Farmers’ Management Practices and Grain Yield of Rice in Response to Different Water Environments in Kamping Puoy Irrigation Rehabilitation Area in Northwest Cambodia

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Abstract: The farmers’ management practices and grain yield were examined in the consecutive 4 cropping seasons from wet season rice (WSR) in 2008 to dry season rice (DSR) in 2010 across upstream, midstream and downstream fields, along two secondary drainage canals (located either upstream or downstream side along the main canal) in the Kamping Puoy Irrigation Rehabilitation area (KPIR). In WSR, standing water depth was much deeper in downstream fields where medium and late maturing varieties were planted from May than in upstream fields where early and early medium maturing varieties were planted later (mostly in July and August). In DSR there was less difference in water conditions between upstream and downstream fields and variation in planting and harvesting time was small. As the area percentage of fields where DSR was introduced increased from 2008 (54%) to 2010 (100%), planting time in WSR was later (e.g. from May to July) with declining proportion of dry seeding method and mid-season tillage. Grain yield was low in DSR, particularly in 2010 (287 and 247 g m−2 in 2009 and 2010 on average, respectively), due to insufficient weed control and small amount of fertilizer, and the yield was lowest in fields which practiced DSR for the first time. Grain yield in WSR (286 and 291 g m−2 in 2008 and 2009 respectively) increased by transplanting, use of high yielding Raing Chey variety, and application of a larger amount of N chemical fertilizer. These findings indicated that the agriculture extension support to farmers, particularly in DSR, is a key important factor for rice yield improvement in KPIR.

Key words: Cambodia, Double cropping, Irrigation rehabilitation, Rice, Water distribution.

Rice grain yield is low (2.7 t ha−1 in 2008; FAOSTAT, 2011) and irrigation development is limited in Cambodia. The area of dry season rice which is produced under complete irrigated conditions was 0.34 million ha, only 14% of the total rice cultivated area in 2008 (JICA, 2010c; USDA, 2010). Productivity is often much higher in the irrigated rice system than rainfed system (e.g., Fairhurst and Dobermann, 2002). Development of irrigated rice production with a higher yield in a sustainable manner is important for Cambodia.

The area of cultivated rice production in Cambodia is about 2.3 million ha (almost 85% of agricultural land) (USDA, 2010), enforces about 70% of total national workforce (Asthana, 2010), and provides the most important export commodity (JICA, 2010a). In the latest policy paper on the promotion of paddy production and rice export reported by Royal Government of Cambodia (RGC, 2010), the government was ambitious to turn Cambodia into a major rice exporting country in the international market. The government recognized the importance of irrigation development as a quick-win measure for increasing agriculture productivity, poverty alleviation and economic growth, and has recently encouraged agricultural and water management sectors as well as investments of donors from foreign countries (i.e. ADB, Japan, Korea and China) to develop irrigation systems for rice production.

In Cambodia, the major existing irrigation systems were built during the Pol Pot regime (69% of 841 schemes) (Perera, 2006), in an estimated 0.72 million ha with a
canal system of 14,000 km (JICA, 2010a). However, most of these systems are defective due to inadequate planning, design and construction (Perera, 2006; Thun, 2008; JICA, 2010a). The Cambodian government encouraged rehabilitating those existing ineffective irrigation schemes, since this was considered to be less costly than new development. As a consequence, the fully irrigated area during the dry season is reported to have risen rapidly during the last decade, compared with only 7% of the total cultivated area during 1998–2002 (Yu and Fan, 2010). The percentage of irrigated area including those in wet season is estimated to be 25% in 2008, with 0.59 million ha (JICA, 2010a). Rapid expansion of the areas including partially irrigated systems is also advocated by Cambodian government (Hun, 2010; CRDB and CDC, 2010). Such a progress in irrigation rehabilitation is considered to have some extent contributed to rice yield increase from 2000 (i.e. only 2.1 t ha$^{-1}$) (FAOSTAT, 2011). However, it is not known to what extent the systems once defunct but now after/under rehabilitation are able to evenly distribute irrigation water. Besides the current national rice yield (i.e. 2.7 t ha$^{-1}$) is still relatively low compared to neighboring countries with similar weather and soil condition such as Thailand, Laos and Vietnam where grain yields in 2008 were 2.9, 3.5 and 5.2 t ha$^{-1}$, respectively (FAOSTAT, 2011). Assessment of rice yield and farm management is needed in those irrigation rehabilitation areas.

Several socio-economic surveys have been made via interviews on rice productivity in irrigation rehabilitation areas in Cambodia (WB, 2006; Try, 2008; Thun et al., 2009). For instance, WB (2006) compared the rice grain yields before and after the conduction of irrigation projects. WB speculated that the yield improvement resulted from the adoption of improved rice varieties and agro-chemicals but gave no detailed information (WB, 2006). In order to introduce suitable and more productive technologies to irrigation rehabilitation areas through agricultural extension activities, farmer management and
yield level must be assessed including the area-wide spatial distribution and the yearly changes in response to the progress of introduction of double cropping.

In this study, we quantified the difference in water environments of paddy fields in the Kamping Puoy Irrigation Rehabilitation area (KPIR), an irrigation rehabilitation area in Northwest Cambodia, and to examine the farmers’ management practices in response to the different water environments and the introduction of the double cropping system. We also assessed grain yield and determined yield limiting factors in the studied area. We examined whether or not (1) field water environment in the irrigation rehabilitation area is spatially varied along drainage canals due to the weakness of the water distribution system; (2) expansion of the DSR area (and double cropping system) will force modification of whole cropping sequence including management practices in WSR, in which technical advice and information is needed; and (3) rice yield of both DSR and WSR will not instantly boost up only as a result of rehabilitation of irrigation infrastructure but will be better improved by agronomic management information by agricultural extension support.

