6
		Low	224	33	132	73	9621	80	29.0
−TD	KDML105	High	270	33	420	27	11323	86	28.5
		Middle	342	37	243	55	13380	88	29.0
		Low	327	40	148	95	14119	79	29.2
	IR57514	High	218	30	325	33	10875	77	29.7
		Middle	247	32	248	36	8957	88	31.2
		Low	218	31	163	51	8283	86	30.3
$LSD_{0.05}$									
Topdressing (TD)			ns	ns	ns	ns	ns	4	ns
Genotype (G)			*55*	*5*	ns	11	*2573*	ns	0.8
TD × G			ns	ns	ns	ns	ns	ns	ns
Seeding Rate (SR)			ns	3	74	8	ns	*4*	ns
TD × SR			ns	ns	ns	ns	ns	ns	ns
G × SR			ns	ns	ns	11	ns	7	ns
TD × G × SR			ns	ns	ns	16	ns	ns	ns

$LSD_{0.05}$ indicates LSD at $P = 0.05$. *Italic values* indicate LSD at $P = 0.10$.

3.1.2. Panicle structure

Panicle got longer with topdressing and with lower seeding rate (Table 3.3). Panicle length of KDML105 was longer than IR57514. Topdressing significantly increased total spikelet number per panicle. KDML105 had larger spikelet number per panicle than IR57514. Spikelet number per panicle in low seeding rate in KDML105 was most greatly increased by topdressing (approx. 30). Topdressing increased spikelet numbers on all the rachis branches and pedicels except for on primary rachis branch. KDML105 had larger spikelet number on all the rachis branches and pedicels than IR57514. Genotype by seeding rate interaction was significant in all the measurements and the effect of seeding rate was larger in KDML105 than IR57514. TD increased the spikelet number on secondary rachis branch more greatly in lower seeding rate. The increment of spikelet number on tertiary pedicel was largest in low seeding rate in KDML105.

Table 3.3. Panicle length and spikelet number on primary rachis branch, secondary pedicel, secondary rachis branch and tertiary pedicel across fertilizer application, genotype and seeding rate in 2004.

Topdressing	Genotype	Seeding rate	Panicle length (mean ± SD[1], cm)	Spikelet number per panicle: Total	On primary rachis branch	On secondary pedicel	On secondary rachis branch	On tertiary pedicel
+TD	KDML105	High	18.5 ± 0.7	41.4	4.9	22.1	5.3	9.1
		Middle	21.0 ± 0.6	68.1	7.9	38.1	8.3	13.8
		Low	24.3 ± 0.8	117.1	8.9	49.5	18.7	40.1
	IR57514	High	16.8 ± 1.0	39.9	5.4	23.5	4.2	6.8
		Middle	18.9 ± 0.9	51.0	6.5	29.7	5.8	9.0
		Low	22.0 ± 0.6	78.6	7.8	39.3	11.1	20.5
−TD	KDML105	High	17.1 ± 0.7	39.5	5.6	23.5	4.5	5.8
		Middle	20.0 ± 0.6	57.0	7.0	32.1	6.7	11.2
		Low	22.4 ± 0.5	87.0	9.1	45.3	11.8	20.8
	IR57514	High	15.8 ± 0.6	32.0	4.9	20.5	2.7	3.9
		Middle	16.7 ± 0.6	37.1	5.5	23.0	3.7	4.9
		Low	20.2 ± 0.7	65.9	8.0	37.8	7.5	12.6
$LSD_{0.05}$								
Topdressing (TD)			0.1	3.5	ns	1.5	0.9	1.7
Genotype (G)			0.1	3.5	0.3	1.5	0.9	1.7
TD × G			ns	ns	*0.3*	ns	ns	2.4
Seeding Rate (SR)			0.1	4.3	0.3	1.8	1.0	2.1
TD × SR			0.2	6.1	0.5	2.6	1.5	2.9
G × SR			0.2	6.1	0.5	2.6	1.5	2.9
TD × G × SR			0.3	8.7	ns	ns	ns	4.1

$LSD_{0.05}$ indicates LSD at $P = 0.05$. Italic value indicates LSD at $P = 0.10$.

3.2. Heading date, shoot dry matter, grain yield and yield components in 2005 and 2006

Shoot dry matter at panicle initiation did not differ between CM1 and CM2, but that at heading and maturity was higher in CM2 than CM1 (Fig. 3.4). June-sowing achieved higher shoot dry matter at maturity than May-sowing. Shoot dry matter of KDML105 was higher than other genotypes at panicle initiation, but there was no genotypic difference in shoot dry matter at heading and shoot dry matter of IR57514 was higher than KDML105 and HY71 at maturity. The combination of CM2 and June-sowing achieved higher shoot dry matter in both years.

Panicle number in CM2 was smaller than CM1, reflecting its smaller seedling number (126 vs. 441 m^{-2}), but grain yield was higher in CM2 than CM1 owing to its larger spikelet number per panicle in both years (Table 3.4). In 2006, harvest index and percentage of ripened grains also tended to be higher in CM2 than in CM1 ($P < 0.10$, data not shown). June-sowing achieved higher grain yield than May-sowing. This was due to larger panicle number in June-sowing than in May-sowing. Although there was no significant difference in seedling number between May- and June-sowing (data not shown), panicle number in June-sowing was larger than in May-sowing. The combination of CM2 and June-sowing achieved higher grain yield in both years. IR57514 had higher grain yield than other genotypes because of its larger panicle number and higher grain weight. Larger panicle number and higher grain weight of IR57514 resulted in higher grain yield than KDML105 or HY71 in May-sowing in 2006. In May-sowing in CM1 in 2005, grain yield of IR57514 was higher than the other 2 genotypes. In other growing conditions, however, grain yield of IR57514 was similar with that of KDML105 or HY71, showing significant Y × G, S × G and Y × S × G interactions.

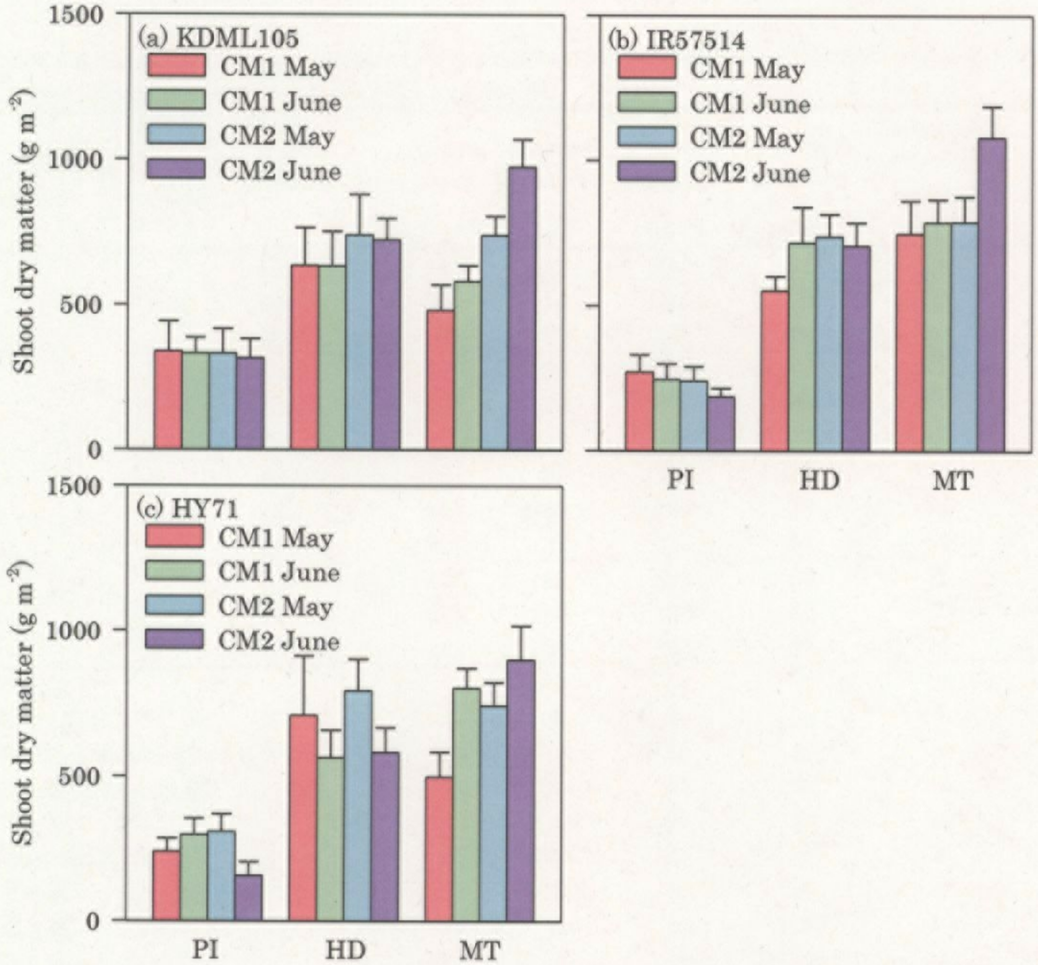

Fig. 3.4. Shoot dry matter at panicle initiation (PI), heading (HD) and maturity (MT) stages across cultivation method and sowing time in KDML105 (a), IR57514 (b) and HY71 (c). The results in 2005 and 2006 were averaged. Vertical bars indicate standard errors.

Table 3.4. Grain yield, harvest index and yield components across cultivation method, seeding month and genotype (average of 2005 and 2006).

