Crop Protection xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com

WEED MANAGEMENT PRACTICES OF SMALLHOLDER RICE FARMERS IN NORTHWEST CAMBODIA

Sokunroth Chhun [a], Virender Kumar [b,*], Robert J. Martin [c,**], Pao Srean [a], Buyung Hadi [b]

[a] Faculty of Agriculture and Food Processing, University of Battambang, Cambodia
[b] International Rice Research Institute, Los Baños, Philippines
[c] Faculty of Science, Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Sydney, NSW, 2006, Australia

ARTICLE INFO

Keywords:
Cambodia
Weed management
Farmers' practices
Weed community
Weed seed contamination
Weedy rice
Direct-seeded rice

ABSTRACT

One-hundred farmers from lowland rice systems of Battambang province in Cambodia were surveyed in 2017 using a structured questionnaire with the objectives to (1) determine farmers' current knowledge and weed management practices and document the effect of adopted agronomic practices on management of weeds in rice, and (2) quantify the extent of weed seed contamination in farmers' own saved paddy seed lots. To estimate the level of contamination by weed seeds, a one kg paddy seed sample was collected from each surveyed farmer. All farmers practiced broadcast direct-seeded rice (DSR), with an average seeding rate of 181 kg ha^{-1}. For sowing the rice crop, 82% of farmers used their own saved seeds or bought seed from their neighbour. All the paddy seed samples were contaminated with seeds of 34 weed species with an average of 1,070 weed seeds kg^{-1} of paddy seed. The most common weed contaminants in the seed samples were *Oryza sativa* f. *spontanea* (weedy rice), *Fimbristylis miliacea*, *Echinochloa colona*, *Echinochloa crus-galli*, and *Ischaemum rugosum.* Weeds, in their rice field, were considered a major problem by 93% of farmers with 70% of farmers indicating a yield loss of >20% due to weed competition. All farmers followed a post-emergence based herbicide program for weed control with no use of pre-emergence herbicides. Farmers (75%) relied on the advice of input dealers on the selection and use of herbicides. Knowledge gaps were found among farmers on herbicide application techniques including selection of the right sprayer, nozzle tips, and sprayer calibration. Although 94% of farmers responded that they were aware of pesticide exposure risk, use of boots and gloves, as personal protective equipment, during spraying was low (10 and 54%, respectively). The fertilizer use was lower than recommended rates (50% of recommended N and around 40% of recommended P and K). An exploitable rice yield gap of 1.3 t ha^{-1} (40%) and 1.1 t ha^{-1} (30%) was found in the wet and dry season, respectively. These results suggest that integrated weed management (IWM) and optimum fertilizer use can play an important role in closing the rice yield gap in Battambang. IWM options using clean/certified seeds free from weed seeds, optimum fertilizer, selection and application of appropriate pre- and post-emergence herbicides at the right time, amount, and accurate application techniques can improve weed control and hence enhance the rice yield in Cambodia. Farmer training is needed to close their knowledge gaps and to educate them on IWM, especially, to manage difficult-to-control weeds such as weedy rice.

1. Introduction

Rice production is crucial for global food security, and of high importance for Asia, as rice is a staple food for half of the world's population (GRiSP, 2013). For Cambodia, rice is even more important because it is a strategic commodity for poverty reduction, income growth, and national and household level food security. A high percentage of Cambodian farmers are dependent on rice directly or indirectly as rice is grown on about 75% of the cultivated land and is an important agricultural export commodity (IFC, 2015). In 2007, rice contributed to >10% of Cambodia's total export value (IMF, 2009). The average daily calorie intake from rice in Cambodia is 63%, which is much higher

* Corresponding author.
** Corresponding author.
Email addresses: virender.kumar@irri.org (V. Kumar); bob.martin@sydney.edu.au (R.J. Martin)

https://doi.org/10.1016/j.cropro.2019.04.017
Received 26 August 2018; Received in revised form 4 April 2019; Accepted 15 April 2019
Available online xxx
0261-2194/

than average of Asia (28.6%) (FAOSTAT, 2017 as reported by Kumar et al., 2017).