**Materials and Methods**

1. **Study site**
   The study was carried out in KPIR (13°02’N, 103°04’E) which is located approximately 25 km west from Battambang City, Battambang province, Northwest Cambodia. KPIR was first developed during the Pol Pot regime from 1975 to 1979 by forced labor including those forced to move from urban areas. Due to poor planning, design and construction, the irrigation system is inadequate. Since 1999, Japanese and Italian governments helped rehabilitate the area with a beneficiary area of about 5,000 ha (JICA 2010b). KPIR is divided into 3 zones: the most upstream zone close to Kamping Puoy (KP) Water Reservoir (700 ha), midstream zone (consisting of 2 areas of 1,200 and 2,200 ha), and downstream zone (950 ha). The area of 2,200 ha in the midstream zone has just been operated irrigating for DSR 2010 (Fig. 1). The downstream zone, rehabilitated by JICA from 2001-2003, was used for this study. This 950 ha zone consisted of 6 irrigation canals (N2-1, N2-3 to N2-11) which vertically branched from the canal N2 (with N2-1 upstream and N2-11 downstream along N2) and 6 drainage canals (D2-1, D2-3 to D2-11) between the 2 adjacent irrigation canals. In this paper, we refer to N2 as the main irrigation canal, N2-1 to N2-11 as secondary irrigation canals, and D2-1 to D2-11 as secondary drainage canals. Tertiary irrigation canals are incomplete, and hence most of the paddy fields except for those along the irrigation canals are supplied with irrigation water by plot to plot irrigation.

The two secondary drainage canals D2-1 (9.8 km from KP Water Reservoir) and D2-7 (15.2 km from KP Water Reservoir) within the 950 ha area were chosen for the transect study during rainy season rice in 2008 and 2009, and dry season rice in 2009 and 2010. D2-1 is located further upstream along N2 than D2-7. The transect study (e.g. Ardales et al., 1996; Van Groenigen et al., 2003; Neumann et al., 2009) is conducted based on the logical assumption that environmental and management conditions may be different along the transect; in our study it was intended to clarify spatial variation along the

Table 1. Numbers and area of surveyed fields, distance from main irrigation canal, and area percentage of dry season rice (DSR) from 2908 to 2010 in the 6 field groups with different distance from Kamping Puoy (KP) lake and main irrigation canal (upstream, midstream and downstream) in the two drainage canals D2-1 and D2-7 in Kamping Puoy irrigation rehabilitation area (KPIR).

| Drainage ID | Field group by water | Number of fields | Area (ha) | Distance from main irrigation canal (km) | % of DSR area |
|-------------|----------------------|-----------------|----------|------------------------------------------|--------------|
|             |                      | N1) n2) Single field Total | Min | Max | 2008 | 2009 | 2010 |
| D2-1        | Upstream (1U)        | 31 4 | 0.3±0.2 8.0 | 0.1 | 0.7 | 100 | 100 | 100 |
|             | Midstream (1M)       | 38 6 | 0.6±0.3 23.9 | 0.8 | 1.7 | 100 | 100 | 100 |
|             | Downstream (1D)      | 29 6 | 0.8±0.4 24.5 | 1.8 | 2.8 | 54  | 100 | 100 |
| D2-7        | Upstream (7U)        | 8 4  | 0.7±0.2 5.7 | 0.0 | 0.2 | 100 | 100 | 100 |
|             | Midstream (7M)       | 20 4 | 1.0±0.6 20.6 | 0.6 | 1.0 | 0  | 100 | 100 |
|             | Downstream (7D)      | 14 4 | 0.8±0.7 10.8 | 1.4 | 1.7 | 0  | 0  | 100 |
| Total       |                      | 140 28 | 0.7±0.5 93.5 | 0.0 | 2.8 | 54  | 88  | 100 |

1) N indicates number of fields where water score, planting time, harvesting time, varieties, and planting method have been periodically monitored.
2) n indicates number of key fields where rice has been sampled for yield evaluation, yield component analysis, weed amount at maturity and farmers’ management practices of the fields have been interviewed.
3) Area was calculated based on N samples.
secondary irrigation and drainage canals in the 950 ha area in KPIR area. There are 98 fields located on both sides along D2-1 and 42 fields located on both sides along D2-7. D2-1 was longer (2.8 km) than D2-7 (1.7 km) and its single field size was slightly smaller (Table 1), which lead to much more numbers of fields along D2-1 than D2-7. In total 140 fields were grouped as (1) upstream D2-1 (1U); (2) midstream D2-1 (1M); (3) downstream D2-1 (1D); (4) upstream D2-7 (7U); (5) midstream D2-7 (7M); and (6) downstream D2-7 (7D). Upstream fields are closer to N2 than downstream fields (Fig. 1, Table 1).

Monthly rainfall and temperature from May 2008 to July 2010 measured at Kamping Puoy Agricultural Development Center, which is located about 7 km from northwest of 950 ha area, are shown in Table 2. Rainfall in 2009 was lower than in 2008, particularly in the beginning (July, August) and the end (November) of rainy season. Maximum and minimum temperatures in 2010 were higher than in 2008, particularly in the beginning (July, August) and the end (November) of rainy season. Maximum and minimum temperatures in 2010 were higher than in 2009, especially in April and May.

2. Measurements

All 140 fields in the 6 groups along D2-1 and D2-7 were monitored about once every 4 weeks except in the rainy season of 2008 (every 8 weeks) to examine differences in water availability, cropping schedule and rice management practices (i.e. planting method, varieties, mid-tillage practice). Water availability was assessed based on the method of Kamoshita et al. (2010) in which field water conditions were recorded as water scores, simple indices of visual wetness of soil surface or standing water depth in paddy fields: –1 (dry), –0.5 (moist but not saturated), 0 (saturated without standing water) and x/10 (flooded with x cm standing water).

Planting dates were estimated based on the leaf number of seedlings in combination with field observation and farmer interview during field surveys in July and August for WSR and in February and March for DSR while harvesting dates were determined based on the estimation of physiological maturity time of the each rice field during field surveys in November, December and January for WSR and in May and June for DSR. Planting methods were divided into direct seeding and transplanting of seedlings. Direct seeding methods were divided further into wet seeding and dry seeding. Pre-germinated seeds were broadcasted into puddled and leveled fields by the wet seeding method while in ploughed fields, dry seeds were broadcasted on dry or moist soil and then incorporated into surface soils by harrow by the dry seeding method. Planting methods were determined from the appearance of rice seedlings during establishment stage and by clarification through interviewing farmers if needed.