Cultivation method	Seeding month	Genotype	Grain yield ($g\ m^{-2}$)	Harvest index (%)	Panicle number (m^{-2})	Spikelet number ($panicle^{-1}$)	Percentage of ripened grains (%)	Grain weight (mg)
CM1	May	KDML105	161	32	213	41	73	27
		IR57514	284	34	315	40	69	33
		HY71	170	30	221	46	64	29
	June	KDML105	229	35	286	42	77	27
		IR57514	262	30	357	39	66	30
		HY71	303	33	338	48	67	29
CM2	May	KDML105	281	35	153	85	79	28
		IR57514	352	39	186	77	74	33
		HY71	269	32	176	81	68	29
	June	KDML105	396	36	205	95	75	27
		IR57514	416	33	289	69	70	30
		HY71	361	36	221	82	73	28
$LSD_{0.05}$								
Year (Y)			ns	4	29	14	*5*	ns
Cultivation method (C)			82	ns	28	10	ns	ns
Seeding month (S)			39	ns	31	ns	ns	0.5
Y × S			ns	ns	43	ns	ns	ns
Genotype (G)			32	ns	33	8	3	0.5
Y × G			*38*	3	ns	*9*	*4*	0.7
C × G			ns	ns	ns	*9*	ns	*0.6*
S × G			46	3	ns	ns	*4*	0.7
Y × S × G			64	ns	ns	ns	*5*	1.0
C × S × G			ns	4	ns	ns	ns	ns

$LSD_{0.05}$ indicates LSD at $P = 0.05$.

Italic values indicate LSD at $P = 0.10$.

ns indicates no significant difference at $P = 0.10$.

Y × C, C × S, Y × C × S, Y × C × G and Y × C × S × G was not significant at any measurement

3.3. Analysis across 3 years

Panicle number did not affect grain yield, but significant correlation was observed between grain yield and spikelet number per panicle and per area and ripened grain number per area (Table 3.5). Spikelet number per panicle decreased with larger panicle number. Spikelet number per panicle and per area and ripened grain number per area correlated each other. Shoot dry matter at maturity and grain yield decreased with the longer period (mainly in May-sowing in 2005 and 2006) from seeding to maturity (Fig. 3.5). Spikelet number per area also tended to decrease with more days to heading. SPAD reading value on the nearest measurement date to heading got lower with the longer days to heading in 2005 and 2006. In KDML105, crop growth rate (CGR) from panicle initiation to heading and from heading to maturity was correlated with grain yield (Table 3.6). CGR from heading to maturity was correlated with higher grain yield also in IR57514 and HY71 (data not shown). Spikelet number per panicle increased with higher biomass production per stem from panicle initiation to heading (Fig. 3.6).

Table 3.5. Correlation coefficient among grain yield and yield components across 3 years.

	Panicle number	Spikelet number per panicle	Spikelet number per area	Percentage of ripened grains	Ripened grain number	Grain weight
Grain yield	0.052	**0.521**	**0.903**	0.153	**0.956**	0.267
Panicle number		**–0.725**	0.067	–0.025	0.062	0.120
Spikelet number per panicle			**0.582**	–0.108	**0.538**	–0.067
Spikelet number per area				–0.186	**0.927**	0.059
Percentage of ripened grains					0.187	–0.108
Ripened grain number						0.001

Bold values indicate significant correlation at 1% level. No correlation was significant at 5% level.

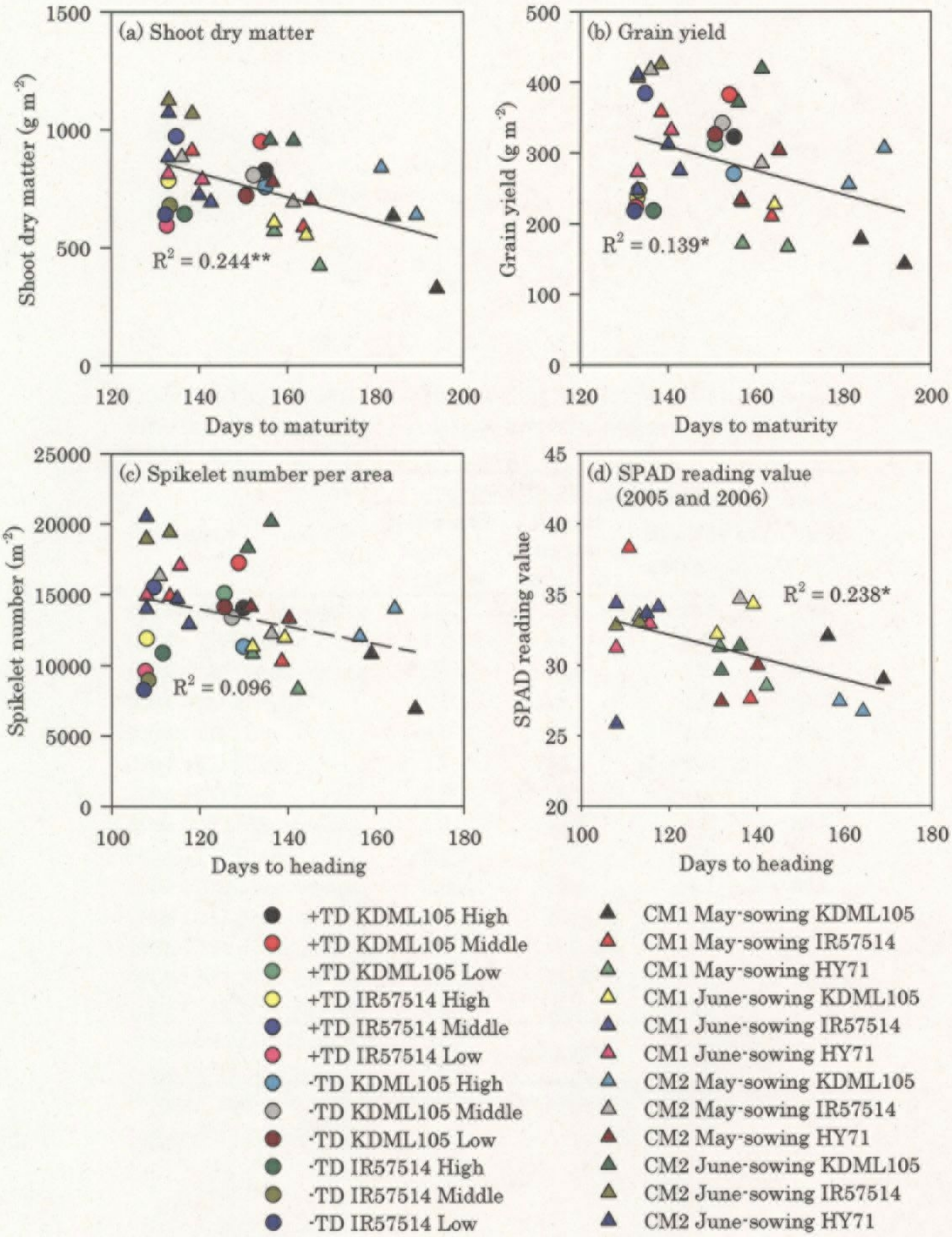

Fig. 3.5. Relationship between days from seeding to maturity and shoot dry matter at maturity (a) and grain yield (b), and between days from seeding to heading and spikelet number per area (c) across 3 years, and between days to heading and SPAD reading value on the nearest measurement date to heading in 2005 and 2006 (d). Circles and triangles indicate the data set in 2004, and 2005 and 2006, respectively. Linear regression line was drawn for each relationship, and ** and * indicate significant regression at 1% and 5% level, respectively.

Table 3.6. Crop growth rate from seeding to panicle initiation, panicle initiation to heading and heading to maturity and grain yield of KDML105.

Treatment	Crop growth rate (g m^{-2} day^{-1})			Grain yield (g m^{-2})
	Seeding to panicle initiation	Panicle initiation to heading	Heading to maturity	
2005 CM2 June-sowing	1.8	16.8	10.6	419
2004 +TD Middle	4.4	14.7	3.2	382
2006 CM2 June-sowing	4.3	12.9	5.6	372
2004 –TD Middle	4.4	11.7	1.2	342
2004 –TD Low	2.9	12.1	3.4	327
2004 +TD High	3.7	17.1	-2.2	323
2004 +TD Low	2.9	15.2	-0.2	313
2005 CM2 May-sowing	1.3	12.0	4.0	307
2004 –TD High	3.7	13.8	-0.9	270
2006 CM2 May-sowing	3.8	15.4	-4.1	256
2006 CM1 June-sowing	3.8	15.4	-9.8	231
2005 CM1 June-sowing	2.5	4.9	5.5	227
2006 CM1 May-sowing	4.1	11.6	-9.8	178
2005 CM1 May-sowing	1.0	8.3	-2.7	143
Correlation coefficient between grain yield	0.193	0.533*	0.705**	-

** and * indicate significant correlation with grain yield at $P = 0.01$ and *0.05*, respectively.

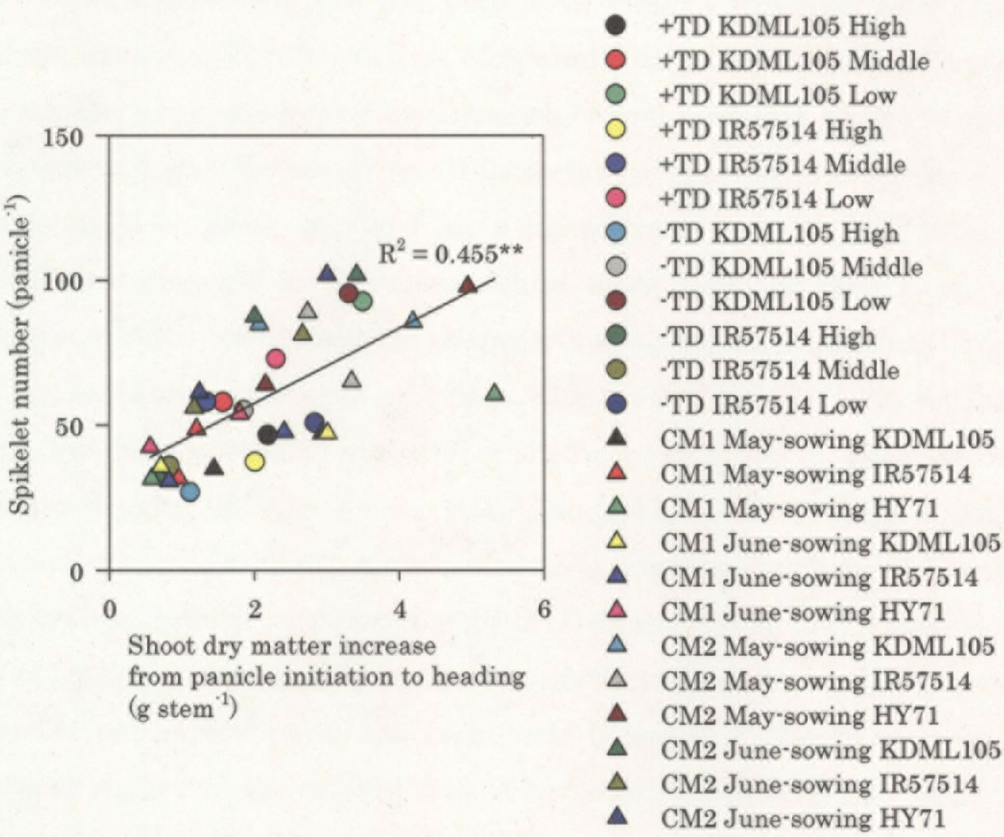

Fig. 3.6. Relationship between shoot dry matter increase per stem from panicle initiation to heading and spikelet number per panicle across 3 years. Circles and triangles indicate the data set in 2004, and 2005 and 2006, respectively. Linear regression line was drawn. ** indicates significant regression at 1% level.