The tremendous progress Cambodia has made in improving rice productivity in recent years has changed the status of the country from rice deficit to surplus. The rice productivity increased from 1.6 t ha^{-1} in 1994–97 to current average yield of 3.5 t ha^{-1} (FAOSTAT, 2017), which is still only 58% of the yield potential (6.0 t ha^{-1}) (Martin et al., 2017). In addition, rice productivity and profitability in Asia is threatened by rising scarcity of resources such as labor and water, rising cost of inputs and cultivation, imbalanced input use of especially overuse of pesticides and under use of fertilizer., fluctuating farm-gate rice prices, emerging socio-economic changes, and climate change (Bouman, 2007; Stuart et al., 2017). The future challenge is to improve rice productivity using fewer resources (labor, water, energy, and agro-chemicals), and minimizing the environmental footprint while buffering the risk of climatic change.

The exploitable rice yield gap in Cambodia can partially be closed by minimizing yield losses caused by weeds, as yield losses due to weed competition are as high as 46% (Ikeda et al., 2008). Oerke et al. (1999) estimated that the potential and actual yield losses due to weeds in rice for Cambodia were 50–60% and 27%, respectively. Changes in rice farming practices can have implications for weed management practices, and therefore it is important to document farmers' current management practices, their knowledge gaps, and key emerging issues such as shifts to new methods/technologies, so that appropriate solutions can be developed and disseminated. For example, recently, Cambodian farmers rapidly shifted from puddle transplanted rice to direct seeded rice (DSR) and from hand weeding to herbicide-based weed control to cope with rising scarcity of agricultural labor in the country (Martin et al., 2017). In addition, there has been rapid adoption of mechanization for land preparation and harvesting (Chim et al., 2015). Prior to 2000, DSR was practiced in 10–30% of the total rice area, but by 2017, $>90\%$ farmers practiced DSR (Martin et al., 2017). This change can have strong implications for agronomic practices affecting weed management and weed population dynamics. For example, with the shift from transplanted rice to DSR, the seeding rate increased from 15 to 25 kg ha^{-1} to 100–200 kg (Martin et al., 2017). The trade-off with high seed rates was that farmers started using their own saved seed to reduce cost. This poses a high risk of weed seed contamination for growers (Martin et al., 2017). Many weed-related issues have emerged in areas where transplanted rice is largely replaced by DSR such as: (i) higher weed infestation with complex and diverse weed flora, (ii) increased reliance on herbicides for weed control leading to a higher risk of herbicide resistance, and (iii) shifts in weed flora towards more difficult-to-control weeds such as weedy rice (*Oryza sativa* f. *spontanea*) (Kumar et al., 2017; Rao et al., 2017).

Household studies are a useful approach to characterize farmers' weed management practices, identify key important weed species prevalent in the region, document agronomic practices influencing weed management, and identify knowledge gaps of farmers.

The purpose of this study is to provide an appraisal of the current situation regarding weed management in the lowland rice systems of Battambang province in Cambodia. The specific objectives were to: (1) understand farmers' agronomic practices related to weed management, (2) document farmers' knowledge and practices used for weed control, (3) identify key knowledge gaps in the current weed management practices of farmers, and (4) assess the level of weed seed contamination in farmers' saved paddy seed. The information obtained in this study will help researchers and extension agents develop and extend to farmers the appropriate weed control tactics tailored to improve weed management and other agronomic practices, and thus reduce the rice production yield gap for farmers in Battambang province in Cambodia.

2. Materials and methods

2.1. Study sites

This study was conducted in four communes of Battambang province in northwestern Cambodia in 2017: Ou Mal, Phnum Sampov, Preaek Norint, and Ta Kream (Fig. 1).

2.2. Household survey of rice farmers on agronomic practices, weed problems, management, and knowledge

A household survey of 100 farmers was conducted using a structured survey questionnaire with 25 farmers randomly selected from each of the four communes. The survey consisted of 49 questions that documented the farmer's profile/socio-demographic characteristics, farm characteristics, major weed species invading their rice farms in the main (wet) season, key agronomic practices, and farmers' knowledge and perception on weeds and their management practices. The survey questionnaire was developed in English and then translated verbally to Khmer during farmer interviews.

Data were collected on methods of land preparation, crop establishment, source of seed, seeding rates, rice varieties used and reasons for their preference, and fertilizer management. Farmers were asked to describe the severity of the weed infestation in their fields, their perception on losses caused by weed infestations, and major sources of weeds occurring in their rice fields and ranking these in order of importance. Details on farmers' current weed control practices were collected for both the dry and wet-season. Farmers were also asked about factors that affect their decision on herbicide selection, their major source of

Fig. 1. Location of Communes surveyed in Battambang provinces (shaded areas).

information on herbicide use, how satisfied they are with the performance of herbicides, which weeds are poorly controlled by herbicides, and which weed species were no longer controlled by herbicides (potential case of resistance evolution). Farmers were asked to describe their perceptions on the trends of weed problems and herbicide use in the last five years.

