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High-yielding Crop Management by Enhancing Growth in Reproductive Stage of Direct-Seeded Rainfed Lowland Rice (*Oryza sativa* L.) in Northeast Thailand

Satoshi Hayashi[1, 2], Akihiko Kamoshita[3], Junko Yamagishi[2], Anuchart Kotchasatit[4] and Boonrat Jongdee[4]

([1]National Agricultural Research Center for Hokkaido Region, 1, Hitsujigaoka, Sapporo, Hokkaido 062-8555, Japan;
[2]Field Production Science Center, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1, Midoricho, Nishitokyo, Tokyo 188-0002, Japan;
[3]Asian Natural Environmental Science Center, The University of Tokyo, 1-1-1, Midoricho, Nishitokyo, Tokyo 188-0002, Japan;
[4]Ubon Ratchathani Rice Research Center, P.O. Box 65, Ubon Ratchathani, 34000, Thailand)

Abstract: The crop management in direct-seeded rice to promote growth during the reproductive stage was evaluated in weed-controlled toposequentially intermediate fields in a small watershed in Northeast Thailand. In 2004, the effectiveness of topdressing with 21 kg ha^{-1} of nitrogen at the panicle initiation stage were examined using two genotypes, KDML105 and IR57514-PMI-5-B-1-2 (IR57514) seeded at the rates of 500, 250 and 125 seeds m^{-2}. In 2005 and 2006, the effectiveness of a new management (seeding rate of 125 seeds m^{-2} and nitrogen application of 90-101 kg ha^{-1}; CM2) was compared with that of conventional management (seeding rate of 500 seeds m^{-2} and nitrogen application of 50 kg ha^{-1}; CM1) using 3 genotypes (KDML105, IR57514 and HY71) seeded in May and June. In 2004, the number of spikelets on the tertiary pedicel at a low seeding rate in KDML105 was greatly increased by topdressing. In 2005 and 2006, CM2 had higher grain yield than CM1 (346 vs. 235 g m^{-2}), owing to its larger spikelet number per panicle, heavier shoot dry weight and greater nitrogen uptake. May-seeding resulted in longer non-flooded period in the seedling to tillering stage, lower SPAD reading value around heading and less shoot dry weight increase from heading to maturity, and had lower grain yield than June-seeding (253 vs. 328 g m^{-2}). This reduction in grain yield was larger for late-heading KDML105 than in early heading IR57514. These results indicated the effectiveness of the new crop management (CM2) for direct-seeded rice in toposequentially intermediate fields with less weed infestation or weed-controlled conditions.

Key words: Biomass production, Growth duration, Nitrogen uptake, Reproductive stage.

Northeast Thailand has 5.27 million ha of rainfed lowland rice growing area, which is about 57% of the rice-growing area in the whole country (Office of Agricultural Economics [OAE], 2006). Average grain yield in this region is low (1.92 t ha^{-1}) (OAE, 2007), due to unstable water availability (Wade et al., 1999) and low soil fertility (Bell et al., 2001; Bell and Seng, 2004). Water availability of a field is greatly affected not only by seasonal rainfall patterns but also by its toposequential position in a small watershed (Oberthür and Kam, 2000; Homma et al., 2001; 2003; 2004; 2007; Tsubo et al., 2005; 2006; 2007a; 2007b; Haefele et al., 2006; Kamoshita et al., 2009). Generally, toposequentially lower fields are submergence-prone and upper fields are drought-prone. Fields with intermediate toposequential position between them (referred to as intermediate fields) are most common (172 fields out of 244 in a watershed, by Homma et al., 2007). Standing water starts appearing from July in intermediate fields (Tomita et al., 2003), with its timing delayed by several weeks to August (Hayashi, S., unpublished data). In general, these fields have less risk of extreme submergence or severe drought, compared with lower or upper fields,

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Abbreviations: CM, crop management; TD, topdressing.

and growing conditions in the intermediate fields can be favourable.

Farmers adjust amounts of applied fertilizers depending on characteristics of each field such as toposequential positions (Homma et al., 2007). Farmers do not apply fertilizer in the upper fields due to the high risk of late season drought. Fertilizer is also omitted in some of the lower fields since the soil is fertile and there is a considerable risk of lodging and submergence. In intermediate fields, fertilizer application is recommended but its rate is small in Northeast Thailand (45–50 kg N ha^{-1} for both transplanting and direct-seeding) (Naklang, 1997), and the actual rates applied by farmers tend to be lower (i.e. only 25–41 kg N ha^{-1}, by Lefroy and Konboon, 1998 and Homma et al., 2007). Considering the less risk to encounter severe drought or submergence and the advantage of favourable growing conditions in the intermediate fields, more intensive fertilizer use should potentially increase grain yield.

In Northeast Thailand, conventional transplanting has been rapidly replaced by dry-seed broadcasting (referred to as direct-seeding) with less labour-requirement, owing to the shortage of agricultural labour and increasing labour cost for transplanting (Naklang, 1997; Miyagawa et al., 1999; Watanabe et al., 1999; Pandey et al., 2002). The percentage of direct-seeding in Northeast Thailand increased from 4% in 1989 (Pandey et al., 2002) to 36% in 2005 (OAE, 2006). Grain yield in direct-seeding was lower than in transplanting under non-flooded and weedy conditions, but was equally high as transplanting under shallow flooded and weed-controlled conditions (Ikeda et al., 2008). It would be necessary to classify the target environment by water availability (i.e. toposequential position) and intensity of weeds, when providing recommended crop management for direct-seeding.