4. Discussion

4.1. Effect of topdressing on spikelet number per panicle in 2004

Panicle number increased and spikelet number per panicle decreased in higher seeding rate. Effect of topdressing at panicle initiation stage on spikelet number per panicle in yield component analysis was not significant, but topdressing significantly increased total spikelet number per panicle in panicle structure analysis. Clearer difference in panicle structure analysis compared with yield components analysis was owing to smaller error of sampled panicles, which had moderate panicle length (mean panicle length ± 1 cm). Relatively small increment of spikelet number per panicle by topdressing could be partly due to limited indigenous nitrogen supply from the soil (0.033% of total nitrogen in the experimental field). Naklang (1997) recommended same amount of fertilizer application in transplanting and direct seeding ($N:P_2O_5:K_2O$ = 16:16:8 kg ha^{-1} at transplanting or 30 days after seeding and N = 20 kg ha^{-1} at panicle initiation), but higher amount of fertilizer should be required in direct seeding with higher plant density (Schnier et al., 1990; Dingkuhn et al., 1992a,b; Fukai, 2002). Investigation of panicle structure revealed that topdressing increased spikelet on secondary rachis branch and tertiary pedicel especially in lower seeding rate of KDML105. In direct seeding under irrigated or favourable water conditions, spikelet or grain number per panicle limits the grain yield (Chapter 2; Dingkuhn et al., 1992a). These results suggested the combination of low seeding rate (e.g. 125 seeds m^{-2}) and topdressing at panicle initiation stage could increase spikelet number per panicle and per area. However, percentage of ripened grains was significantly lower in +TD than –TD, hence continuous application of fertilizer should be necessary to have good grain filling and higher grain yield.

4.2. Effectiveness of the combination of low seeding rate and high amount of fertilizer in 2005 and 2006

Grain yield in CM2 with the combination of low seeding rate and high fertilizer application was higher than CM1 (high seeding rate and low fertilizer application), owing to its larger spikelet number per panicle. In KDML105 in June-sowing in CM2, grain yield of 396 g m^{-2} was achieved with the spikelet number per panicle of 95 in the average of 2 years. This value was comparable to the highest grain yield reported in transplanting (Romyen et al., 1998; Ohnishi et al., 1999). This indicated direct seeding had as high yielding performance as transplanting under favourable water conditions.

Grain yield decreased with the longer period from seeding to maturity. May-sowing had lower grain yield than June-sowing, but days to matuirty of IR57514 in May-sowing in 2006 was short (136 to 138 days), and it had high grain yield (358 in CM1 and 418 g m^{-2} in CM2) (this resulted in significant interaction among year, seeding month and genotype). The days to maturity of IR57514 in May-sowing in 2005 were longer (161 to 164 days) compared with 2006 and its grain yield was also lower. This longer growing period in 2005 was partly owing to longer non-flooded period in early growth stage. This suggested genotype with shorter growth period might be more suitable compared with KDML105 if seeding time is earlier. Fukai (2002) also reported that photoperiod-insensitive genotypes with shorter growth period are suitable for early seeding to avoid overgrowth in vegetative stage. The trend that cultivation method or genotype with shorter growth duration had higher grain yield should be different from transplanting, in which it was reported that genotypes with longer growth duration had higher grain yield (Romyen et al., 1998; Pantuwan et al., 2002). This difference should be owing to the difference in plant density. In direct seeding with higher plant density than transplanting, rice canopy could be overluxuriant especially when vegetative growth was prolonged by early seeding.

4.3. Required growth dynamics in direct seeding under favourable water conditions

The yield component contributing to higher grain yield was spikelet number per panicle. Spikelet number per panicle was pointed out as the important character for higher grain yield under favourable water condition, also in Chapter 2. Spikelet number per area tended to increase with larger panicle number in the treatments other than CM2 (treatments with the nitrogen application of 50 kg ha^{-1} or less) (data not shown). However, the largest spikelet number per area (20526 m^{-2}) was achieved in CM2, with the panicle number of 201 m^{-2} and spikelet number per panicle of 102 (with the combination of relatively small panicle number and large spikelet number per panicle). Grain yield decreased with the longer days to maturity. This was mainly owing to the low grain yield in May-sowing in 2005 and 2006. The correlation coefficient between days to maturity and grain yield in CM1 and CM2 was –0.801 and –0.633, respectively (data not shown), and the effect of the number of days to maturity was stronger in CM1 than in CM2. SPAD reading value around heading was especially low in the treatments with longer days to heading in CM1 with less fertilizer application, and grain yield was also lower in those treatments. These results suggested that long vegetative growth was disadvantageous especially with less fertilizer application. Earlier seeding of photoperiod sensitive cultivars should better be avoided under infertile soils and without sufficient amounts of available fertilizers because it could subject rice to nutrient deficiency caused by too long vegetative growth. Spikelet number per panicle was negatively correlated with panicle number and positively with the increment of shoot dry matter per stem or per area from panicle initiation to heading (weakly with R^2 of 0.138, data not shown). In addition, crop growth rate from panicle initiation to heading (only in KDML105) and from heading to maturity was correlated with grain yield. These results indicated the importance of higher biomass production in reproductive stage for higher grain yield. Under favourable water conditions, cultivation method (i.e. sowing time, seeding rate, fertilizer application rate and cultivar) which avoids nutrient deficit in later growth stage should be adopted. The combination of low seeding rate and high fertilizer application should be effective to supply nutrient and have greater biomass production in later growth stage.

5. Conclusions

Analysis of panicle structure revealed that spikelet on tertiary pedicel in low seeding rate of KDML105 greatly increased by topdressing in the experiment in 2004. The combination of lower seeding rate and higher fertilizer application rate (CM2) had higher grain yield than CM1 (higher seeding rate and less fertilizer application) in 2005 and 2006, owing to its larger spikelet number per panicle. Grain yield of KDML105 in June-sowing in CM2 was as high as the highest yield reported in transplanting, and this study showed direct seeding had as high yielding performance as transplanting under favourable water conditions. Regression analysis indicated higher biomass production from panicle initiation to heading associated with larger spikelet number per panicle. Biomass production from heading to maturity also correlated with grain yield. These results indicated the importance of the biomass production in reproductive stage. Under favourable water conditions, cultivation method avoiding nutrient deficit in later growth period should be adopted and higher biomass production in reproductive stage should be achieved by appropriate seeding rate and nutrient management (the combination of low seeding rate and high fertilizer application).

Summary: The effect of seeding rate and fertilizer application on grain yield was evaluated under favourable water conditions. In 2004, seeding rates of 500, 250 and 125 seeds m^{-2} were examined under topdressed (with 45 kg ha^{-1} of urea at panicle initiation stage; +TD) and non-topdressed (–TD) conditions, using 2 genotypes, KDML105 and IR57514-PMI-5-B-1-2 (IR57514). In 2005 and 2006, 2 cultivation methods (seeding rate of 500 seeds m^{-2} and nitrogen application of 50 kg ha^{-1}; CM1 and seeding rate of 125 seeds m^{-2} and nitrogen application of 90-100 kg ha^{-1}; CM2) were compared with 2 seeding time (May and June) and 3 genotypes (KDML105, IR57514 and HY71). In 2004, spikelet number per area tended to be higher in +TD than –TD ($P = 0.12$), but there was little difference in grain yield between +TD and –TD. Analysis of panicle structure revealed that spikelet on tertiary pedicel in low seeding rate of KDML105 greatly increased by topdressing. These results suggested the combination of lower seeding rate and continuous application of nitrogen was necessary for higher grain yield. In 2005 and 2006, CM2 had higher grain yield than CM1 owing to its larger spikelet number per panicle. Grain yield of KDML105 in June-sowing in CM2 was as high as the highest yield reported in transplanting, and this study showed direct seeding had as high yielding performance as transplanting under favourable water conditions. Regression analysis using the data sets in 3 years indicated higher biomass production from panicle initiation to heading associated with larger spikelet number per panicle. Biomass production from heading to maturity also correlated with grain yield. These results indicated the importance of the biomass production in reproductive stage. Under favourable water conditions, cultivation method avoiding nutrient deficit in later growth stage should be adopted and higher biomass production in reproductive stage should be achieved by appropriate seeding rate, seeding time and nutrient management.

Chapter 4. Spatial variability in growth of direct seeded rice

1. Introduction

Within-field variations in the growth of direct seeded rice can be large (Lantican et al., 1999; Rickman et al., 2001), particularly in broadcasted (BC) crops in rainfed lowlands such as those in Northeast Thailand, and this could cause substantial production losses.

In the BC process in Northeast Thailand, fields are usually ploughed once or twice before the seeds are broadcast onto dry soil, and then the fields are harrowed (Naklang, 1997). Land preparation is generally conducted using two-wheeled hand tractors under dry conditions before the onset of the rainy season (Pandey et al., 2002), which is likely to result in a less-even soil surface and larger within-field variation in the distribution of standing water and in soil water content compared with the conditions in flooded paddy fields with puddling (e.g., for transplanting or wet seeding). In addition, plant populations will exhibit large variation within a BC field because seeds are broadcast by hand. Within-field variation in the extent of weed infestation is also expected.