Mid-season tillage is a practice of weed management by plowing when rice seedlings are at more than 30 days or sometimes up to 80 days after emergence depending on water accumulation in the field. This practice, used only in direct seeded fields for medium and late varieties, intends to control weeds and redistribute seedling density. The mid-season tillage practice in KPIR was described in detail by Kamoshita et al. (2009, 2010). We clarified whether mid-season tillage was conducted or not in each field based on field surveys from August to November. Rice varieties were identified with a help of a knowledgeable local farmer during field surveys in November and December.

For yield assessment, 16 and 12 key fields along D2-1 and D2-7 respectively were selected (Table 1 and Fig. 1), and the farmers of these fields were interviewed to identify the estimated yield and management practices. Each field group contained 4 to 6 key fields. One field in 7M in WSR 2009 (WSR cropping in 2009) and 4 fields in 7D in DSR 2009 were uncultivated while 1 field in 7U and 1 field in 7M were not sampled in DSR 2009. Therefore, total key fields with yield data were 28, 27, 22 and 28 for WSR 2008, WSR 2009, DSR 2009 and DSR 2010, respectively. Three 1 m × 1 m samples for WSR 2008 and DSR 2009 and one 1 m × 1 m sample for WSR 2009 and DSR 2010 were harvested from the ground level in each key field. Sample positions for each key field were located in the areas with average growth/yield based on visual observation of the

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| 2008 | –   | –   | –   | –   | –   | –   | –   | –   | –   | –   | –   | –   | 177.0 |
| 2009 | 0.0 | 0.0 | 74.9| 162.7| 196.4| 128.4| 73.3| 166.4| 275  | 281.6| 32.5 | 0.0   | 1390.5|
| 2010 | 8.3 | 12.0| 25.2| 69.9 | 77.3 | 121.2| 241.9| –   | –   | –   | –   | –   | 1530.2|

| Year | max  | min  | avg  |
|------|------|------|------|
| 2008 | 29.7 | 18.6 | 25.0 |
| 2009 | 34.2 | 22.9 | 30.9 |
| 2010 | 35.3 | 24.4 | 32.6 |

| Year | max  | min  | avg  |
|------|------|------|------|
| 2008 | 77.3 | 73.3 | 75.3 |
| 2009 | 166.4| 121.2| 143.3|
| 2010 | 241.9| 241.9| 241.9|
whole field. For each rice sample, the number of panicles with fertile grains was counted, and dry weights (after putting into oven for 2 days at 70°C) of straw, ripened grains (those sinking in the tap water), un-ripened grains (those floating on the tap water), and 100 counted both ripened and un-ripened grains were determined. Fraction of ripened grain, 1,000-grain weight, number of spikelets per panicle, and harvest index were calculated. Grain yield calculated from dry weight of ripened grain and 1,000-grain weight were presented at 14% moisture content. Yield components were not measured in WSR 2008.

For the 28 key fields, weed infestation at maturity was also evaluated by collecting all the weeds with their plant height greater than approximately 3 cm in a quarter of every quadrat of the 1 m × 1 m for the rice sampling mentioned above, to determine weed dry weights. Amounts of organic and chemical fertilizers and amounts of active ingredients of herbicides and insecticides were determined by interviews at ending time for each rice season.

Analysis of variance and Waller-Duncan tests (Waller and Duncan, 1969) were conducted to examine the differences in yield and yield components among the 4 combinations of crop seasons and years (WSR 2008, WSR 2009, DSR 2009 and DSR 2010), and the differences in yield among the 6 field groups (1U, 1M, 1D, 7U, 7M and 7D), both regarding field numbers as replications. The effects of planting method (transplanting vs direct seeding) and variety (Raing Chey vs other varieties) were tested by the t-test for independent samples. The simple correlation coefficient between grain yield and environmental and management factors were calculated. Statistical analysis was conducted using SPSS software.

**Results**

1. **Field water environments**

   All fields were non-flooded (negative values of water score) or saturated (water score = 0) at the beginning of WSR cropping (i.e., August), but field water depth became deeper (larger positive water score) with the progress of rainy season from September to November and started decreasing in late November (Fig. 2). In WSR 2009 water depth increased sharply from August to September; especially in downstream fields the average depth reached 27 cm (while the depth of the deepest field in 7D was 58 cm) in early September 2009. Water depth was much deeper in downstream fields than in upstream fields in both canals, and deeper in fields in D2-7 than those in D2-1. For example, average water score in early November 2009 were ~0.1 (with the maximum score in the deepest field 0.3 in 1U and 4.2 (with the maximum score 7.6) in 7D, respectively. At the end of season, the disappearance of standing water in upstream fields was generally earlier
than that in mid and downstream (e.g. early November vs. mid December to January), and earlier in 2009 than 2008.

In contrast to WSR, there was smaller variation in field water condition in both between field groups and during the crop season of DSR (Fig. 2). Water depth in DSR cropping was also shallower in comparison to that in WSR cropping. Irrigation water was fully provided during growing season in both 2009 and 2010. However, irrigation started 7 days earlier in 2010 (1 February) than in 2009 (7 February). All fields were under shallow flooded condition with the average water score ranged from 0.5 to 1.7 in March and April except for fields in 7D which were fallowed with non-flooded dry condition (water score = −0.9 in March and −0.8 in April) in 2009 and which were planted but with non-flooded dry condition in March (water score = −0.2) in 2010.