Seeding rate is often high in direct-seeding in Northeast Thailand (i.e., recommended seeding rate in Ubon Ratchathani province is 90–125 kg ha^{-1} (Konboon, Y., personal communication)). Although high seeding rate is effective to suppress weeds in weedy fields (Naklang, 1997; Romyen et al., 2002; Phuong et al., 2005), consequently, the quick and dense canopy coverage could consume soil and fertilizer nitrogen quickly and lead direct-seeded rice to a nitrogen deficit in the reproductive stage (Dingkuhn et al., 1991; 1992a; 1992b). If current crop management is altered so as to continue to supply enough nitrogen from soil or fertilizers until reproductive stage, direct-seeding in the toposequentially intermediate fields should be able to achieve higher grain yield.

Another factor which could limit grain yield of direct-seeded rice in the toposequentially intermediate fields is early seeding in current crop management. May-seeding is commonly practiced in direct-seeding in the lower and intermediate fields in Ubon Ratchathani province in Northeast Thailand (Hayashi, S., unpublished data). This current practice, although suitable for the lower fields where standing water appears earlier, sometimes causes rice plants to encounter with a long non-flooded period in early growth stage in the intermediate fields, resulting in stagnated early plant growth, which may suppress yield formation.

In this study, it was hypothesized that the combination of lower seeding rate, more intensive fertilizer application and later seeding should maintain better plant nitrogen status in reproductive stage and result in higher grain yield of direct-seeded rice in toposeqentially intermediate fields. The objectives of this study were to evaluate the effectiveness of this new crop management, to propose the management for higher grain yield and to clarify the optimum growth dynamics in direct-seeding in intermediate fields.

Materials and Methods

1. Experimental design and crop management

Experiments were conducted from 2004 to 2006 at Ubon Ratchathani 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), available phosphorus (the Bray P2 method), and exchangeable potassium (the ammonium acetate method at pH 7.0) were 0.33 g kg^{-1}, 77.08 mg kg^{-1}, and 0.2 mmol kg^{-1}, respectively. Every year, dry-seed broadcasting method was used. Field was irrigated when there was no standing water in the field after seedling establishment stage. Weeds were controlled by hands. Three genotypes, KDML105, IR57514-PMI-5-B-1-2 (hereafter referred to as IR57514) and HY71 (except for in 2004) were used. KDML105 is an improved traditional cultivar with strong photoperiod sensitivity, and widely grown in Northeast Thailand (Jongdee, 2001). IR57514 is an early to intermediate maturing genotype with weak photoperiod sensitivity. HY71 is an intermediate maturing genotype with strong photoperiod sensitivity. These two genotypes were selected because they showed high grain yield in direct-seeding under favourable water conditions in a previous study (Hayashi et al., 2007). In every year, split-split plot design with 3 replicates was adopted. All sub-subplots were bunded.

In 2004, topdressing (with topdressing, +TD; and without topdressing, −TD) as main-plot, two genotypes, KDML105 and IR57514 as subplot and three seeding rates (high, middle and low seeding rates were 500, 250 and 125 seeds m^{-2}, respectively; or approximately 125, 62.5 and 31.3 kg ha^{-1}) as sub-subplot were examined. Seeds were sown on 18 June, and 185 kg ha^{-1} of compound fertilizer ($N:P_2O_5:K_2O$=16:16:8%, henceforth) was applied on 23

Table 1. Fertilizer application rate and date across crop management (CM), seeding month and rice genotype in 2005 and 2006.

	$N:P_2O_5:K_2O$ (kg ha^{-1})	May-seeding			June-seeding		
		KDML105	IR57514	HY71	KDML105	IR57514	HY71
2005							
CM1	30:30:15	15 Jun	15 Jun	15 Jun	6 Jul	6 Jul	6 Jul
	21:0:0	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
	21:0:0	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
	21:0:0	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
	21:0:0	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 30.0).

July in all the plots. In +TD plots, 45 kg ha^{-1} of urea (N=46%) was topdressed at the panicle initiation stage (21 September for KDML105 and 2 September for IR57514). Each sub-subplot was 4 m×4 m.

In 2005 and 2006, two crop managements, CM1 (the combination of higher seeding rate and less fertilizer application) and CM2 (the combination of lower seeding rate and more fertilizer application) as main-plot, two seeding times, May and June as subplots and three genotypes, KDML105, IR57514 and HY71 as sub-subplot were examined. Seeding rate in CM1 and CM2 was 500 and 125 seeds m^{-2}, respectively. Fertilizer application rates were 185 kg ha^{-1} of compound fertilizer for both CM1 and CM2 around 30 days after seeding, 45 kg ha^{-1} (cf. additional 22.5 kg ha^{-1} was applied to amount to 67.5 kg ha^{-1} in total when SPAD reading value of the uppermost fully expanded leaf got lower than 30.0) of urea for CM2 at tillering stage, 45 kg ha^{-1} of urea for CM1 or 185 kg ha^{-1} of compound fertilizer for CM2 at panicle initiation stage and 22.5 kg ha^{-1} of urea for CM2 at heading stage (Table 1). Seeding rate and fertilizer application rate in CM1 was determined from the recommended seeding rate in Ubon Ratchathani province and the recommended fertilizer application for direct-seeding by Naklang (1997). Seeding date in 2005 was 10 May for May-seeding and 9 June for June-seeding. In 2006, seeding date for May-seeding was 18 May and that for June-seeding was 16 June. Each sub-subplot was 4 m×4.5 m.

2. 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 29.9ºC, and it was generally high in May and decreased to November. In 2005, soil moisture potential was measured at a depth of 20 cm by tensionmeters (Watermark, GI-Supply, Hokkaido, Japan), using the data logger (WatchDog 400 Data Logger, Spectrum Technologies Inc., Illinois, U.S.A.).