Analysis of spatial variability using tools such as semivariogram should effectively clarify the significance of spatial variability. In previous studies, semivariogram analysis was used in several crops: rice (Dobermann et al., 1995; Inamura et al., 2004; Lee et al., 2001; Moritsuka et al., 2004; Yanai et al., 2000, 2001), wheat (Nakamoto and Yamagishi, 2003; Nakamoto et al., 2002; Yamagishi et al., 2003), maize (Nakamoto and Yamagishi, 2003; Nakamoto et al., 2002; Yamagishi et al., 2003), and pearl millet (Stein et al., 1997). Most of these studies focused on precision farming and the spatial variability in soil chemical properties and crop growth in temperate regions in the presence of irrigation. Under tropical rainfed lowland conditions, however, the relationship between spatial variability in soil water conditions and rice growth has not yet been studied.

The adoption of row seeding (RS) instead of BC could potentially reduce the within-field variation in direct-sown rice. Sowing within rows should decrease the variation in plant populations, and should facilitate weed management (e.g., by means of inter-row weeding) compared with BC.

In this chapter, spatial variability in BC was analysed by means of variography based on the assumption that data from spatially close points would be more similar than data from points located farther apart, and the within-field variation in rice growth and the degree of weed infestation were compared between BC and the combination of RS with inter-row weeding. The objectives of this chapter were to clarify the effect of spatial variability in soil water content and weed infestation on the growth of BC rice, and to assess the advantages of RS in terms of within-field variability in rice growth and the degree of weed infestation in direct-sown rainfed lowland rice in Northeast Thailand.

2. Materials and Methods

2.1. Experimental design, materials, and cultivation management

The study was conducted at Ubon Rice Research Center, Ubon Ratchathani, Thailand (15°20′N, 104°41′E, 110 m asl), in 2004 and 2005. According to the Department of Agriculture (1993) classification, the soil type in the experimental field was a silt loam (sand:silt:clay = 6:74:20%), and total nitrogen (calculated from the concentration of organic matter; 5% of the organic matter), available phosphorus (measured with the Bray P2 method), and exchangeable potassium (measured with the ammonium acetate method at pH 7.0) were 0.041%, 36.87 ppm, and 9.94 ppm, respectively. In 2004, one BC and one RS plot was used, and in 2005, 3 plots were used as replications for BC (BC1, BC2, and BC3) to confirm the consistency of the within field variation, and one RS plot was used. Size of each plot was 14 m by 20 m in both years. In 2004, one ploughing and 2 rotary tillage was conducted by a four-wheeled tractor on 20 and 27 May and 3 June, respectively. In 2005, ploughing was conducted twice (on 19 May and 1 June) using a two-wheeled hand tractor. In both years, one *indica* cultivar, KDML105 was grown. In the BC plots, seeds were broadcast-sown by hand on 4 and 1 June in 2004 and 2005, respectively. Seeds were sown manually in rows on 8 and 2 June in 2004 and 2005, respectively in the RS plot. Seeding rate was 250 seeds m^{-2} (approx. 65 kg seeds ha^{-1}) for both years and both BC and RS plots. Inter-row spacing was 30 cm in RS (75 seeds m^{-1} in a row). Immediately after sowing, the BC plots were harrowed using the two-wheeled hand tractor, and seeds in the RS plot were covered manually with soil. Fertilization used 185 kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 16:16:8%) (on 1 July in 2004 and 29 June in 2005) and 45 kg ha

$^{-1}$ of urea (N = 46%) (on 20 September in 2004 and 21 September in 2005), both of which were applied by hand. In all the BC plots, no weeding was conducted; in the RS plot, inter-row weeding was conducted using hoes on 7 July in 2004 and 28 July in 2005. The experiment was conducted under rainfed conditions.

2.2. Measurements

Air temperature was recorded at the weather station nearest to the study site (about 22 km) in Ubon Ratchathani city (Table 4.1). Rainfall in 2004 was also measured in the same weather station, and that in 2005 was recorded with a tipping-bucket rain gauge at the Ubon Rice Research Center.

In 2004, both of BC and RS plots were divided into 9 grid cells of 4.7 m × 6.7 m. In 2005, BC plots were divided into grids containing 70 cells of 2 m × 2 m, and the RS plot into 9 cells of 4.7 m × 6.7 m. A 50-cm-square quadrat was established in the centre of each grid cell and all data was collected in this quadrat. In 2004, plant number on 23 June and shoot dry matter, panicle dry matter and panicle number at maturity of rice and shoot dry matter of weeds at rice maturity was measured. In 2005, the presence of standing water was recorded, and the volumetric water content of the soil from the surface to a depth of 12 cm was measured by time-domain reflectometry (HydroSense, Campbell Scientific Inc., Logan, Utah, USA) at about 14-day intervals (except at the end of July). The number of rice plants was counted on 27 June. The heading date was recorded, and rice was harvested at maturity to determine shoot dry matter, panicle weight, and panicle number. Weed growth was scored visually using the index shown in Table 1.2 in Chapter 1. Weeds in BC2 were harvested at rice maturity to evaluate the degree of correlation between this visual scoring and the shoot dry matter of the weeds. Dry weights of the rice and weeds were measured after drying at 80 °C in a forced-air oven for 3 days.

2.3. Statistical analysis

Correlation, multiple regression and principal components analysis of the data collected in the BC plots in 2005 was conducted using Systat Version 11 for Windows (Systat Software Inc., San Jose, Calif., USA).

In the BC plots in 2005, the spatial dependence of the data was evaluated by means of variography using the GS^{+} Version 7 software for Windows (Gamma Design Software, 2004). Semivariance, $\gamma(h)$, is defined as

$$\gamma(h) = \sum_{i=1}^{n(h)}[Z(x_i+h) - Z(x_i)]^2 / 2n(h)$$

where $n(h)$ is the number of pairs separated by distance h, and $Z(x_i)$ and $Z(x_i+h)$ are the sampled values at locations x_i and x_i+h, respectively. The plot of $\gamma(h)$ against h is a semivariogram. In this study, active lag distance to make semivariogram was set to 10 m (semivariance of the lag distance longer than 10 m was not used because the reliability of semivariance was low owing to small number of pairs). $\gamma(h)$ increases with increasing h and often reaches a theoretical asymptotic maximum at a certain distance, h. The asymptotic maximum and distance are called the sill and range, respectively (Cressie, 1993). Range indicates the limit of the spatial dependence: if data is spatially dependent, sample pairs within the range are correlated, whereas beyond that range, they are independent. When h approaches 0, $\gamma(h)$ should also approach 0, but in practice, it often has a certain positive value. This value, $\gamma(0)$, is called the nugget (Cressie, 1993). The nugget indicates the existence of spatial variation within the minimum sampling distance and of experimental error. The analysis used the following procedures: (1) plotting the semivariogram, (2) fitting a suitable model to the plot (the best fitted model was chosen from among exponential, Gaussian, linear, and spherical models), (3) calculating values for the sill, nugget, range, and index of spatial dependence (the Q value), and (4) block kriging. The Q value represents the spatial structure at the sampling scale, and is given by the following equation:

$$Q = (S - N) / S$$

where S and N are the sill and nugget, respectively. If Q equals 0 (i.e., if the nugget equals the sill), no spatial dependence is detected at the sampling scale that was used. As Q approaches 1 (i.e., as the nugget approaches 0), spatial dependence develops (i.e., the similarity among sampled data at closely spaced locations increases), and more of the spatial variation can be explained by the semivariogram model at the scale of analysis that was chosen.

Cross-dependence of two variables (Z_1 and Z_2) was evaluated using cross-semivariogram. Cross-semivariance, $\gamma_{12}(h)$, is defined as

$$\gamma_{12}(h) = \sum_{i=1}^{n(h)}[Z_1(x_i+h) - Z_1(x_i)]\,[Z_2(x_i+h) - Z_2(x_i)] / 2n(h)$$

where $n(h)$ is the number of pairs separated by distance h, and $Z_1(x_i)$, $Z_1(x_i+h)$, $Z_2(x_i)$, and $Z_2(x_i+h)$ are the sampled values at locations x_i and x_i+h in each pair (Z_1 and Z_2), respectively. The cross-semivariance is negative if the correlation between Z_1 and Z_2 is negative.

Table 4.1. Mean air temperature and rainfall from June to November in 2004 and 2005.

	2004		2005	
	Mean air temperature (°C)	Rainfall (mm)	Mean air temperature (°C)	Rainfall (mm)
Jun	28.0	458	28.7	256
Jul	27.8	335	27.9	256
Aug	27.9	191	27.4	72
Sept	27.4	262	27.4	172
Oct	26.8	1	27.5	31
Nov	26.7	0	26.3	0

Data in 2004 and air temperarure in 2005 were measured at weather station in Ubon Ratchathani city, 22 km apart from experiment site.

3. Results

3.1. Mean and within-field variation

The mean soil water content (%, v v^{-1}, henceforth) of all cells in 2005 increased from 30% on 15 June to 39% on 29 June (Fig. 4.1). Thereafter, soil water content was nearly constant until 16 September, ranging from 37% to 41%, then decreased sharply to 8% on 19 October. The soil water content in the flooded grid cells ranged from 40% to 43% from June to early October, and was higher than that in the non-flooded grids at all times. The coefficient of variation (CV) in the flooded grid cells (1% to 5%) was smaller than that in the non-flooded grid cells (5% to 58%). The CV in the non-flooded cells was highest in October (31% to 58%). Non-flooded cells comprised 207 of the 219 cells (sum of BC and RS plots) on 15 June, but this number decreased to 42 by 19 August, increased to 155 on 2 September, decreased to 75 on 16 September, and then increased until the end of October. These fluctuations paralleled the changes in precipitation (Table 4.1).