2. Dry season rice area
DSR was planted in all the 3 field groups (1U, 1M and 7U) and only partly in 1D (54% of the area) but not in 7M and 7D in 2008 (Table 1). In 2009, DSR was planted in all the field groups except 7D, and in 2010 DSR was planted in all the field groups. DSR area percentage within the two transects D2-1 and D2-7 was 54% in 2008 and gradually increased to 100% in 2010. These percentages were similar to the values for the whole 950 ha area (increasing from 567 ha (60%) in 2008 to 950 ha (100%) in 2010) (personal communication with the chief of the water user group in...
3. Management practices

WSR seeding started in downstream fields (e.g., late May 2008 for 7D), then in midstream fields (e.g., early June 2008 for 7M), and finally in upstream fields (e.g., late July 2008 for 1U) (Fig. 3). On the other hand, rice harvest started from upstream fields (e.g., mid November 2008 for 1U) and moved to downstream fields (e.g., late December 2008 for 7D). Direct seeding started earlier (i.e. late May to mid August) than transplanting (i.e. late July to late August). For the direct-seeded fields, sowing time in 2009 was generally later than that in 2008 (e.g., around early July in 2009 and around early June in 2008 for 1D and 7M). Sowing time became less varied within each field group and among field groups except 1U and 7D in WSR 2009 compared with WSR 2008. Planting time and harvesting time of DSR were similar among and within the field groups in 2009 and 2010 (Fig. 3). In general, rice was planted in mid to late February in 2009 and early to mid February in 2010, while harvested in early to mid June in 2009 and late May to early June in 2010. Most of the fields were harvested by machine, especially in DSR 2010.

San CraOrb, a photoperiod insensitive variety with a growth duration of 110 − 120 days, was the only variety grown in DSR 2009 and 2010 in the 950 ha area. There was a problem of misusing a photoperiod- sensitive variety Phka Rumduol (PKRD) in the studied fields in DSR 2009, which accounted for approximately 10% of the area of the studied fields. As WSR, 5 photoperiod-sensitive varieties and San CraOrb (for producing seeds for DSR) were used (Table 3). PKRD and Raing Chey are varieties developed by the Cambodian Agricultural Research and Development Institute (CARDI) while the other three are traditional local varieties. In general, early and early medium varieties such as San CraOrb or PKRD were planted in upstream fields while medium and late varieties such as Raing Chey and Neang Khon were planted in midstream and downstream fields. San CraOrb variety was most dominantly planted in 1U (100% and 96% of the surveyed area in 2008 and 2009, respectively). Raing Chey, the most widely planted variety in the whole area, with its area percentage increasing from 36% in 2008 to 58% in 2009, was consistently most popular in 1M and 1D. Neang Khon, the second popular variety, with its area percentage declining from 28% in 2008 to 29% in 2009, was most popularly grown in 7D (95% and 83% of the surveyed area). Kong Sach, grown in 1M and 1D in WSR 2008, was no longer grown in WSR 2009.

While wet seeding was the only farmers’ choice in DSR cropping, dry seeding, wet seeding and transplanting methods were observed to be practiced in WSR cropping. Transplanted fields were observed only in upstream and midstream fields and the proportion of transplanted area to the total surveyed area rose from 11% in 2008 to 20% in 2009 (Table 4). Dry seeding was only practiced in fields where rice was not cultivated in the preceding dry season such as 1D, 7M and 7D in 2008 and 7D in 2009. There was a large decrease in area with dry seeding from 35% in 2008 to 12% in 2009 while small increase in area with wet seeding from 54% to 68%.

Mid-season tillage was practiced only in midstream and downstream fields in both years except 7U in WSR 2009 (Table 4). The practice percentage area was high in 2008 (62%) but decreased sharply in 2009 (only 18%). The largest decrease was observed in 1D (100% down to 6%).

| Year | Field location | Early variety | Early medium variety | Medium variety | Late variety |
|------|----------------|---------------|----------------------|----------------|-------------|
|      | San CraOrb     | Phka Rumduol  | Phka Knei            | Raing Chey     | Kong Sach   | Neang Khon  |
| 2008 | 1U             | 8.0 (100%)    | 0.0 (0%)             | 0.0 (0%)       | 0.0 (0%)    | 0.0 (0%)    |
|      | 1M             | 4.9 (29%)     | 0.0 (0%)             | 5.9 (24%)      | 11.3 (48%)  | 3.3 (14%)   |
|      | 1D             | 0.0 (0%)      | 0.0 (0%)             | 1.0 (4%)       | 13.8 (56%)  | 1.9 (8%)    |
| 7U   | 3.2 (57%)      | 1.1 (19%)     | 0.0 (0%)             | 1.0 (4%)       | 14.2 (56%)  | 0.0 (0%)    |
|      | 7M             | 0.0 (0%)      | 0.0 (0%)             | 2.2 (10%)      | 6.7 (33%)   | 0.0 (0%)    |
|      | 7D             | 0.0 (0%)      | 0.0 (0%)             | 0.0 (0%)       | 0.5 (5%)    | 0.0 (0%)    |
| Total| 16.1 (17%)     | 1.1 (1%)      | 9.1 (10%)            | 33.7 (36%)     | 7.2 (8%)    |

| Year | Field location | Early variety | Early medium variety | Medium variety | Late variety |
|------|----------------|---------------|----------------------|----------------|-------------|
| 1U   | 7.7 (96%)      | 0.3 (4%)      | 0.0 (0%)             | 0.0 (0%)       | 0.0 (0%)    |
| 1M   | 4.4 (19%)      | 0.6 (2%)      | 3.2 (13%)            | 14.7 (61%)     | 0.0 (0%)    |
| 1D   | 0.0 (0%)       | 0.0 (0%)      | 0.0 (0%)             | 22.7 (93%)     | 0.0 (0%)    |
| 7U   | 0.7 (13%)      | 0.0 (0%)      | 1.5 (27%)            | 2.3 (41%)      | 0.0 (0%)    |
| 7M   | 0.0 (0%)       | 0.0 (0%)      | 0.8 (5%)             | 9.7 (65%)      | 0.0 (0%)    |
| 7D   | 0.0 (0%)       | 0.0 (0%)      | 0.0 (0%)             | 1.8 (17%)      | 0.0 (0%)    |
| Total| 12.9 (15%)     | 0.9 (1%)      | 5.6 (6%)             | 54.2 (58%)     | 0.0 (0%)    |
4. Yield and yield components

The 2-yr average grain yield was 289 g m\(^{-2}\) in WSR, with a range of 44 g m\(^{-2}\) to 475 g m\(^{-2}\), and 267 g m\(^{-2}\) for DSR, with a range of 31 g m\(^{-2}\) to 394 g m\(^{-2}\) among the 28 fields (Table 5). Grain yield in DSR 2010 was significantly lower than in WSR 2008, WSR 2009 and DSR 2009 with only 86% of that in DSR 2009. The size of CV was also largest in DSR 2010. Harvest index, percentage of ripened grains and 1000-grain weight in DSR 2010 were significantly higher than that in DSR 2009. The size of CV was also observed in WSR 2008.