Plant number in 0.5 m^2 was measured at the establishment stage (on 29 July in 2004, on 13 June for May-seeding and on 13 July for June-seeding in 2005 and 15 June for May-seeding and 14 July for June-seeding in 2006) (hereafter referred to as seedling number). SPAD (SPAD-502, Minolta Co., Japan) reading value, an index of plant nitrogen status (Chubachi et al., 1986; Peng et al., 1996; 2002), of the centre of the uppermost fully expanded leaf was measured from 19 August to 3 October in 2005 and from 2 August to 26 October in 2006 at about 2-wk intervals. Heading date was recorded every year. Shoot dry weight at panicle initiation, heading and maturity, grain yield and yield components were determined from samples (including dead leaves and stems, but dropped leaves and stems were not included) from 0.5 m^2 in 2004 and 2005 and from 1 m^2 in 2006. Dry weight was measured after drying at 80ºC in an oven for 3 d. Nitrogen uptake at maturity was measured with a N-C analyzer (Sumigraph NC-90A, Sumika Chemical Analysis Service Ltd., Japan).

In 2004, length of all the panicles in the samples taken

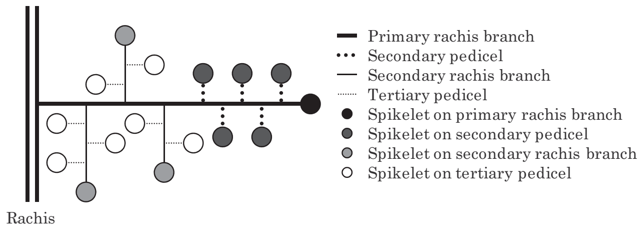

Fig. 1. Classification of rachis branches, pedicels and spikelets in one panicle of rice. (Matsuba, 1991)

at heading was measured and mean panicle length was determined. Fifteen panicles which had moderate panicle length (mean panicle length ± 1.0 cm) were sampled to investigate panicle structure. Spikelets on sampled panicles were classified into spikelets on primary rachis branches, secondary pedicels, secondary rachis branches and tertiary pedicels (Fig. 1), according to the method of Matsuba (1991).

3. Statistical analysis

Analysis of variance (ANOVA) was conducted by the method of Gomez and Gomez (1984). Phenotypic observation within a year was modelled with split-split plot design to assess the effects of topdressing, genotypic difference, seeding rate, crop management and seeding time, and their interactions. For the results in 2005 and 2006, combined analysis over years was also conducted.

Results

Fig. 2 shows the rainfall pattern, period with standing water and growth period of KDML105 (May-seeding for 2005 and 2006). There was standing water from late or mid July in 2004 and 2006, respectively, but standing water was absent until 17 August in 2005. In 2005, soil water potential measured at a depth of 20 cm fluctuated from −42 to −1 kPa until 23 July, and thereafter 0. Standing water was maintained until the grain-filling stage of KDML105 (the latest genotype used in this study) in 2004 to 2006.

1. Experiment in 2004

Heading date of KDML105 and IR57514 ranged from 21 to 26 October and from 3 to 12 October, respectively, with the tendency of earlier heading at a lower seeding rate. Grain yield increased with the increase in spikelet number per area (R^2=0.826, significant at P=0.01). Although spikelet number per area in +TD tended to be larger than in −TD, there was a relatively small difference in grain yield between them (Fig. 3), due to the lower percentage of ripened grains (79 vs. 84%) and grain weight (28.8 vs. 29.6 g per 1000 grains). Grain yield of IR57514 was lower than that of KDML105, owing to the damage by blast, which occurred soon after the topdressing at panicle initiation in IR57514. Owing to the

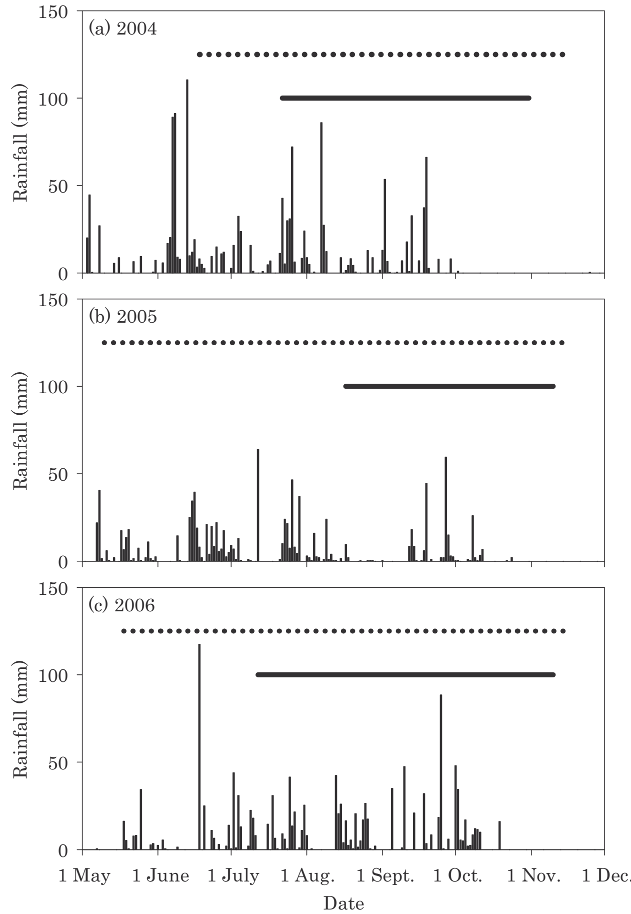

Fig. 2. Rainfall patterns from May to November in 2004 (a), 2005 (b) and 2006 (c) in Ubon Ratchathani, Thailand. Horizontal solid and dotted bars indicate the period with standing water in the field and the growth duration of a rice genotype KDML105 [May-seeding for (b) and (c)], respectively.