Table 4.2 presents the descriptive statistics for soil water content in 2005 (averages for eight measurement dates from 15 June to 19 October), for rice growth (both for 2004 and 2005), and for weed growth (both for 2004 and 2005). In 2004, there was not a significant difference in plant number between BC and RS, but the CV in RS was smaller than RS. Heading date in RS was earlier than BC. Shoot dry matter, panicle dry matter, panicle-to-shoot ratio in dry matter, panicle number and dry matter per panicle in RS was all significantly higher than BC, together with the smaller CV. Visual weed score in RS was significantly lower than BC in both July and rice maturity, although CV was larger. Shoot dry matter of weeds in RS was also lower than BC. In 2005, mean soil water content did not differ significantly between the BC and RS treatments, and the CV of mean soil water content throughout the rice growth period ranged from 6% to 14%. The number of plants on 27 June was significantly larger and the CV of plant number was smaller in RS than in BC. Heading date ranged from 15 to 28 October, and did not differ significantly among treatments. Significantly higher shoot dry matter and more panicles were produced in RS than in BC. Although the difference in panicle dry matter between BC and RS was not significant at $P = 0.05$, panicle dry matter tended to be higher in RS than in BC. The variation in shoot dry matter, panicle dry matter per unit area, the panicle/shoot ratio in dry matter, panicle number, and dry matter per panicle was larger than that in soil water content, and was smaller in RS than in BC. The visual weed score increased with later growth stage in BC, but remained roughly constant in RS, and was significantly lower in RS than in BC on 30 August and 14 November. Plots with fewer weeds (weed score = 0 or 1) and with many weeds (score = 6 to 8) existed in all the study plots, with the exception of 30 August (about 1 month after weeding) in RS, when no plots with a weed score higher than 3 were found. The CV of the weed score decreased from 13 July to 30 August in all four plots. The correlation between the visual weed score and shoot dry matter of weeds at rice maturity was 0.510 in BC2 ($P < 0.01$, $n = 70$).

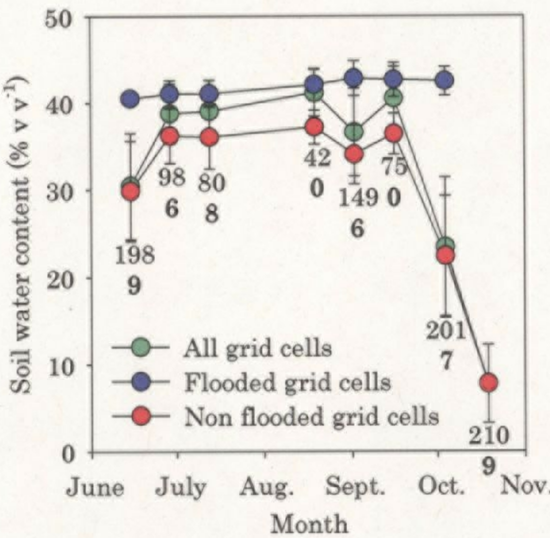

Fig. 4.1. Time course of the volumetric soil water content from the soil surface to a depth of 12 cm in all grid cells, in flooded grid cells, and in non-flooded grid cells in 2005. Vertical bars indicate standard deviations. Numbers below the symbols indicate the sample size for the non-flooded grid cells (N) on each measurement date. Normal and **Bold** numbers indicate the sample size for BC and **RS**, respectively. Sample size for all grid cells combined and for the flooded grid cells are 210 and (210 – N) for BC and 9 and (9 – N) for **RS**, respectively.

Table 4.2. Mean, maximum, and minimum values and coefficients of variation (CV) for soil water content, rice growth, and weed growth in the broadcast-sowing (BC) and row-seeding (RS) treatments in 2004 and 2005.

	Soil water content[1] (% v v^{-1})	Plant number (m^{-2})	Heading date	Shoot dry matter (g m^{-2})	Panicle dry matter (g m^{-2})	Panicle/ shoot ratio (%)	Panicle number (m^{-2})	Panicle dry matter (panicle^{-1})	Visual weed score			Shoot dry matter of weeds (g m^{-2})
				Maturity[3]	Maturity[3]	Maturity[3]	Maturity[3]	Maturity[3]	July[4]	30 Aug	Maturity[3]	Maturity[3]
2004												
BC												
Mean	–	153	26 Oct	155	41	23	67	0.62	2.4	–	4.4	295
Maximum	–	352	29 Oct	248	112	45	104	1.64	4	–	5	806
Minimum	–	28	25 Oct	22	1	5	4	0.26	2	–	3	62
CV (%)	–	60	-	47	76	45	49	69	26	–	16	73
RS												
Mean	–	124	22 Oct	579	249	42	138	1.87	1.2	–	1.9	69
Maximum	–	148	28 Oct	852	392	49	184	2.54	2	–	3	154
Minimum	–	84	18 Oct	371	138	31	72	0.82	1	–	1	9
CV (%)	–	16	-	31	38	14	29	34	36	–	32	74
Difference[4]	–	ns	**	**	**	**	**	**	**	–	**	*
2005												
BC2												
Mean	33	128	23 Oct	293	78	16	60	0.78	2.3	4.2	4.6	200
Maximum	40	328	28 Oct	1227	402	47	356	3.13	7	7	8	522
Minimum	21	8	17 Oct	0	0	0	0	0.00	1	1	0	0
CV (%)	14	62	-	95	145	98	116	104	75	44	42	64
RS												
Mean	38	190	23 Oct	413	86	18	112	0.65	3.2	1.8	3.0	–
Maximum	42	272	27 Oct	685	224	35	188	1.30	6	3	6	–
Minimum	36	104	19 Oct	180	3	2	12	0.23	1	1	1	–
CV (%)	6	31	-	44	91	58	53	52	53	38	47	–
Difference[4]	ns	**	ns	*	ns	ns	*	ns	ns	**	**	–

[1]Mean of eight measurements from 15 June to 19 October.

[2]Measured on 23 June in 2004 and 27 June in 2005.

[3]Maturity of rice (16 November in 2004 and 14 November in 2005).

[4]The t-test was conducted to assess the differences between the broadcasting (BC) and row seeding (RS) treatments within year. **, *, and ns indicate a significant difference at P = 0.01 and 0.05 and no significant difference, respectively.

Sample size was 9 for both BC and RS in 2004 and 70 for BC and 9 for RS in 2005.

3.2. Auto-semivariogram

Table 4.3 shows the semivariogram parameters, the model that produced the best fit, and the regression coefficient for soil water content, rice growth, and weed growth in BC plots in 2005. The low and non-significant regression coefficients for the number of plants on 27 June indicated that none of the models provided a good fit for this parameter. None of the model analyses produced a good fit with linear models, but exponential, Gaussian, and spherical models all produced good fits for various parameters, indicating that these parameters had different ranges of spatial dependence. Q values for parameters with a good degree of fit were larger than 0.5, and thus more than 50% of their within-field variations were spatially dependent. Soil water content measured on 15 June in all the plots and on 19 August in BC1 was not spatially dependent (a low goodness of fit for all models; data not shown). The range value for rice growth in BC1 was similar for all parameters except for heading date (7.3 to 7.6 m), but the range values varied more widely in BC2 (8.2 to >10 m) and BC3 (4.7 to 9.8 m). The range for the visual weed score was greater in BC1 and BC2 (≥7.9 m) than in BC3 (≤5.1 m).

Table 4.3. Semivariogram results (range, Q value, model with the best fit, and regression coefficient) for soil water content, rice growth, and weed growth in the three broadcast-sowing (BC) treatments in 2005.

	Soil water content[1] (% v v^{-1})	Plant number	Heading date	Shoot dry matter	Panicle dry matter (g m^{-2})	Panicle/shoot ratio	Panicle number	Panicle dry matter (panicle^{-1})	Visual weed score			Shoot dry matter of weeds
		27 Jun		14 Nov	14 Nov	14 Nov	14 Nov	14 Nov	13 Jul	30 Aug	14 Nov	14 Nov
BC1												
Range (m)	6.8	>10	>10	7.6	7.3	7.3	7.3	7.3	9.7	7.9	>10	–
Q value	0.95	0.56	0.94	0.77	0.86	0.94	0.83	0.57	0.68	0.91	0.61	–
Model	Gau[2]	Exp[2]	Gau	Sph	Sph	Gau	Sph	Sph	Gau	Sph	Gau	–
R^2	0.774	*0.521*[4]	0.997	0.848	0.754	0.927	0.831	*0.633*	0.998	0.968	0.976	–
BC2												
Range (m)	>10[3]	3.5	7.8	>10	8.3	>10	>10	8.2	8.5	>10	>10	>10
Q value	0.89	0.95	1.00	0.62	0.79	0.72	0.61	0.61	0.76	0.75	0.56	0.51
Model	Gau	Exp	Sph	Gau	Sph	Gau	Gau	Gau	Sph	Sph	Gau	Gau
R^2	0.968	*0.554*	0.871	0.811	0.845	0.994	0.935	0.971	0.924	0.993	0.809	0.997
BC3												
Range (m)	5.1	2.5	>10	5.4	9.8	4.7	4.8	5.8	3.6	4.4	5.1	–
Q value	0.95	1.00	0.74	1.00	0.56	1.00	1.00	0.67	1.00	0.97	0.82	–
Model	Sph[2]	Exp	Sph	Exp	Sph	Exp	Exp	Sph	Gau	Sph	Sph	–
R^2	0.976	*0.143*	0.897	0.993	0.989	*0.555*	0.853	*0.565*	0.710	0.729	0.872	–

[1]Mean of eight measurements from 15 June to 19 October.

[2]Exp, Gau, and Sph represent exponential, Gaussian, and spherical models, respectively.

[3]The calculated range was greater than 10 m (active lag distance).

Italicized values indicate a non-significant regression coefficient ($P > 0.05$).