To identify the major weeds infesting their rice fields, farmers were shown photos of rice weeds and then asked to list the major species present in their fields and to rank the five most important. Farmers were asked about weedy rice and the level of infestation in their rice fields. Farmers' current seed cleaning practices were recorded. In addition, information on farmers' awareness of health hazards associated with herbicide application and use of personal protective equipment (PPE) during herbicide application were collected.

2.3. Estimating the weed seed contamination level in paddy seed

Paddy seed samples were collected at the end of the 2017 main wet-season to assess the level of weed seed contamination. One kg of paddy seed was collected from paddy seeds kept by farmers for sowing from each of the 100 farmers who were surveyed.

All paddy seed samples were inspected for the presence of weed seeds of different species. For this purpose, 300 g subsamples were taken from 1 kg collected samples. Weed seeds were collected by hand and inspected with a HOT S06 digital microscope with magnification up to 200x. For identification, weed seed specimens were compared with a collection of HOT seed images of 186 weed species commonly occurring in Cambodia (R. Martin unpublished). Weed species with seeds < 1 mm in length were most commonly represented in the paddy samples as intact capsules, spikes, spikelets or pod segments. For the purpose of this study, capsules, spikes, spikelets and pod segments were counted as single dispersal units, and the number of individual seeds contained in these was not recorded.

2.4. Statistical analysis

Data were analysed using R statistical software (R Core Team, 2017). The socio-demographic characteristics of the farmers were analysed using chi-square test to test the association between these parameters and study sites (communes). Reported yield data among communes were compared using ANOVA and the means separated using Tukey HSD post-hoc analysis. Exploitable rice yield gap was calculated using farmers' survey data as described by Stuart et al. (2016) using the equation: Exploitable yield gap = $EY_f - FY$, where.

EY_f: mean yield of the top decile farmers (yield of farmers above the 90^{th} percentile).

FY: mean yield of the full sample size.

Redundancy Analysis (RDA) was conducted using the 'vegan' package (Oksanen et al., 2016) in R statistical software to analyze the relationship between weed species diversity and commune location for species found as contaminants in paddy seed samples and for weed species reported by farmers as problematic in their rice fields and presented as a biplot chart.

3. Results

3.1. Socio-demographic characteristics of surveyed farmers

Rice farms in northwestern Cambodia are managed equally by both men and women; there was no significant difference between communes (Table 1). The age of rice farmers from different communes did not differ significantly. 50–60%, farmers were in the age group of 30–50 years. The education level of the farmers varied significantly between communes. Only 8% of farmers from Ta Kream and Preaek Norint had no formal education, whereas 12–16% farmers from Ou Mal and Phnom Sampov had no formal education. The majority of the farmers (68–84%) had lower or upper secondary or college education across four communes (Table 1). In addition, the rice environment did differ with commune; Ta Kream was mostly irrigated (92%), whereas other communes were mostly rainfed (favorable lowland) (76–92%). Among the surveyed farmers, 33% of farms had access to irrigation. The surveyed farmers ranged from small (0.0–1.0 ha), medium (1.1–3.0 ha) and large (> 3.0 ha). About 76% of the farmers had small or medium scale rice fields. The average farm size was 2.76 ± 0.25 ha. All farmers grew rice in the wet season and 53% grew rice in the dry season. In irrigated areas, the majority of the farmers preferred wet

Table 1
Socio-demographic characteristics of surveyed farmers from four communes in Battambang province of Cambodia in 2017.