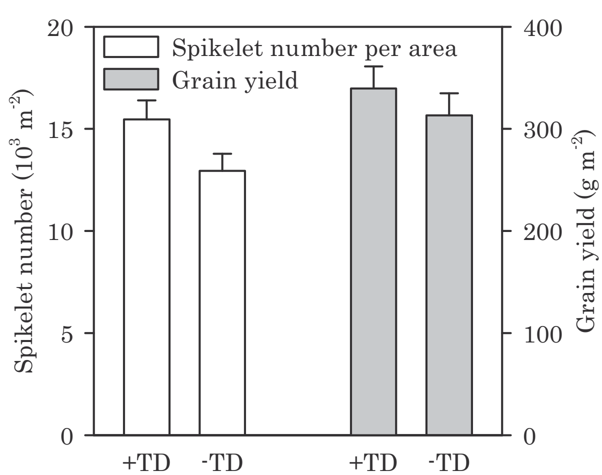

Fig. 3. Spikelet number per area and grain yield of a rice genotype KDML105 across topdressing treatment (TD) in 2004. Seeding rate was averaged since there was no significant difference. Data of IR57514 was omitted because of the damage by blast. Vertical bars indicate standard errors.

trade-off relationship between panicle number and spikelet number per panicle among seeding rates, neither of them were closely correlated with spikelet number per area, but the latter had a relatively closer correlation (R^2=0.172) than the former (R^2=0.013).

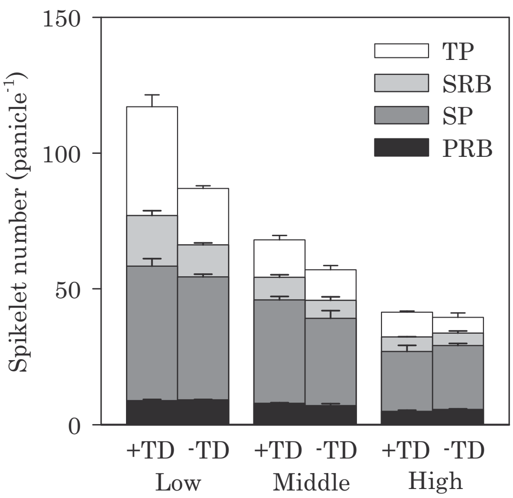

Fig. 4. Spikelet number on primary rachis branch (PRB), secondary pedicel (SP), secondary rachis branch (SRB) and tertiary pedicel (TP) of a rice genotype KDML105 across topdressing (TD) and seeding rate [125 (low), 250 (middle) and 500 (high) seeds m^{-2}] in 2004. Data of IR57514 was omitted because of the damage by blast. Vertical bars indicate standard errors.

Topdressing significantly increased spikelet number per panicle by increasing the number of spikelets on the secondary rachis branches and tertiary pedicels (Fig. 4). KDML105 had more spikelets on all the rachis branches and pedicels than IR57514. Genotype by seeding rate interaction was significant at all the positions of spikelet, and the effect of seeding rate was larger in KDML105 than in IR57514. TD increased the spikelet number on tertiary pedicel especially at the low seeding rate in KDML105. The total spikelet number per panicle at the low seeding rate in KDML105 was increased the most by TD (total spikelet number per panicle was increased approximately 30).

Nitrogen uptake at maturity tended to be higher in +TD (5.22 g m^{-2} on the average of genotypes and seeding rates) than in –TD (4.03 g m^{-2}). Nitrogen uptake did not differ between genotypes or among seeding rates.

2. Experiment in 2005 and 2006

Shoot dry weight at the panicle initiation stage in CM2 did not differ from that in CM1, but that at heading and maturity was heavier than in CM1 (Fig. 5). Although there was little difference in shoot dry weight at panicle initiation

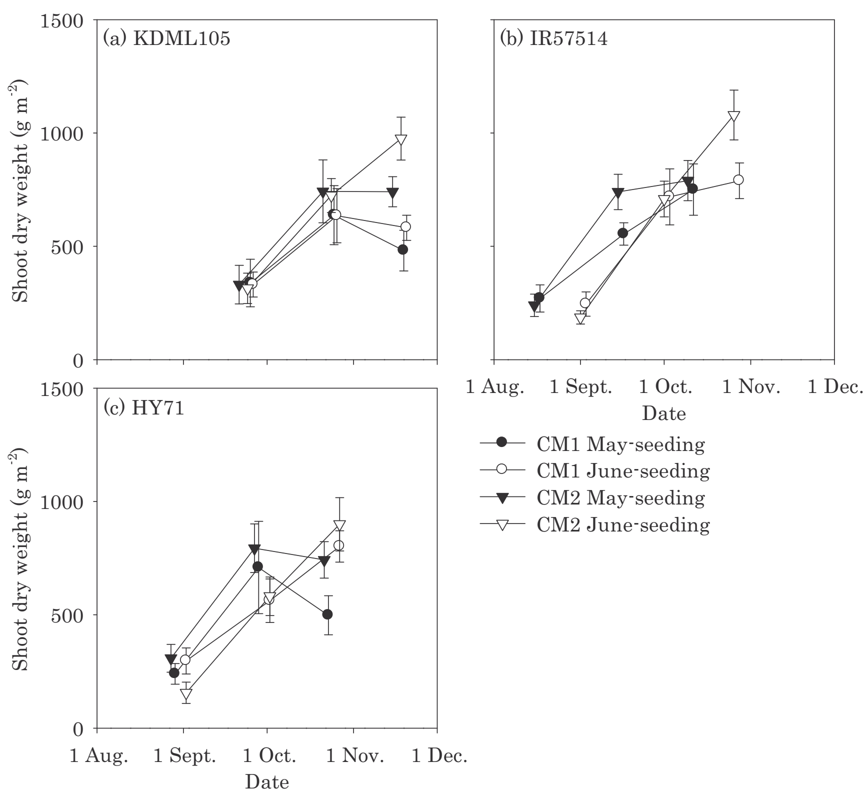

Fig. 5. Time course of shoot dry weight from panicle initiation stage to maturity stage across crop management (CM) and seeding month in rice genotypes KDML105 (a), IR57514 (b) and HY71 (c). The results in 2005 and 2006 were averaged. Vertical bars indicate standard errors.