3.3. Relationships among soil water content, rice growth, and visual weed score

The correlation between soil water content on different measurement dates was significant at $P = 0.05$, except for the June measurements in RS and the October measurements in BC3 and RS (data not shown). Hence the correlation was analysed using the mean soil water content on eight measurement dates. Mean soil water content was significantly negatively correlated with heading date and significantly positively correlated with shoot dry matter, panicle dry matter per unit area, the panicle/shoot ratio in dry matter, the number of panicles, and the dry matter per panicle (Table 4.4, which presents the results in BC2 in 2005. The results only for a single BC field were presented, because the results for the other BC fields in 2005 were generally similar). A negative correlation was observed between soil water content and visual weed score, and the correlation was non-significant only on 30 August in BC2. Although the number of plants on 27 June was not spatially dependent with the lag distance of 2 m (the shortest distance between sampled grid cells), it was positively correlated with rice shoot dry matter and number of panicles. The correlation between number of plants and number of panicles was smaller than that between soil water content and number of panicles. Multiple-regression analysis using soil water content and number of plants as independent parameters and number of panicles as the dependent parameter produced better fitting regression (R^2 was 0.525 in BC2).

Panicle dry matter per unit area was significantly correlated with shoot dry matter, the panicle/shoot ratio in dry matter, the number of panicles, and dry matter per panicle. The correlation between panicle dry matter per unit area and shoot dry matter (0.924) and number of panicles (0.881) was high. A significant negative correlation was also observed between the visual weed score on all dates and shoot dry matter, panicle dry matter per unit area, panicle/shoot ratio in dry matter, number of panicles, and dry matter per panicle. As the result of principal components analysis of the plant number, soil water contents and visual weed scores, the first three components (PC1 to PC 3) were derived as components with eigenvalues higher than 1.0, and they accounted for 76% of the total variance (Table 4.5). The first, second and third components showed high loadings with variables for soil water content, visual weed score and plant number, respectively. Multiple-regression analysis using standardized scores of the first and second principal components as independent parameters and panicle dry matter as the dependent parameter resulted in R^2 of 0.460 (the third component was omitted from the regression because its effect on panicle dry matter was not significant).

Table 4.4. Correlation coefficients among mean soil water content, rice growth, and weed growth in BC2 (broadcast-sowing) in 2005.

	Plant number	Heading date	Shoot dry matter	Panicle dry matter (g m^{-2})	Panicle/ shoot ratio	Panicle number	Panicle dry matter (panicle^{-1})	Visual weed score			Shoot dry matter of weeds
	27 Jun		14 Nov	14 Nov	14 Nov	14 Nov	14 Nov	13 Jul	30 Aug	14 Nov	14 Nov
BC2											
Soil water content[1]	0.042	**–0.733**	**0.589**	**0.626**	**0.749**	**0.596**	**0.678**	**–0.593**	–0.252	**–0.533**	0.059
Plant number		0.008	**0.391**	0.166	0.013	**0.437**	–0.114	–0.183	–0.050	0.042	–0.093
Heading date			**–0.772**	**–0.841**	**–0.848**	**–0.721**	**–0.762**	**0.415**	**0.485**	**0.683**	**0.324**
Shoot dry matter				**0.924**	**0.758**	**0.937**	**0.669**	**–0.507**	**–0.554**	**–0.600**	**–0.425**
Panicle dry matter (g m^{-2})					**0.865**	**0.881**	**0.785**	**–0.417**	**–0.484**	**–0.662**	**–0.348**
Panicle/shoot ratio						**0.760**	**0.904**	**–0.506**	**–0.527**	**–0.658**	<u>–0.252</u>
Panicle number							**0.568**	**–0.483**	**–0.542**	**–0.579**	**–0.343**
Panicle dry matter (g panicle^{-1})								**–0.426**	**–0.433**	**–0.625**	–0.222
Visual weed score											
13 Jul									**0.375**	**0.491**	<u>0.280</u>
30 Aug										**0.422**	**0.567**
14 Nov											**0.510**

[1]Mean of eight measurements from 15 June to 19 October.

Bold and <u>underlined</u> values indicate significant correlations at 1% and 5%, respectively.

Table 4.5. Component loadings, eigenvalues and the percentage of total variance explained for the first three principal components in BC2 in 2005.

Variable	PC1	PC2	PC3
Plant number on 27 Jun.	0.18	–0.04	–0.97
Soil water content on 13 Jul.	0.84	0.32	0.03
Soil water content on 2 Sept.	0.82	0.44	0.02
Soil water content on 19 Oct.	0.78	0.34	0.09
Visual weed score on 13 Jul.	–0.50	0.62	0.17
Visual weed score on 2 Sept.	–0.43	0.61	–0.06
Visual weed score on 19 Oct.	–0.48	0.65	–0.23
Eigenvalue	2.70	1.60	1.03
Percentage of total variance explained (%)	38.5	22.8	14.7

3.4. Spatial distribution of soil water content, rice growth, and visual weed score

Flooded areas (Fig. 4.2) and areas with a high soil water content (higher than 36%) (Fig. 4.3, made from the results of semivariogram, using block kriging) in BC2 in 2005 generally corresponded to each other from 29 June to 4 October. The spatial distribution of heading date, shoot dry matter, panicle dry matter per unit area, panicle/shoot ratio in dry matter, number of panicles, and dry matter per panicle, plus the visual weed score and shoot dry matter of weeds on 14 November (the date of rice maturity), in BC2 were plotted using block kriging (Fig. 4.4, made from the results of semivariogram). Soil water content and heading date showed opposite patterns. Areas with higher soil water content corresponded to areas with higher values for shoot and panicle dry matter per unit area, for the panicle/shoot ratio in dry matter, for the number of panicles, and for the dry matter per panicle. Shoot dry matter, panicle dry matter per unit area, the panicle/shoot ratio in dry matter, the number of panicles, and dry matter per panicle tended to be higher in areas with earlier heading dates. The distribution of visual weed scores and shoot dry matter of weeds were similar. A higher visual weed score or shoot dry matter content of weeds corresponded to a lower soil water content and lower values of shoot dry matter, panicle dry matter per unit area, panicle/shoot ratio in dry matter, number of panicles, and dry matter per panicle.

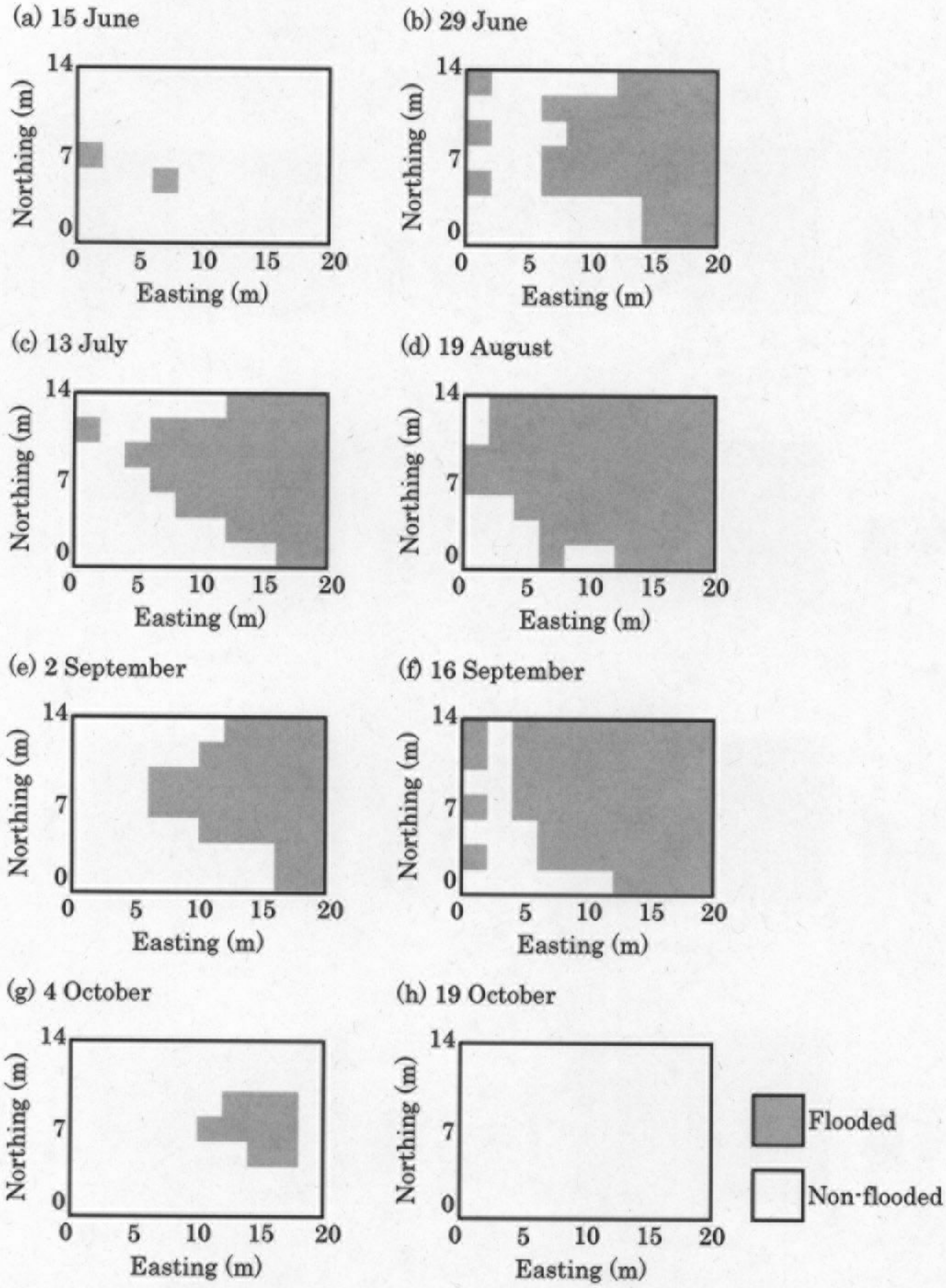

Fig. 4.2. Spatial distribution of standing water in BC2 (broadcast-sowing) in 2005 on eight measurement dates. Cells in grey and white indicate flooded and non-flooded conditions, respectively.