Grain yield was also negatively affected by weed infestation in both DSR 2009 and 2010. Amount of herbicide significantly contributed to grain yield increment in WSR 2009. Use of larger amounts of N chemical fertilizer significantly increased grain yield in both WSR 2008 and WSR 2009.

The correlation coefficients of distance from main irrigation canal in D2-7 in 2008 and 2009, respectively, in WSR (Table 7). Grain yield was correlated positively with water score in August but negatively with that in December in WSR 2009. Transplanting method, Raing Chey variety, and larger amount of herbicide significantly contributed to grain yield increment in WSR 2009. Use of larger amounts of N chemical fertilizer significantly increased grain yield in both WSR 2008 and WSR 2009.

The correlation coefficients of distance from main irrigation in D2-7 with the grain yield were negative in both DSR 2009 and 2010 (Table 7). Grain yield was negatively correlated with both planting time and crop duration in DSR 2010. Lower values of water score in March and high values of water score in June negatively affected grain yield in DSR 2010. Grain yield was also negatively affected by weed infestation in both DSR 2009 and 2010. Amount of organic fertilizer, chemical N fertilizer and herbicide were moderately positively correlated with grain yield in DSR 2010.

5. Yield and environmental management factors

In WSR 2008, the values of grain yield in 1M (341 g m\(^{-2}\)) and 7D (331 g m\(^{-2}\)) were significantly higher than the value in 7U (196 g m\(^{-2}\)) (Table 6). Conversely, the grain yield was highest in 7U (358 g m\(^{-2}\)) and lowest in 7D (201 g m\(^{-2}\)) while there was no significant difference among other field groups in WSR 2009. In DSR 2009, there were no significant differences in grain yield among field groups except 7M with the lowest value of 200 g m\(^{-2}\) (Table 6). The grain yield in DSR 2010 was highest in 7U (322 g m\(^{-2}\)) and lowest in 7D (only 131 g m\(^{-2}\)).

The grain yield of Raing Chey was significantly higher than that of other varieties and yields in transplanted fields were higher than those in direct seeded fields in WSR 2009 (Table 6). The tendency of higher yield in Raing Chey was also observed in WSR 2008.

Grain yield showed strong positive and negative correlations with distance from the main irrigation canal in D2-7 in 2008 and 2009, respectively, in WSR (Table 7). Grain yield was correlated positively with water score in August but negatively with that in December in WSR 2009. Transplanting method, Raing Chey variety, and larger amount of herbicide significantly contributed to grain yield increment in WSR 2009. Use of larger amounts of N chemical fertilizer significantly increased grain yield in both WSR 2008 and WSR 2009.

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Discussion

1. Spatial variation in water environment in irrigation rehabilitation area

This study supported the first hypothesis of large spatial variation in field water environment within the irrigation rehabilitation area. Water depth of the surveyed fields during WSR cropping increased along the transects of the 2 secondary canals D2-1 and D2-7, from upstream to downstream, and the standing water disappeared earlier.
(i.e. November) in the upstream fields (e.g., 1U), and remained longer with deeper depth in the downstream fields (e.g., 1D, 7D) (Fig. 2). This spatial variation in water depth is similar to the toposequential variation in rainfed lowlands i.e., upper and lower toposequential fields (e.g., Miyagawa and Kuroda, 1988; Wade et al., 1999; Tsubo et al., 2006; Homma et al., 2007; Boling et al., 2008). The deepest field in 7D (water depth 76 cm in early November 2009) can be grouped into intermediate rainfed area according to Huke and Huke (1997). Deep water in downstream fields during WSR cropping resulted from the poor drainage system in KPIR. Thun et al. (2009) also indicated unequal distribution of irrigation water in upstream and downstream fields in small irrigation rehabilitation schemes in Takeo province, which was caused by poor irrigation design, field toposequences, and illegal water use by farmers.

Farmers have adapted to the variation in the water environments in WSR cropping by planting different types of rice variety with different maturity times. Medium and late maturing varieties were generally planted early but harvested late in midstream and downstream fields with deeper water depth while early and early medium maturing varieties were planted later but harvested earlier in upstream shallower fields (Table 3 and Fig. 3). Such differences in planting time and type of rice variety between the upstream and downstream fields were also similar to those observed in rainfed lowlands with toposequential variation (Wade et al., 1999, Ouk et al., 2001). However the differences between our study and rainfed lowland studies are (1) that both single field area and single farm size in KPIR are much larger (e.g., 0.7 ha per field from Table 1, and 2−4 ha per household from Kamoshita et al. (2009), respectively) than the small scale rainfed lowlands farms and (2) that WSR in KPIR is not only for family-consumption but also for selling to market.