Table 2. Heading date, grain yield and yield components of rice across crop management (CM), seeding month (SM) and genotype (G).

Crop management	Seeding month	Genotype	Heading date	Grain yield (g m^{-2})	Panicle number (m^{-2})	Spikelet number ($panicle^{-1}$)	Spikelet number (m^{-2})
2005							
CM1	May	KDML105	26 Oct	143	197	35	6927
		IR57514	25 Sep	210	324	32	10299
		HY71	29 Sep	167	263	32	8318
	June	KDML105	26 Oct	227	333	36	11960
		IR57514	4 Oct	276	420	31	12917
		HY71	2 Oct	332	400	43	17046
CM2	May	KDML105	21 Oct	307	165	85	14016
		IR57514	23 Sep	285	188	65	12230
		HY71	27 Sep	304	208	64	13312
	June	KDML105	23 Oct	419	231	87	20179
		IR57514	30 Sep	426	345	56	19407
		HY71	2 Oct	312	240	61	14717
2006							
CM1	May	KDML105	24 Oct	178	229	47	10822
		IR57514	8 Sep	358	305	49	14900
		HY71	27 Sep	172	179	61	10840
	June	KDML105	26 Oct	231	239	47	11327
		IR57514	2 Oct	248	293	48	14009
		HY71	2 Oct	273	276	54	14927
CM2	May	KDML105	21 Oct	256	141	86	12037
		IR57514	6 Sep	418	184	89	16333
		HY71	26 Sep	234	145	98	14161
	June	KDML105	25 Oct	372	180	102	18304
		IR57514	2 Oct	407	233	81	18938
		HY71	2 Oct	410	201	102	20526
Average (main effect)							
Crop management		CM1	9 Oct	226	323	35	11244
		CM2	6 Oct	342	230	70	15644
Seeding month		May	5 Oct	236	224	52	10850
		June	9 Oct	332	328	52	16038
Genotype		KDML105	24 Oct	274	232	61	13271
		IR57514	28 Sep	299	319	46	13713
		HY71	30 Sep	279	278	50	13348
$LSD_{0.05}$							
Year (Y)			ns	ns	29	14	ns
Crop management (CM)			2	82	28	10	2867
Seeding month (SM)			1	39	31	ns	1788
Y×SM			2	ns	43	ns	ns
Genotype (G)			1	32	33	8	1469
Y×G			2	ns	ns	ns	ns
SM×G			2	46	ns	ns	ns
Y×SM×G			3	64	ns	ns	ns
CM×SM×G			ns	ns	ns	ns	ns

$LSD_{0.05}$ indicates LSD at P = 0.05, and ns indicates no significant difference at P = 0.05.
Y× CM, CM × SM,Y × CM × SM, CM × G, Y × CM × G, CM × SM × G and Y× CM × SM × G was not significant at any measurement.

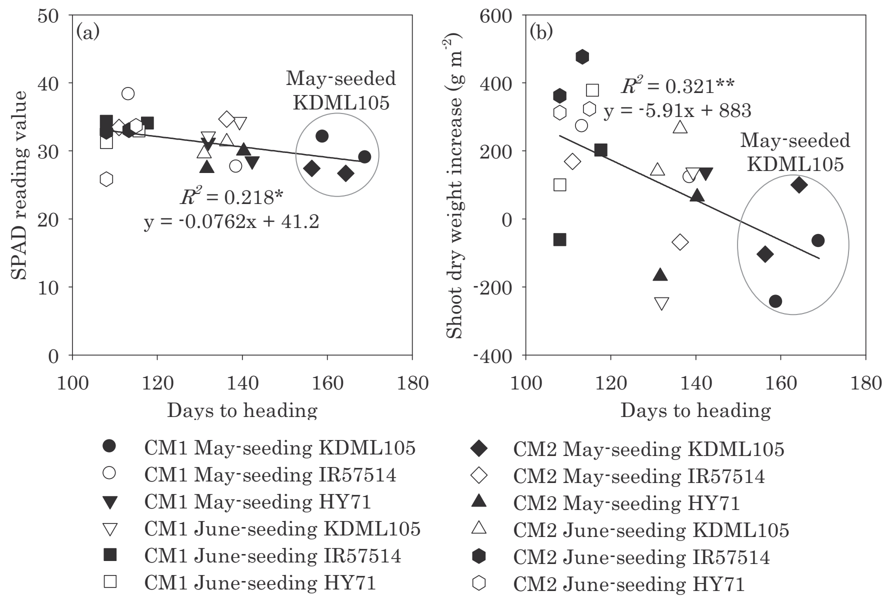

Fig. 6. Relationship between days to heading and SPAD reading value (on the nearest measurement date to heading) (a) and shoot dry weight increase from heading to maturity (b) of rice in 2005 and 2006. Data of CM1 May-seeding HY71 in 2006 was omitted from (b) because of the outlying shoot dry weight increase due to rodent damage. Linear regression was drawn and ** and * indicate significant regression at P=0.01 and 0.05 level, respectively. CM indicates crop management.