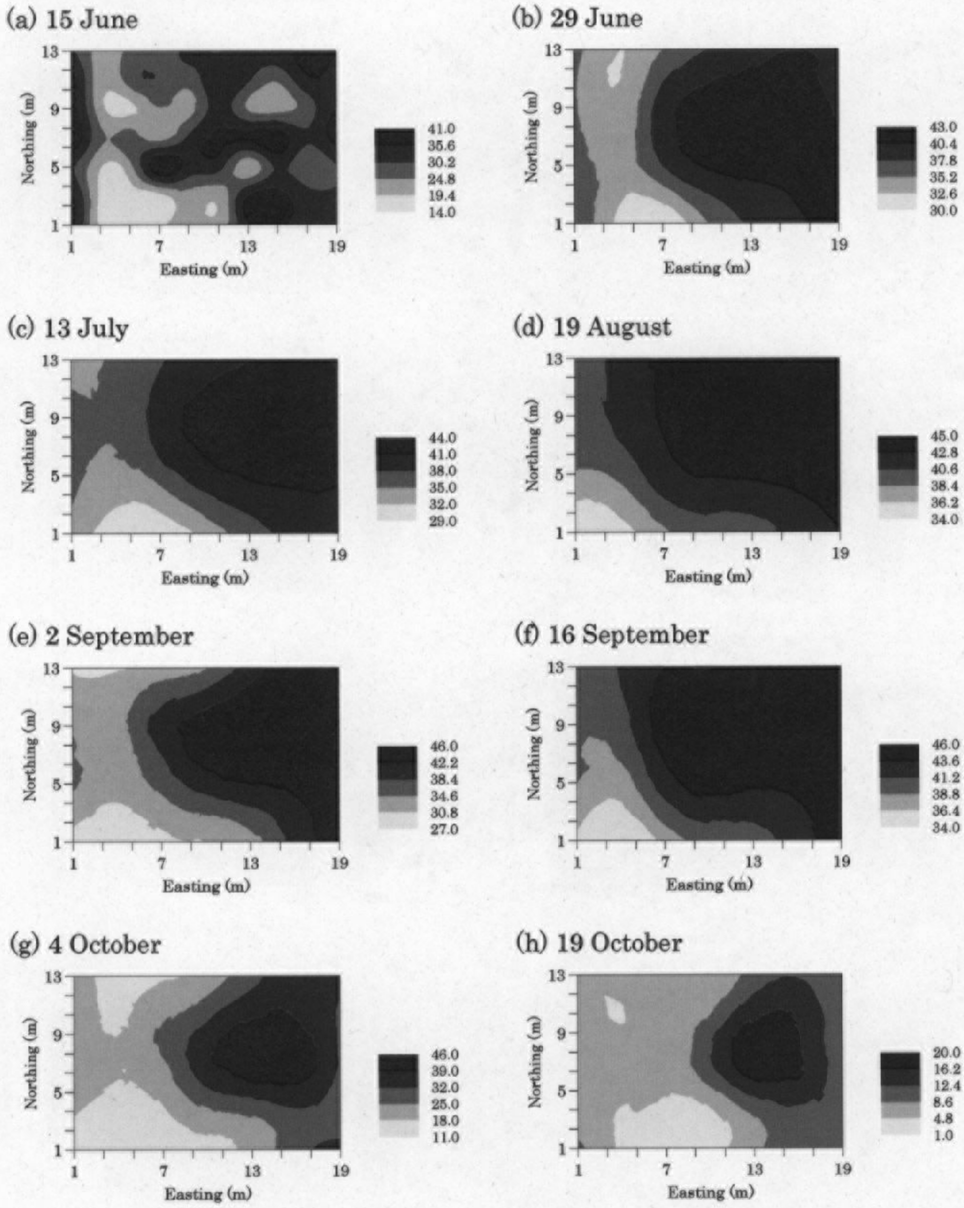

Fig. 4.3. Spatial distribution of soil water content in BC2 (broadcast-sowing) in 2005 on eight measurement dates based on block kriging.

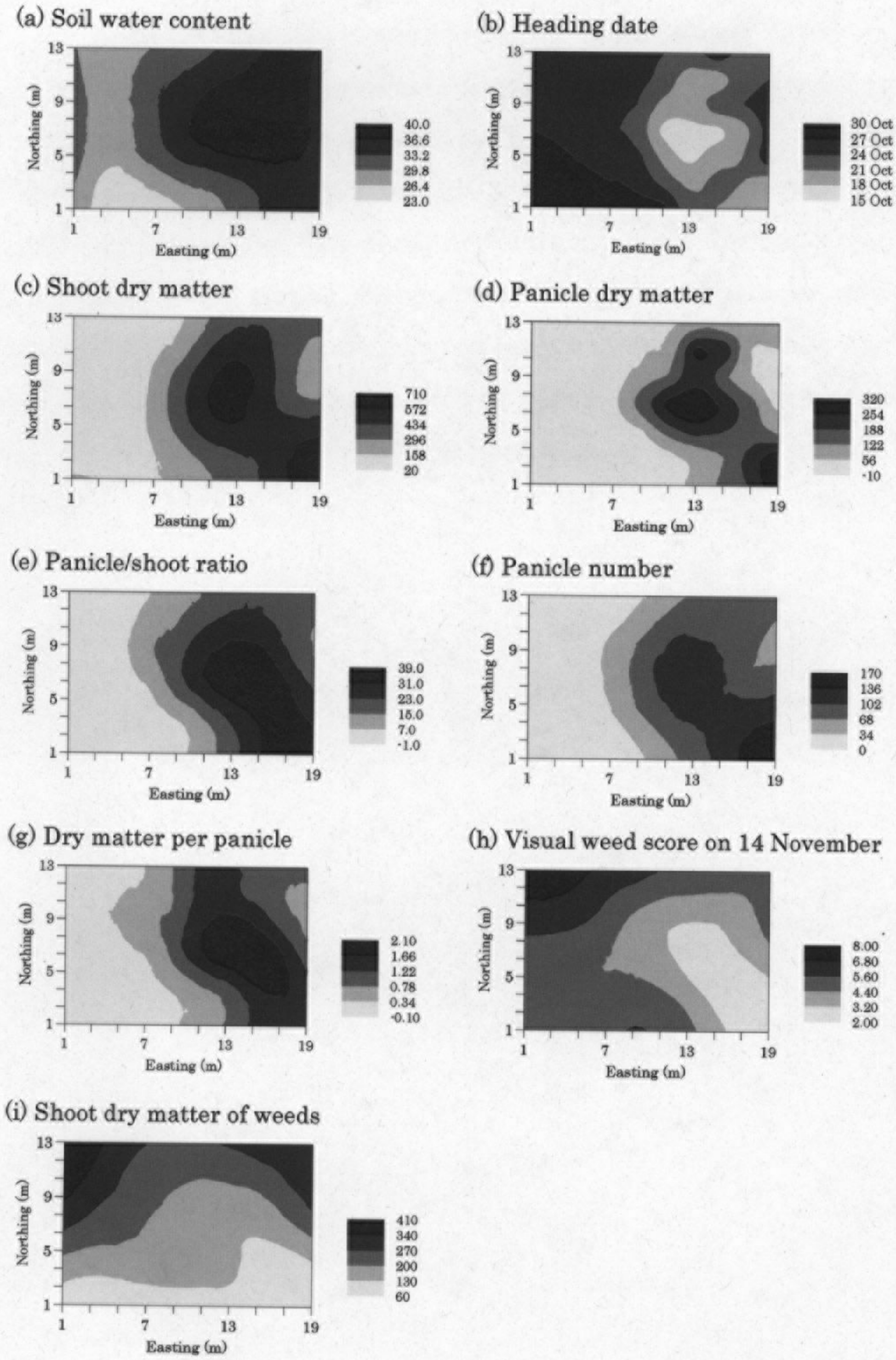

Fig. 4.4. Spatial distribution of (a) mean soil water content of eight measurement dates (b) heading date, (c) shoot dry matter, (d) panicle dry matter per unit area, (e) panicle/shoot ratio in dry matter, (f) number of panicles, (g) dry matter per panicle, (h) visual weed score on 14 November (the date of rice maturity), and (i) shoot dry matter of weeds in BC2 (broadcast-sowing) in 2005 based on block kriging.

3.5. Cross-semivariogram

Table 4.6 presents the cross-semivariogram parameters, fitted models, and regression coefficients between soil water content, rice growth, and weed growth in BC plots in 2005. Significant negative cross-correlations were observed between soil water content and heading date in BC1 and BC2. Soil water content was positively and significantly cross-correlated with shoot dry matter, panicle dry matter per unit area, panicle/shoot ratio in dry matter (except for BC3), number of panicles, and dry matter per panicle (except in BC3). The visual weed score was negatively cross-correlated with soil water content and with all rice growth parameters, and the correlations were significant for all parameters except the panicle/shoot ratio and panicle dry matter (both in BC3).

Table 4.6. Range, Q value, model with the best fit, and regression coefficient for the cross-semivariograms for mean soil water content (SWC), rice growth parameters, and weed growth parameters (including the visual weed score, VWC) in the three broadcast-sowing (BC) treatments in 2005.

	SWC[1]-Heading date	SWC-Shoot dry matter	SWC-Panicle dry matter (g m^{-2})	SWC-Panicle/shoot ratio	SWC-Panicle number	SWC-Panicle dry matter (panicle^{-1})	SWC-VWS[6]	Shoot dry matter-VWS	Panicle dry matter (g m^{-2})-VWS	Panicle/shoot ratio-VWS	Panicle number-VWS	Panicle dry matter (panicle^{-1})-VWS
BC1												
Range (m)	5.7	7.2	6.8	7.6	6.9	7.0	7.2	8.2	6.6	7.1	6.7	8.6
Q value	**1.00**	1.00	1.00	1.00	1.00	1.00	**0.95**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Model	Gau[3]	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau
R^2	0.967	0.843	0.809	0.863	0.830	0.809	0.849	0.942	0.820	0.872	0.790	0.965
BC2												
Range (m)	7.5	10.0	>10[5]	>10	>10	>10	>10	>10	9.3	9.1	>10	8.8
Q value	**1.00**	1.00	1.00	0.95	1.00	0.96	**0.94**	**0.85**	**0.79**	**0.84**	**0.86**	**0.73**
Model	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau	Gau
R^2	0.905	0.965	0.977	0.986	0.980	0.985	0.985	0.715	0.747	0.962	0.813	0.906
BC3												
Range (m)	4.3	5.1	5.5	4.9	5.1	4.3	5.0	7.1	5.9	5.5	4.6	5.8
Q value	**0.97**	1.00	0.90	0.93	0.82	1.00	**1.00**	**0.99**	**0.74**	**0.93**	**0.91**	**0.76**
Model	Sph[3]	Sph	Sph	Sph	Sph	Gau	Gau	Exp[3]	Gau	Sph	Gau	Sph
R^2	*0.170*[4]	0.887	0.786	*0.545*	0.799	*0.637*	0.980	0.863	0.962	*0.645*	0.943	*0.589*

[1]Mean of eight measurements from 15 June to 19 October.
[2]**Bold values** indicate negative cross-correlations.
[3]Exp, Gau, and Sph indicate exponential, Gaussian, and spherical models, respectively
[4]*Italicized correlation values* indicate non-significant regression coefficients ($P \geq 0.05$); all other regression coefficients are significant ($P < 0.05$).
[5]Calculated range was longer than 10 m (active lag distance).
[6]Measured on 14 November (the date of rice maturity).