| Items                      | Season | n  | Mean(1) | Min. | Max. | CV (%) |
|----------------------------|--------|----|---------|------|------|--------|
| Grain yield (g m²⁻²)       | WSR 2008 | 28 | 286  b  | 44   | 398  | 30     |
|                            | WSR 2009 | 27 | 292  b  | 168  | 473  | 28     |
|                            | DSR 2009 | 22 | 287  b  | 152  | 390  | 19     |
|                            | DSR 2010 | 28 | 247  a  | 51   | 394  | 33     |
| Final plant height (cm)    | WSR 2009 | 27 | 128  b  | 58   | 160  | 21     |
|                            | DSR 2009 | 22 | 93   a   | 82   | 104  | 7      |
|                            | DSR 2010 | 27 | 90   a   | 67   | 101  | 9      |
| Shoot dry matter (g m²⁻²)  | WSR 2009 | 27 | 809  b  | 407  | 1,262 | 30    |
|                            | DSR 2009 | 22 | 703  ab | 405  | 907  | 17     |
|                            | DSR 2010 | 27 | 689  a  | 501  | 912  | 13     |
| Harvest index (%)          | WSR 2009 | 27 | 32   a   | 17   | 42   | 16     |
|                            | DSR 2009 | 22 | 35   b   | 26   | 50   | 14     |
|                            | DSR 2010 | 27 | 31   a   | 7    | 41   | 28     |
| No. of panicles per m²     | WSR 2009 | 27 | 199  a  | 71   | 400  | 38     |
|                            | DSR 2009 | 22 | 329  b  | 196  | 402  | 26     |
|                            | DSR 2010 | 27 | 432  c  | 242  | 726  | 32     |
| No. of spikelets per panicle| WSR 2009 | 27 | 95   b   | 30   | 150  | 36     |
|                            | DSR 2009 | 22 | 50   a   | 25   | 76   | 28     |
|                            | DSR 2010 | 27 | 42   a   | 22   | 68   | 29     |
| No. of spikelets per m²     | WSR 2009 | 27 | 6,740 a | 8,978 | 26,365 | 25    |
|                            | DSR 2009 | 22 | 5,728 b | 7,154 | 22,056 | 21    |
|                            | DSR 2010 | 27 | 6,790 a | 8,832 | 24,114 | 19    |
| Percentage of ripened grains| WSR 2009 | 27 | 74   c   | 59   | 85   | 9      |
|                            | DSR 2009 | 22 | 65   b   | 54   | 78   | 9      |
|                            | DSR 2010 | 27 | 60   a   | 26   | 78   | 23     |
| 1000-grain weight (g)      | WSR 2009 | 27 | 24   a   | 19   | 31   | 13     |
|                            | DSR 2009 | 22 | 28   b   | 26   | 30   | 4      |
|                            | DSR 2010 | 27 | 25   a   | 20   | 27   | 6      |

*Yield components were not measured in WSR 2008.
1) Values within column for each item followed by the same letter are not significantly different at the 5% level.
By uniformly planting a single higher yielding and good quality rice variety, it will be easier for farmers to sell rice to wholesalers, especially to rice exporting enterprises. However, field water needs to be more uniform among field groups during WSR cropping and a larger labor force is needed for simultaneous farm operation by agricultural mechanization.

It should be emphasized that field water conditions in DSR cropping were shallower and less variable both in time and in space than in WSR cropping (Fig. 2) which would have allowed a single rice variety San CraOrb (as later discussed) to grow with uniform crop calendar across all the field groups during dry season. This was due to the little rainfall and the controlled irrigation water supply from the reservoir to the planned irrigation area during dry season. However, our study revealed that the judgment of the field to plant DSR is still on trial and error: the fields between upper and lower canals and within a canal. There are 5 water user groups within the 950 ha area, each of which is responsible for the management of each secondary irrigation and drainage canal, and better communication is required. Improving the tertiary canal systems or and better farmers’ collaboration for sharing water between fields nearby may help to enhance more uniform field water distribution in the area.

### Table 6. Grain yield variation among field groups (1U, 1M, 1D, 7U, 7M, 7D), between varieties (Raing Chey (RC), the others), and between planting methods (transplanting (TP), direct seeding (DS)) in wet season rice (WSR) 2008 and 2009 and in dry season rice (DSR) 2009 and 2010.

| Field group | Variety | Planting method | 2008          | 2009          | 2009          | 2010          |
|-------------|---------|-----------------|---------------|---------------|---------------|---------------|
|             |         | TP              | RC            |TP             | DS            | TP            | DS            |
|             |         |                 | 325 ± 77 (7)  | 230 ± 83 (12) | –             | –             |
|             |         |                 | others 273 ± 86 (21) | 261 ± 66 (15) | –             | –             |
| 1U          | 31 ± 94 (4) ab | 257 ± 57 (4) ab | 315 ± 18 (4) b | 195 ± 135 (4) ab | 311 ± 45 (6) b | 277 ± 29 (6) bc |
| 1M          | 341 ± 44 (6) b | 316 ± 88 (6) ab | 288 ± 49 (6) b | 266 ± 33 (6) bc | 288 ± 47 (3) b | 322 ± 57 (4) c  |
| 1D          | 260 ± 64 (6) ab | 315 ± 63 (6) ab | 288 ± 47 (3) b | 322 ± 57 (4) c  | –             | 131 ± 15 (4) a  |
| 7U          | 196 ± 143 (4) a | 358 ± 80 (4) b  | 200 ± 45 (5) a | 266 ± 46 (4) bc | –             | –             |
| 7M          | 262 ± 48 (4) ab | 277 ± 87 (3) ab | –             | –             | –             | –             |
| 7D          | 331 ± 35 (4) b  | 201 ± 38 (4) a  | –             | –             | –             | –             |
| Total       | 286 ± 86 (28) | 292 ± 80 (27)   | 287 ± 54 (22) | 247 ± 81 (28)  | –             | –             |

Values are average ± standard deviation.
1) Values within column followed by the same letter are not significantly different at the 10% for WSR 2008 and WSR 2009 and at 5% for DSR 2009 and DSR 2010.
2) *P<0.05 and **P<0.01. Values in the brackets indicate number of fields.

2. Effects of introduction of double cropping

The second hypothesis of our study on the influences of introduction and expansion of irrigated DSR in KPIR on the whole cropping schedule (including the management of WSR) was supported and qualified by the following data of yearly changes in management practices in WSR cropping such as (1) planting time, (2) planting method and (3) weed management method. (1) The planting time of WSR in 1D, 7M and 7D shifted later (i.e. from late May to early June in WSR 2008, from early June to mid July in WSR 2009) as a consequence of introduction of DSR 2009 in a crop calendar (Fig. 3). (2) With the progress of introduction of DSR cropping, dry seeding method has sharply declined and has been replaced by wet seeding method in WSR (Table 4). When DSR is fully cultivated in KPIR with the present crop calendar, the earliest possible time of planting of the following WSR is late June, which would be too late to use dry seeding methods due to the rainfall in early wet season. (3) As a result of the later sowing and later plant establishment in WSR 2009, the chance for conducting mid-season tillage practice was narrowed, and the area with this practice declined from 2008 to 2009 in the studied area (Table 4).