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

	Panicle number	Spikelet number per panicle	Spikelet number per area	Percentage of ripened grains	Grain weight
Grain yield	0.052	0.521**	0.903**	0.153	0.267
Panicle number		–0.725**	0.067	–0.025	0.120
Spikelet number per panicle			0.582**	–0.108	–0.067
Spikelet number per area				–0.186	0.059
Percentage of ripened grains					–0.108

** indicate significant correlation at 1% level. No correlation was significant at 5% level.

and heading stages between May- and June-seeding, June-seeding produced more biomass after heading and achieved heavier shoot dry weight at maturity than May-seeding. Consequently, the combination of CM2 and June-seeding achieved heavier shoot dry weight than other combinations in all the genotypes (average of two yr). Shoot dry weight was higher in KDML105 than in other genotypes at panicle initiation, but heavier in IR57514 than in either KDML105 or HY71 at maturity. Although shoot dry weight of KDML105 and HY71 decreased or was stable from heading to maturity in May-seeding, that of IR57514 increased, especially in CM2.

Panicle number in CM2 was smaller than in CM1, reflecting its smaller seedling number (126 vs. 441 m^{-2}), but its grain yield was higher than in CM1, owing to heavier shoot dry weight and larger spikelet number per panicle (Table 2). Although there was no significant difference in seedling number between May- and June-seeding (292 vs. 276 m^{-2}, average of two crop managements and three genotypes), stem number decreased during vegetative growth stage in May-seeding and resulted in smaller panicle number and lower grain yield than in June-seeding. On the average of three genotypes, June-seeded CM2 achieved the highest grain yield in both years. May-seeded IR57514 had higher grain yield than KDML105 and HY71 seeded in May because of its larger panicle number, especially in 2006. In other growing conditions, however, grain yield of IR57514 was similar to that of other genotypes, showing significant year by genotype, seeding month by genotype and year by seeding month by genotype interactions.

Longer days to heading resulted in lower SPAD reading value around heading (Fig. 6). Increase in shoot dry weight from heading to maturity also decreased with

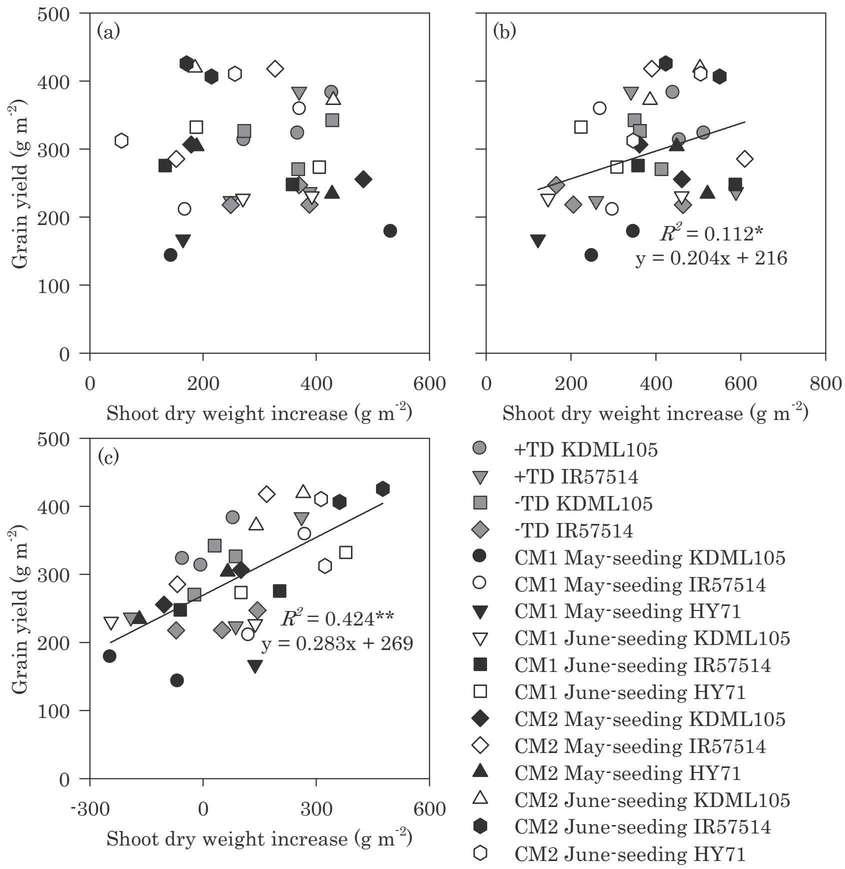

Fig. 7. Relationship between shoot dry weight increase from seeding to panicle initiation (a), from panicle initiation to heading (b) and from heading to maturity (c) and grain yield of rice across 3 yr. Data of CM1 May-seeding HY71 in 2006 was omitted because of the outlying shoot dry weight increase due to rodent damage. Linear regression was drawn and ** and * indicate significant regression at P=0.01 and 0.05 level, respectively. TD and CM indicate topdressing and crop management, respectively.

longer days to heading. Nitrogen uptake at maturity in CM2 was higher than in CM1 (7.2 vs. 4.3 g m^{-2}), and June-seeding had more nitrogen uptake than May-seeding (6.5 vs. 5.0 g m^{-2}). Nitrogen uptake in IR57514 was higher than in KDML105 or HY71 (6.9 vs. 4.7 and 5.6 g m^{-2}).

3. Analysis across 3 years

Spikelet number per area was most clearly correlated with grain yield (Table 3). The effect of panicle number on spikelet number per area or grain yield was small, but spikelet number per panicle was significantly correlated with spikelet number per area and grain yield. The increase in shoot dry weight in later growth stage was more closely related with grain yield than that in earlier growth stage, and grain yield increased with the shoot dry matter production from heading to maturity (Fig. 7). More nitrogen uptake at maturity significantly increased shoot dry weight and grain yield (Fig. 8). Shoot dry weight at maturity, grain yield and nitrogen uptake at maturity was lower in May-seeding with the longer growth period (especially in KDML105) (Fig. 9).