Farmers' profile	Overall	Ou Mal	Phnom Sompov	Preaek Norint	Ta Kream	Chi-square	
	%					x^2 value	Prob
Gender							
Male	48	40	52	44	56		
Female	52	60	48	56	44	1.40	NS
Age							
17-30	18	16	16	20	20		
31-40	30	40	20	24	36		
41-50	24	20	40	20	16		
51-60	12	4	12	12	20		
> 60	16	20	12	24	8	11.3	NS
Education level							
No formal	11	16	12	8	8		
Primary	15	16	4	24	16		
Lower secondary	25	28	16	40	16		
Upper secondary	42	40	52	20	56		
College graduate	7	0	16	8	4	21.8	0.039[a]
Rice environment							
Irrigated	33	24	8	8	92		
Lowland rainfed (F)[a]	72	88	92	100	8	68.7	0.000***
Farm size							
0.0–1.0 ha	38	56	32	40	24		
1.1–3.0 ha	38	32	48	28	44		
3.1–5.0 ha	17	12	16	16	24		
> 5.0 ha	7	0	4	16	8	11.6	NS

Statistically significant at *P < 0.05; ***P < 0.001; NS = non significant.
[a] Lowland rainfed (F) is favorable lowland rainfed.

seeding of rice (e.g. in Ta Kream) and in favorable lowland rainfed sites, preference was more towards dry seeding of rice.

3.2. Farmers' reported paddy yields and exploitable yield gap in the surveyed areas

Paddy yields in the four communes varied significantly (Table 2). In the wet season, the mean yield of Ta Kream commune was highest (3.7 t ha^{-1}) and it was lowest in Ou Mal in 2016 and in Ou Mal and Phnum Sampov in 2017. In the dry season, in both years, rice yields in Preaek Norint were lowest and other communes did not differ in rice yields. During the wet season, rice yields were higher under irrigated environment than under lowland rainfed environment. Also, rice yields were higher for wet-seeding compared to dry seeding. However, in the dry-season, rice yields were similar in both rice environments. The exploitable/achievable rice yield gap in the study area ranged from 1.3 t ha^{-1} (40%) in the wet season to 1.1 t ha^{-1} (27–30%) in the dry season (Table 2).

3.3. Crop establishment, seeding method, seeding rate, source of rice seed, and varieties

Direct-seeding of rice was practiced by 100% of farmers with dry- and wet-seeding in equal proportion (Table 3). However, the type of direct-seeding method varied with the commune. For example, 88% farmers were using wet-seeding in the irrigated commune (Ta Kream), whereas dry-seeding was more commonly practiced (68–72%) in Ou Mal and Phnum Sampov, and both dry- and wet-seeding were equally practiced by farmers in Preaek Norint. A big variation was observed in the type of DSR depending on rice environment. In the irrigated environment, 96% of farmers opted wet-seeding and only 4% of farmers used dry-seeding. In rainfed lowland, 70% of farmers preferred dry-seeding and 30% wet-seeding. Both dry- and wet-seeding was established by manual broadcast methods by 100% of the farmers. The average seeding rate was 182 ± 3 kg ha^{-1} in the wet season and 181 ± 3 kg ha^{-1} in the dry season and it did not vary significantly with crop establishment method. Seed rate also did not vary with rice environment and rice establishment methods as average seed rate was in the range of 180–183 kg ha^{-1}. The seed rate ranged from 100 to 300 kg ha^{-1}. Pre-germinated seed was used for wet seeding with an average soaking time of 28 h and incubation for 38 h (majority followed 24 h soaking followed by 24 or 48 h of incubation).

In both wet and dry seasons, the source of seed was farmer–kept or bought from the neighbour (82–83%), 17% of farmers bought seed from seed companies or seed growers and 1% from government sources (Table 4).

Eight different varieties of rice were grown in the wet season and five in the dry season (Fig. 2). The most popular varieties for the wet season were Sen Kra Oub (31%), Srov Ngor (20%), Neang Khon (17%), Phka Rumduol (12%), and Riang Chey (7%) and in the dry season, Sen Kra Oub, and Srov Ngor were the most popular. With the exception of Sen Kra Oub (106 days), varieties grown in the wet season were of medium to long duration (130–180 days), whereas in the dry season most varieties were of short duration (100–120 days). Yield, pest/disease resistance, early maturity, ease of harvest, and price were the main criteria farmers considered when choosing a rice variety (data not shown).

The communes varied a lot in the choice of variety in both seasons (Fig. 2). In the wet season, Srov Ngor was widely used in Ta Kream (64%), whereas in other communes it was used by 0% (Preaek Norint), 4% (Ou Mal), and 12% (Phnum Sampov) of farmers. Preaek Norint farmers (88%) preferred San Kra Oub, whereas its adoption ranged from 4 to 24% in other communes. Neang Khon (48%) and Riang Chey (24%) were preferred in Ou Mal. Phkha Rumduol and Somaly were more preferred in Phnum Sampov than other communes. In the dry season, Srov Ngor was most popular in Ta Kream but was not grown by surveyed farmers in other communes. In Ou Mal, Preaek Norint, and Phnum Sampov communes, San Kra Ob was the most dominant variety (69–92%). Phka Malis was only grown in Preaek Norint by 31% farmers, and IR 504 was only grown in Ou Mal by 17% farmers.