Farmers in KPIR are facing 3 technical challenges in rice production due to these changes in management practices as a consequence of introduction of double cropping system. The first challenge is the tight schedule and shortage of labor from DSR harvest to WSR planting. In the present cropping calendar, in which DSR was harvested mainly in June, planting window for WSR (e.g., late June to August) was narrow and farmers had to
become too busy. One possible solution to mitigate the labor pressure would be the earlier harvest of DSR by planting earlier. The planting time in DSR 2010 (early February) was earlier due to earlier beginning of irrigation (1 February 2010) than that in DSR 2009 (late February); this would probably be as the result of the farmer’s experience of the very tight labor requirement in June and July in the newly introduced double cropping system in 2009. The planting time of DSR can be shifted further earlier in January only if the late maturing varieties (i.e. Neang Khon) with their harvest time around early to mid January were replaced by earlier maturing varieties of WSR, as will be discussed in the next section. Introduction of harvesting machine for both WSR and DSR will be also helpful to reduce the duration of harvest so as to provide wider windows for WSR planting.

The second challenge is techniques for improving plant establishment of WSR. While dry seeding method allows wider windows for planting and requires less managerial efforts, wet seeding method requires careful land preparation (i.e. land leveling) and field water management for successful crop establishment. Furthermore, farmers in KPIR, particularly in the 950 ha area may be lack of options for wet seeding methods because of just recent introduction of DSR. Therefore, the introduction of improved technologies related to wet seeding method (i.e. land leveling method, drum seeding) may help increase rice productivity in KPIR.

The third challenge is an alternative weed management in WSR cropping. Mid-season tillage is a unique traditional practice in Northwest Cambodia in order to control weeds in an ecologically harmonized way without solely relying on herbicides (Kamoshita et al., 2009, 2010). The decrease or disappearance of this practice may lead to the necessity for new weed management such as use of herbicide in KPIR. Effective herbicide types and proper application

Table 7. Simple correlation coefficients between grain yield and environmental and management factors in wet season rice (WSR) 2008 and 2009 and in dry season rice (DSR) 2009 and 2010.

| Items |
|-------|
|       | WSR 2008 | WSR 2009 | DSR 2009 | DSR 2010 |
| Distance from main irrigation canal (m) |
| D2I   | -0.457  | 0.169    | -0.368   | 0.217    |
| D27   | 0.672*  | -0.826** | -0.768*  | -0.925** |
| March | -       | -        | -0.034   | 0.651**  |
| April | -       | -        | -0.340   | 0.193    |
| June  | -       | -        | -0.113   | -0.469*  |
| Water score |
| August| 0.130   | 0.396*   | -        | -        |
| October| -0.080 | -0.130   | -        | -        |
| December| -0.172 | -0.393*  | -        | -        |
| Weed at maturity of rice (g m⁻²) |
| -0.102 | 0.115  | -0.627** | -0.547** |
| Planting time (DOY) ²) |
| -0.188 | 0.310  | 0.313    | -0.810*** |
| Crop duration ³) |
| 0.182  | -0.289 | -0.252   | -0.501**  |
| Transplanting method ⁴) |
| -0.176 | 0.499**| -        | -        |
| Raing Chey variety ⁵) |
| 0.269  | 0.539**| -        | -        |
| Hand seeding (times) |
| -0.018 | -0.031 | 0.380    | 0.139    |
| Organic fertilizer (kg ha⁻¹) |
| 0.277  | 0.047  | -0.132   | 0.492**  |
| Chemical N fertilizer (kg ha⁻¹) |
| 0.541** | 0.599**| -0.068   | 0.401*   |
| Herbicide 2,4 D (g a.i. ha⁻¹) |
| 0.346  | 0.387* | 0.268    | 0.490**  |
| Insecticide (g a.i. ha⁻¹) |
| 0.147  | -0.090 | 0.102    | 0.124    |

1) Total sample numbers for distance from main irrigation canal: n = 16 for D2-1 and n = 12, 11, 6 and 12 in WSR 2008, WSR 2009, DSR 2009 and DSR 2010, respectively, for D2-7. Total sample number for all the other items: n = 28, 27, 22 and 28 for WSR 2008, WSR 2009, DSR 2009 and DSR 2010, respectively.

²) P<0.1, *P<0.05 and **P<0.01.

3) Day of the year from 1 January (e.g. if rice was sowing on 15 February, DOY for sowing time will be equal to 46).

4) Values for transplanting method and those for direct seeding method were 1 and 0 respectively, as dummy variables.

5) Values for Raing Chey variety and for those for other varieties were 1 and 0 respectively, a dummy variable.
techniques should be introduced to the farmers.

3. Grain yield assessment

Irrigated rice is usually taken as much higher yielding than rainfed rice (e.g., Fairhurst and Dobermann, 2002), but our study supported the third hypothesis, showing lower actual yield level in KPIR than expected yield potential of irrigated rice, clarifying several yield limiting factors, and indicating the necessity of agronomic analysis and extension support to farmers.

Grain yield on average in both DSR 2009 and 2010 in our study were 32% lower than that of 4 t ha$^{-1}$ (USDA, 2010) recorded for the whole Cambodia in DSR 2008. This is primarily due to the low yield potential of San CraOrb in KPIR in our study with a maximum yield of only 3.9 t ha$^{-1}$ (Table 5) while most of the Cambodian DSR (estimated as 85% in area) is cultivated with one of the high yield potential IR varieties, IR66 (Koma, 2008). In addition, Cambodian government figures on grain yield of DSR refer to both irrigated rice in the double cropping system (such as in KPIR) and rice in a single cropping system using receding water in a deep water area with a larger proportion of the latter (Ouk et al., 2001; USDA, 2010), whose yields are generally higher than the former (because of high fertility of the silt deposited by the floods). These might be the reasons for the differences between the yield of DSR in this study and the national recorded data.

Grain yield in KPIR has been reported previously such as by JICA (2005) and Try (2007). In comparison with the average grain yield in DSR 2002 in KPIR with the value of 2.3 t ha$^{-1}$ (JICA, 2005), the average grain yield in both DSR 2009 and 2010 was only 17% higher. According to Try (2007), grain yield in KPIR was estimated to range from 2.5 to 4 t ha$^{-1}$ (no average data presented) in DSR 2007. In our study, the higher limit of grain yield was similar to that reported by Try (2007), but the lower limit was much lower. This is probably because our study considered a wider variation in environment and farmers’ management practices from upstream to downstream fields. It should also be noted that grain yields in our study were from the downstream zone (950 ha area), not necessarily representing for the whole KPIR (about 5,000 ha); the 950 ha area might have been less advantageous in irrigation water access. The lower yield (2.5 t ha$^{-1}$) than the expected outputs from the irrigation rehabilitation project was also reported in Stung Chinit irrigation scheme (Try, 2008).