Discussion

More nitrogen application at the reproductive stage was necessary to increase grain yield of direct-seeded rice in toposequentially intermediate rainfed lowlands. In 2004, spikelet number per area was closely correlated with grain yield, and spikelet number per panicle tended to influence spikelet number per area more strongly than panicle number. In addition, topdressing at panicle initiation stage (+TD) significantly increased the spikelet number per panicle, especially spikelets on tertiary pedicel in the low seeding rate of KDML105. In direct-seeding under irrigated or favourable rainfed conditions, spikelet or grain number per panicle limits grain yield (Dingkuhn et al., 1992a; Hayashi et al., 2007). These results suggested that management to increase spikelet number per panicle should result in higher grain yield, and the combination of low seeding rate and topdressing to increase spikelet number per panicle (i.e. CM2) might increase grain yield.

CM2 yielded higher than CM1, the conventionally recommended management with high seeding rate and

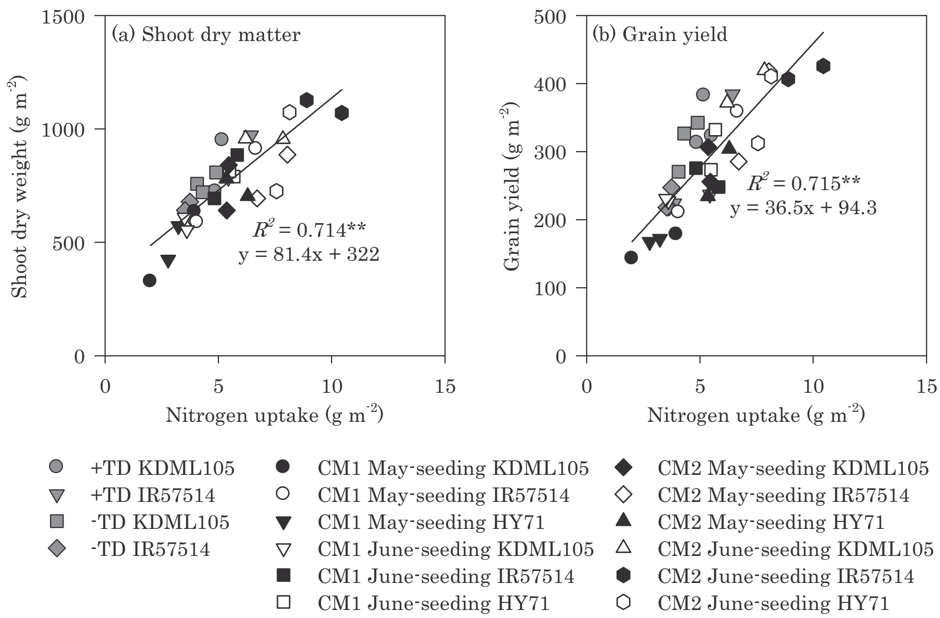

Fig. 8. Relationship between nitrogen uptake and shoot dry weight at maturity (a) and grain yield (b) of rice across 3 yr. Linear regression was drawn and ** indicates significant regression at P=0.01 level. TD and CM indicate topdressing and crop management, respectively.

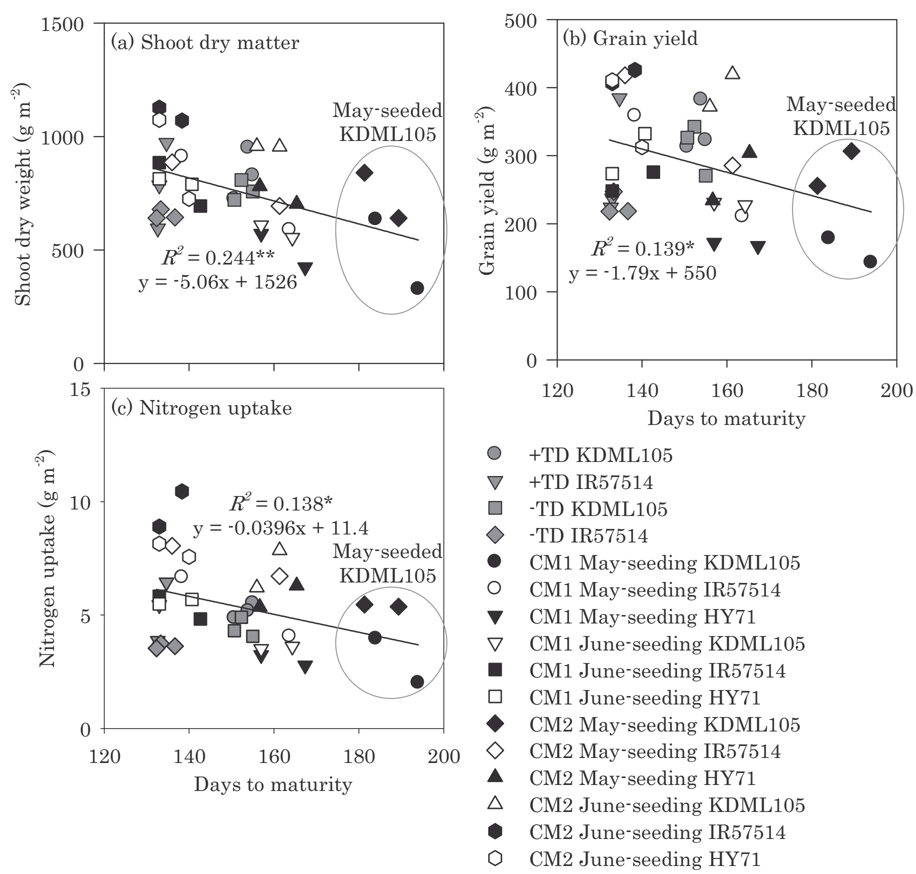

Fig. 9. Relationship between days from seeding to maturity and shoot dry weight at maturity (a), grain yield (b) and nitrogen uptake at maturity (c) of rice across 3 yr. Linear regression line was drawn for each relationship, and ** and * indicate significant regression at 1% and 5% level, respectively. TD and CM indicate topdressing and crop management, respectively.