3.4. Land preparation

Primary tillage was predominantly done by a 4-wheel tractor (97%), mostly by contractors, and the average month for first tillage in the wet season was June but primary tillage was done as early as March and as late as August. Seventy-three percent of primary tillage was done in the absence of water in the field. Secondary tillage was mostly done using a 2-wheel tractor owned by the farmer (85%), usually two weeks after the primary tillage. Wet-tillage (puddling) was carried out for wet-seeding whereas, no puddling was done for dry-seeding. The median duration of land preparation was 30 days and the duration of land preparation ranged from 15 to 75 days. In general,

Table 2
Mean paddy yield and exploitable yield gap in north-western Battambang province during wet and dry-season 2016 and 2017.

Parameter	Wet-season					Dry-season				
	N	2016		2017		N	2016		2017	
	Paddy yield (t ha^{-1})									
Commune										
Ou Mal	25	2.90	b[a]	3.16	b	7	4.37	a	4.25	a
Phnum Sampov	25	3.20	ab	3.06	b	11	3.95	ab	4.05	ab
Preaek Norint	25	3.38	ab	3.24	ab	12	3.30	b	3.25	b
Ta Kream	25	3.70	a	3.68	a	23	3.96	ab	3.69	ab
Crop establishment method										
Dry-seeding	51	3.09	b	3.10	b	11	4.09	a	4.00	a
Wet-seeding	49	3.48	a	3.53	a	42	3.64	a	3.82	a
Rice environment										
Irrigated	33	3.62	a	3.61	a	31	3.69	a	3.94	a
Lowland rainfed	67	3.11	b	3.13	b	22	3.80	a	3.75	a
	Exploitable yield gap									
Mean yield (t ha^{-1})	100	3.30		3.29		53	3.90		3.81	
Mean yield from top decile farmers' yield (t ha^{-1})	100	4.60		4.60		53	5.00		5.00	
Exploitable yield gap (t ha^{-1})	100	1.30		1.31		53	1.05		1.14	
Exploitable yield gap (%)	100	40		40		53	27		30	

[a] Within a column for each parameter (commune, crop establishment method and rice environment), means followed by the same letter are not different at the 0.05 level of probability using Tukey's HSD test.

Table 3
Rice establishment method, seeding method, and seed rate practiced by farmers in four communes of Battambang province in Cambodia (n = 100 farmers).

Parameter	Overall	Ou Mal	Phnum Sampov	Preaek Norint	Ta Kream
	%				
Rice establishment method[a]					
Dry-seeding	51	72	68	52	12
Wet-seeding	49	28	32	48	88
Seeding method					
Hand broadcast	100	100	100	100	100
Row-seeding	0	0	0	0	0
Seed rate (kg ha^{-1})[b c d]					
<100	0	0	0	0	0
100-150	23	24	24	16	28
151-200	67	76	72	56	64
201-300	10	0	4	28	8
>300	0	0	0	0	0

[a] In irrigated environment: 96% wet-seeding and 4% dry-seeding; In rainfed lowland (favorable) environment: 70% dry-seeding and 30% wet-seeding.
[b] Average seed rate = 182 ± 3 kg ha^{-1} in wet-season and 181 ± 3 kg ha^{-1} in dry-season.
[c] Average seed rate = 180 ± 4 kg ha^{-1} in dry-seeding and 183 ± 5 kg ha^{-1} in wet-seeding.
[d] Average seed rate = 183 ± 4 kg ha^{-1} in rainfed lowland, and 180 ± 6 kg ha^{-1} in irrigated system.

land preparation duration was longer (average 42 days) for wet-seeding compared to dry-seeding (32 days).

3.5. Fertilizer use

Ninety-five percent of farmers used fertilizer on rice in the wet season. Urea (82%) was the most commonly used fertilizer, followed by di-ammonium phosphate (DAP, 52%), ammonium phosphate (27%), N:P:K fertilizers (12%), and muriate of potash (8%). Overall, 91% of farmers applied N, 86% applied P and only 30% applied K. In the dry season, only 53% of farmers planted rice and among them 96%, farmers used fertilizer. Urea (75%) was the most commonly used fertilizer in the dry season, followed by DAP, 42%, N:P:K fertilizers (32%), ammonium phosphate (30%), and muriate of potash (9%). Overall, 96% of farmers applied N, 94% applied P and 35% applied K.