Yield limiting factors for DSR identified in our study are (1) weed infestation, (2) disease occurrence (in 2010), (3) high temperature (for 2010), (4) small agricultural inputs such as chemical N fertilizers and herbicides, (5) unavailability of some agricultural resources such as herbicides for grass and fungicides, (6) farmers’ lack of knowledge for photoperiod sensitivity of varieties of DSR, (7) immature experiences of water management for DSR.

For example, the average rates of herbicide used in the studied area (628 and 367 g a.i. ha$^{-1}$ in 2009 and 2010, respectively; data not shown) were lower than recommended rate written on the products (about 800 g a.i. ha$^{-1}$), which had allowed weed infestation and reduced yield of DSR. Besides all of the herbicides used were 2,4-D, and no herbicides effective in killing grass was available for the surveyed farmers in KPIR, in spite of common presence of grass species such as Echinochloa oryzae (N. Araki, unpublished data). Another problem of plant protection was the extensive occurrence of brown spot (Bipolaris oryzae) and narrow brown spot (Cercospora oryzae) diseases from flowering stage in most of the fields in the 950 ha area in DSR 2010, which reduced 1000-grain weight and yield. The high planting density in DSR 2010 (432 panicles m$^{-2}$ in DSR 2010 vs. 329 panicles m$^{-2}$ in DSR 2009) might have been a factor creating a favorable condition for the development of these diseases, but the problem was that fungicides are not sold in the shops in KPIR, and that farmers wrongly applied insecticide in DSR 2010 instead of fungicides.

The amounts of N fertilizer applied to DSR (about 44 kg ha$^{-1}$; data not shown) were also small, only about one-third of the recommendation rate for DSR (129 kg N ha$^{-1}$ in Balasubramnian and Hill, 2002). It is not known whether insufficient application is derived from lack of money for purchasing, lack of knowledge for the optimum application of N fertilizer, or farmers’ consideration of risk, and further investigation is needed.

Some farmers bought and planted seeds of inappropriate photoperiod-sensitive varieties from rice millers in the village for DSR, and lowest yields of DSR were recorded in 7M (2009) and 7D (2010) where DSR was cultivated for the first time (Table 6).

As the other possible cause for lower grain yield in DSR 2010 than in DSR 2009, with lower percentage of ripened grain, 1000-grain weight and harvest index (Table 5), we speculated the occurrence of high temperature in April and May (i.e. average max. of about 37ºC) in 2010 (5). According to Jagadish et al. (2007), less than 1 hour exposure to high temperature (≥35.7ºC) at flowering stage caused rice spikelet sterility while Lin et al. (2010) found that high temperature (35/30ºC day/night) during grain-filling significantly reduces grain weight and grain quality. Although the higher temperature in 2010 was an extreme event not only in Cambodia but also in many parts of the world which was mainly due to El Niño effect (NOAA, 2011), air temperature in Cambodia was relatively high in every dry season with peak in April (average max. of 35ºC). Therefore, sowing time of DSR is an important factor affecting on grain yield through the timing of flowering and grain-filling which are sensitive to high temperature. Sowing early in January will give an advantage to widen the planting window for WSR as discussed in the previous section but there will be a high risk for flowering and/or
grain-filling period falling in the highest temperature period in April.

Average grain yield in WSR 2008 and 2009 in KPIR in this study was almost comparable (about 12% higher) to the reported value of yield for improved varieties for the whole Cambodia in 2008 (2.6 t ha$^{-1}$) (USDA, 2010). In comparison with the grain yield in WSR 2002 (2.4 t ha$^{-1}$) recorded in irrigated area in KPIR (JICA, 2003), the average grain yield in both WSR 2008 and 2009 in this study were about 20% higher.

The results of our study suggested that increasing farmers' adoption of higher yielding Raing Chey variety has contributed to the yield improvement of WSR in KPIR. This variety also has been increasingly adopted by farmers in many provinces in Cambodia (Fukai, 2006). However, the constraint of further adoption of Raing Chey variety in the 950 ha area in KPIR is deep water in downstream fields. Improving the drainage system may help prevent the 7D fields from flood and expand Raing Chey variety to this downstream area for increasing productivity of WSR. Enlarging and deepening the main drainage canal as well as improving the connection from the canal to the Otaki River may help drain the exceeding water in the canal during October and November.

In general, agricultural extension is extremely needed in order to enhance productivity in both DSR and WSR in KPIR. As dry season rice has still been news to the farmers, knowledge on DSR varieties, technical advice and agricultural resources for crop management and plant protection should be introduced to them as soon as possible. High temperature may be also an important factor limiting grain yield of DSR in KPIR and it should be further studied including the optimum planting time for maximizing attainable yield and for reducing labor demand pressure from DSR harvest to WSR planting seasons in June to August. Irrigation water management in DSR cropping and a drainage system also need to be improved so that downstream fields in D2-7 will not encounter water shortage at the establishment stage in DSR cropping and to prevent flooding in WSR cropping.

Acknowledgments

We acknowledge Mr Sareth Chea and Mr Sophors Heng of the Cambodia Agricultural and Development Institute, and Mr Sovannmony In, Mr Chanthy Suos, Ms Lina Pou of Battambang Provincial Department of Agriculture for their assistance during our field survey, sample processing and language interpretation. We also acknowledge Drs Kauzuki Yagi, Kenichiro Yoshii and Mr Masahiro Otake of Japan International Cooperation Agency for providing useful information of rice development in Cambodia. We thank all the villagers for the monitored fields, particularly Mr Soun Phitor for helping us to identify the variety names, and chiefs of water user groups for responding to our interviews. This study was supported by a Grant-in-Aid for Scientific Research (No. 20405019) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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