4. Discussion

Compared with the yield of direct seeded rainfed lowland rice in Northeast Thailand (137 g m^{-2}; OAE, 1994), mean panicle dry matter in BC fields was generally low (around 52 g m^{-2}), with a high degree of variation (ranging from 0 to 414 g m^{-2}, with a CV ranging from 139% to 230%). The low BC yield should be owing to the lower soil water content during later growth stages and relatively severe weed infestation. The principal components analysis (PCA) using plant number on 27 June, soil water content on 13 July (early season), 2 September (mid season) and 19 October (late season) and visual weed score on 13 July (early season), 30 August (mid season) and 14 November (late season), and the multiple regression analysis conducted after PCA indicated that 46% of the variation in panicle dry matter was explained by the variation in plant number, soil water content and visual weed score. The variation which could not be explained by PCA could be the variation caused by soil property. Although within-field variation in soil property was not measured in this study, Yanai et al. (2001) reported that variation in soil chemical factors explained 43% of the spatial variability in rice yield in transplanted field in Japan. Therefore, the variation in soil water content, weed infestation and plant number and their relationships between rice growth are discussed in this section.

4.1. Variations in soil water content

In this study, soil water content was higher and the flooded area was larger from June to September, and both parameters declined sharply in October due to lower rainfall and a consequent loss of standing water. Within-field variation in soil water content was relatively small while soil water content remained high (June to September), but increased in October after standing water disappeared. Significant correlations between different measurement dates (except for the measurements in June in RS and October in BC3 and RS; data not shown) and maps of soil water content on every measurement date based on block kriging indicated a generally similar distribution of soil water content from June to October. Large variations in panicle dry matter were associated with variations in mean soil water content (based on eight measurement dates) judging from the results of correlation and cross-semivariogram analysis. Panicle dry matter, shoot dry matter, the panicle/shoot ratio in dry matter (except for BC3), the number of panicles, and dry matter per panicle (except for BC3) were all cross-correlated with soil water content.

Flooded and non-flooded areas existed simultaneously during rice growth (except on 19 October). Soil water content was higher in flooded areas than in non-flooded areas, and grid cells with standing water on 16 September maintained significantly higher soil water content than grid cells without standing water until October (data not shown). The distribution of flooded areas matched the distribution of slopes and undulations within the field. Site preparation by means of careful harrowing and levelling should thus reduce the uneven distribution of standing water (Lantican et al., 1999; Rickman et al., 2001). Rotary tilling could also help level the land (Kabaki et al., 2003).

4.2. Variations in the degree of weed infestation

The mean visual weed score in the BC plots increased from 2.7 in July to 5.0 in November (rice maturity). On every measurement date in 2005, the visual weed score had a high degree of variation (from 0, representing no weeds, to 7 or 8, representing weeds that were taller than the rice plants). The visual weed score at rice maturity (14 November) was negatively correlated with soil water content and with rice shoot dry matter, panicle dry matter, and number of panicles. This indicates that the effects of weed infestation were more severe in areas with low soil water content and that rice growth was lower in areas with more severe weed infestation. Hence, the variation in the degree of weed infestation could be at least partly reduced by site management to reduce the variations in soil water content, using the methods discussed in section 4.1.

Although the number of plants on 27 June was not spatially dependent, it was correlated with shoot dry matter and number of panicles. The number of plants in BC plots varied widely (from 4 to 604 m^{-2}) in this study. A density of 200 plants m^{-2} was required to produce higher grain yield in fields with manual weed control under drought conditions around the heading stage of KDML105 (Exp. 1 in Chapter 2). In BC plots in this study, however, mean plant density was rather low (120 plants m^{-2}) due to unexpectedly heavy rainfall after sowing, and a plant density greater than 200 m^{-2} was achieved in only 22 grid cells out of 210 (10.5% of the total). In grid cells with a plant density greater than 200 m^{-2}, higher levels of shoot dry matter (461 vs. 217 g m^{-2}), panicle dry matter (106 vs. 49 g m^{-2}), and panicle number (114 vs. 48 m^{-2}) were achieved compared with cells having a lower plant density, on average, and the visual weed score on 13 July (1.7 vs. 2.8) was lower than in grid cells with a plant density of 200 m^{-2} or less. Increasing the seeding rate should increase the proportion of the area with a plant density greater than 200 m^{-2} and should thus improve panicle dry matter per unit area. An appropriately higher seeding rate should be combined with site management designed to reduce the spatial variability in soil water content and the degree of weed infestation, because a larger number of panicles or a higher panicle dry matter content was not achieved even in grid cells with a high plant density when soil water content was low or weed infestation was severe in this study.

In the BC approach, mechanised weed control is difficult because of the random distribution of the rice plants (within-field variation in plant number was also larger in BC compared with RS in both years). Adoption of the RS approach combined with inter-row weeding should effectively reduce the spatial variability in rice growth by reducing the spatial variability in plant number and weed infestation. The visual weed score in RS after inter-row weeding was significantly lower than that in BC in both years. Both in 2004 and 2005, higher shoot and panicle dry matter and more panicles were achieved in RS compared with BC (although the difference in panicle dry matter in 2005 was not significant), and the within-field variation in rice growth was smaller. The greater number of plants in RS in 2005 may result from better manual covering of the seeds than using the two-wheeled hand tractor to cover seeds in the BC plots. In this study, sowing and weeding were conducted manually, but manual sowing is time-consuming, hence the development of economical machines with affordable price for farmers should be indispensable. The combination of RS with inter-row tillage to control weeds was also recommended by Kabaki et al. (2003).

5. Conclusion

Large within-field variation in the BC plots was observed in the number of plants, heading date, shoot dry matter, panicle dry matter, number of panicles, and visual weed score. Except for the number of plants, these properties were spatially dependent. Within-field variation in soil water content was not large, especially when soil water content was high (from June to September), but soil water content was also spatially dependent. The within-field distribution of standing water and the higher soil water content in flooded grid cells than in non-flooded cells indicated that one cause of the spatial variability in soil water content was topography (slopes and undulations within a field). Multiple-regression analysis and analysis of cross-semivariograms revealed the positive effects of high soil water content and a large number of plants, and the negative effects of a high visual weed score, on the shoot dry matter, panicle dry matter, and number of panicles of rice. These results suggested that careful site preparation to produce a more uniform soil surface and reduce the uneven distribution of standing water, combined with a higher sowing rate and effective weed management, should reduce the spatial variability in rice growth in the BC treatment. Compared with the BC plots, within-field variation in rice growth was smaller in the RS plot due to the larger number of plants (only in 2005) with smaller variation and the effective weeding. RS combined with inter-row weeding should thus effectively reduce the within-field variation in rice growth.

Summary: Large within-field variation in rice growth is often a problem in broadcast-sown (BC) rainfed lowland rice. In this chapter, field experiment was conducted in 2004 and 2005 to evaluate the spatial relationships between the variations in soil water content, rice growth (cv. KDML105), and weed infestation, by using geostatistics (semivariogram) in three BC plots (only in 2005), and to compare the within-field variation in BC rice growth with a row-sown (RS; inter-row spacing of 30 cm) rice. BC plots were not weeded, but inter-row weeding was conducted in the RS plots for both years. Size of each plot was 14 by 20 m in both years, and data was collected from the centre of 70 grid cells (2 m × 2 m) in 3 BC plots in 2005 or 9 grid cells (4.7 m × 6.7 m) in BC and RS plots in 2004 and RS plot in 2005. In BC plots, large within-field variation was observed in number of emerged rice plants (seedling number), heading date, shoot and panicle dry matter, panicle to shoot ratio in dry matter, number of panicles, and dry matter per panicle, as well as in weed infestation in both years. In the semivariogram analysis in 2005, these properties except for seedling number were spatially dependent (i.e., data from nearby locations were most similar). Within-field variation in soil water content, which was also spatially dependent, was relatively small, with a coefficient of variation (CV) of 8% to 14%, when soil water content was high (June to September), but the CV became larger (28% to 64%) as plots dried in October. Flooded and non-flooded cells existed simultaneously in

the plots (except for 19 October). Analysis of correlations and cross-semivariograms in the BC plots revealed a positive correlation between soil water content and shoot and panicle dry matter, the panicle to shoot ratio in dry matter, panicle number, and dry matter per panicle. Weed infestation at rice maturity was negatively correlated with soil water content and rice growth. Within-field variation in rice growth in RS was smaller than that in BC in both years due to the larger seedling number (only in 2005) and its smaller variation, as well as the reduced weed infestation. These results suggested that reducing the spatial variability in rice growth requires careful land preparation to level the soil surface and to reduce the uneven distribution of standing water and the variability in soil water content, combined with effective weed management. RS with inter-row weeding should be an effective management to reduce the within-field variation through smaller variation in seedling number and less weed infestation compared with BC. This is the first report that examined spatial variability in the growth of direct-sown rice as a function of soil water content and weed infestation in a rainfed lowland environment.