In the wet and dry season, the average amount of elemental N:P:K applied was 44 kg N ha^{-1}; 11 kg P ha^{-1}; and 4 kg K ha^{-1} and 49 kg N ha^{-1}, 13 kg P ha^{-1}, and 4 kg K ha^{-1}, respectively. Among communes, the lowest use of N and P was in Preaek Norint in both wet and dry season. In the wet-season, N use was 26 kg N ha^{-1} in Preaek Norint, whereas in other communes it was 46–54 kg ha^{-1}. P use was 4 kg ha^{-1} in comparison to 14 kg ha^{-1} in other communes. Similarly, in the dry season, N use in Preaek Norint was 37 kg ha^{-1}, whereas it was 50–56 kg ha^{-1} in other communes, and P use was 4 kg ha^{-1} in comparison to 12–21 kg ha^{-1} in other communes.. The overall use of K was low (3.3–7.5 kg ha^{-1} in both seasons) in all communes but there was almost no K use in Phnum Sampov commune in either dry or wet season.

The average N: P: K use in wet and dry season reported by farmers were 42: 10: 3.4 kg ha^{-1} and 45: 13: 4.4 kg ha^{-1}, respectively. On average, fertilizer use was slightly higher in irrigated compared to rainfed lowland environment. The N, P, and K use in the irrigated environment was 49, 16 and 6 kg ha^{-1}, respectively whereas; in rainfed lowland, it was 42, 10, and 3 kg ha^{-1}. The 10% of farmers who applied the most fertilizer in the wet and dry season applied an average of 88 kg N ha^{-1}; 22 kg P ha^{-1}; and 5 kg K ha^{-1}.

3.6. Farmers' perception on weed problem and yield loss caused by weeds

Ninety-three percent of farmers said that weed management was a major problem in their rice fields and infestations were ranked as moderate to severe (54 and 30% farmers, respectively) and only 16% of the farmers reported a low infestation level (Table 5). The majority of farmers (55%) said that the yield loss from weeds was >25%. The remaining farmers said yield losses were 20–25% (15%), 15–20% (13%), and 10–15% (10%). Only 7% farmers reported low yield loss (5–10%) due to weeds.

Perception of weed problems varied with the type of direct-seeding (wet- or dry-seeding) (Table 5). Ninety-eight percent of farmers reported weeds as a major problem in wet-seeding whereas, in dry-seeding, only 88% of farmers reported weeds as a major problem. The same trend was reflected in the farmers' reported yield loss –a high percentage of farmers (63%) reported yield loss >25% in wet-seeding whereas, in dry-seeding, only 47% farmers reported yield loss >25%. Similarly, about 90% of farmers reported moderate to severe weed problem in wet-seeding whereas in dry-seeding this number was 79%.

3.7. Important weeds nominated by farmers and farmers' knowledge on the source of the weed problem

Overall, the five most important weed species identified by farmers were *Fimbristylis* spp., *Echinochloa crus-galli*, *Oryza sativa* f. *spontanea*, *Cyperus iria* and *Leptochloa chinensis* (Table 6). Other weed species of importance were *Echinochloa colona*, *Ischaemum rugosum*, and *Eleusine indica*. According to farmers, weed species that were becoming an increasing problem included: *C. iria*, *E. crus-galli*, *E. colona*, *Fimbristylis* spp., *L. chinensis* and *O. sativa* f. *spontanea* (weedy rice).

Farmer's ranking of weeds invading their fields varied with the commune, rice establishment methods and rice environment (Table 6). For example, weedy rice was reported by only 8% of farmers in Ta Kream, whereas in other communes 55–84% farmers reported it as a major weed invading their rice fields. *E. crus-galli* was reported by the majority of farmers (88%) in Ta Kream but in other communes, it was reported by 44–48% farmers. Similarly, *L. chinensis* was reported by 72% farmers in Ta Kream but only 8% of farmers from Phnum Sampov and 28–40% farmers from other communes reported this weed as a problem in their rice fields. *E. indica* was more associated with Phnum Sampov as reported by 28% farmers whereas in other communes it was not (4%) reported as a problem weed. *E. prostrate* was more associated with Ou Mal and it was not reported by farmers from Ta Kream and Preaek Norint and only by 4% farmers from Phnum Sampov.