low fertilizer application, through larger shoot dry weight and more nitrogen uptake. June-seeded KDML105 in CM2 achieved grain yield of 396 g m^{-2} on the average of 2 yr, which was higher than the average grain yield in toposequentially intermediate fields (273 g m^{-2}, mainly transplanting) reported in the study by Homma et al. (2007) in the same province, and which was comparable to the highest grain yield reported in transplanting in this region (Romyen et al., 1998; Ohnishi et al., 1999). This indicated that farmers can reduce the cost for transplanting labour and have as high grain yield by adopting CM2. In addition, the cost for seeds can be also reduced compared with conventionally recommended management when they buy new seeds (seeding rate in CM2 was about 31.3 kg ha^{-1}, which is only a quarter to one third of the recommended seeding rate in Ubon Ratchathani province, i.e., 90–125 kg ha^{-1} (Konboon, Y., personal communication)). Although a large amount of chemical fertilizer was used in CM2 than the recommended rate (45–50 kg N ha^{-1} (Naklang, 1997)) or actual rate in farmers' fields (on average 36 kg N ha^{-1} (Pandey et al., 2002)), the first application of chemical fertilizer (on about 30 d after seeding) can be replaced or its amount can be reduced by the application of manure from their own farmyard or by the use of green manure (e.g., *Sesbania rostrata, Stylosanthes guianensis*, Herrera et al., 1997; Homma et al., 2008) to reduce the cost for chemical fertilizer.

Grain yield decreased with the increase in the period from seeding to maturity, especially in May-seeding in 2005 and 2006 (Fig. 9), owing to the decrease in shoot dry weight from heading to maturity. May-seeding had lower grain yield than June-seeding especially in CM1, except for IR57514 in 2006. The lower grain yield in May-seeding was due to poor nitrogen status such as lower SPAD reading values around heading and less nitrogen uptake at maturity. This negative effect of early seeding was alleviated by the adoption of CM2 (which had higher grain yield than CM1 in May-seeding as well). One possible reason of the low grain yield in May-seeded CM1 was nitrogen loss by leaching or denitrification derived from long non-flooded period and alternate dry and wet conditions in seedling to tillering stage (cf. the field was flooded since July (2004 and 2006) or mid August (2005) until grain-filling stage of KDML105), as suggested by previous studies (Fukai et al., 1999; Bell et al., 2001; Bell and Seng, 2004). These results indicated that May-seeding, which is commonly practiced in Ubon Ratchathani province (Hayashi, S., unpublished data), should be practiced with caution in lower fields with earlier flooding (i.e. since June), and better be avoided in toposequentially intermediate fields which start accumulating standing water later from July or August, unless there is a strong prospect for sufficient rainfall in early growing period in the coming season.

As shown in Table 1, the additional urea application of 22.5 kg ha^{-1} at the tillering stage in June-seeded CM2 was for KDML105 and IR57514 in 2005 and KDML105 in 2006, and in May-seeded CM2 only in 2006 not in 2005. The decision of this additional application, which was determined by the SPAD value of 30.0, seemed to have been affected by both nitrogen deficiency from soil (i.e. leaching or denitrification) and relatively vigorous growth of rice (which had required more amounts of nitrogen). For example, in June-seeded CM2, relatively vigorous vegetative growth of KDML105 and IR57514 in 2005 (shoot dry weight at panicle initiation stage was 186 and 171 g m^{-2}) and KDML105 in 2006 (430 g m^{-2} of shoot dry weight at panicle initiation stage) caused apparent SPAD reading values lower than 30.0. On the other hand, in May-seeded CM2 in 2005, suppressed leaf area development (due to longer non-flooded conditions) resulted in apparent SPAD values higher than 30.0. Even if the additional urea had been applied in May-seeding in 2005, it would have been lost as mentioned above and would not have improved rice growth much. The differences in application of the additional urea among treatments was unlikely to have affected our conclusion to recommend June-seeding; May-seeded HY71 had a lower grain yield than June-seeding not only in CM1 but also in CM2 in 2006, although additional urea was applied on 11 August in May-seeding but not in June-seeding.

Our study suggested that use of non- or weakly-photoperiod-sensitive cultivars such as IR57514, with their shorter growth duration, reduces the risk of nitrogen deficit in reproductive stage, in case farmers have to start seeding early in the beginning of rainy season (i.e. conventional May-seeding). May-seeded IR57514, particularly in 2006, had earlier maturity (136 to 138 d, compared with 181 to 194 d in KDML105), higher SPAD reading value (33.4 in CM1 and 38.3 in CM2) and higher grain yield (358 in CM1 and 418 g m^{-2} in CM2), than in KDML105 or HY71.

Conclusions

The combination of lower seeding rate and more topdressing (CM2) increased spikelet number per panicle and that per area, enhanced biomass production from heading to maturity, and resulted in higher grain yield than the conventional direct-seeding practice of higher seeding rate and less fertilizer application (CM1). Conventional early seeding in the beginning of the rainy season (e.g. May) was not recommended in toposequentially intermediate fields where standing water appeared from July or August, because of nitrogen deficit around the heading stage (low SPAD reading value) and consequently lower grain yield; this reduction was larger in KDML105, a photoperiod sensitive cultivar, than in IR57514, a weakly-photoperiod sensitive cultivar. The proposed new crop management (CM2) is effective for direct-seeding in intermediate fields.

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