L. chinensis and *C. difformis* were more associated with wet-seeding compared to dry-seeding (Table 6). In contrast, *E. prostrate* and *I. rugosum* were more associated with dry seeding. Weed species such as *F. miliacea, C. iria, E. crus-galli, E. colona* and weedy rice were reported by both dry and wet-seeding farmers.

Farmers recognized that the major sources of weed seeds in their fields were the seed bank (in the soil, 68%), contaminants in sowing

Table 4
Source of rice seed for sowing used by farmers in Battambang province of Cambodia (N = 100).

Season	Own seed	Own + Neighbour	Neighbour	Seed company	Own + Seed grower	Own + seed company	Own + Govt
	%						
Wet season	32	32	18	8	5	4	1
Dry season	20	43	20	13	4	0	0

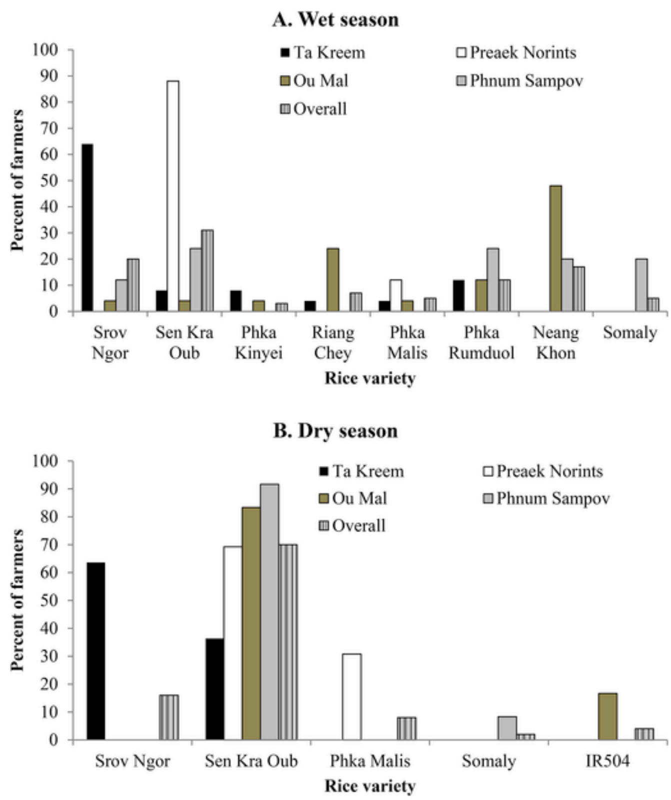

Fig. 2. Rice varieties grown in the wet (A) and dry season (B) from four communes in Battambang province.Note: Overall is the average value of all the four communes.

Table 5
Farmers' perception on weed problems and losses caused by weeds in their rice fields (N = 100).

Parameter	Overall (N = 100)	Dry-seeding (N = 51)	Wet-seeding (N = 49)
	% farmer		
Are weeds a major problem in your field?			
Yes	93	88	98
No	7	12	2
Yield losses caused by weeds (%)			
5-10	7	12	2
10-15	10	10	10
15-20	13	14	12
20-25	15	18	12
>25	55	47	63
Severity of weed problem			
Low	16	21	10
Moderate	54	57	51
Severe	30	22	39

seed (64%), transfer from field-to-field by machinery (46%), livestock and irrigation water (13–14%) [Data not shown].

3.8. *Farmers knowledge on weed control (herbicide use, hand weeding, application techniques, and emerging weed management issues*

One hundred percent of farmers used herbicides (Table 7). All the farmers relied on post-emergence herbicides for weed control and no farmer used pre-emergence herbicides. Only 18% of farmers hand-weeded. Most of the farmers (72%) who used hand weeding did so once; only 28% hand weeded their field twice. If doing hand weeding once, most of farmers hand weeded at 30 days after sowing (DAS), whereas when hand weeded twice, the timing was either at 15 and 30 DAS or 30 and 55–60 DAS.

The most commonly used herbicide was 2,4-D (76%) and 18% of farmers used 2,4-D as the only herbicide. Other herbicides used were bispyribac-sodium (32%), pyribenzoxim (27%), quinclorac + pyrazosulfuron + fenoxaprop (26%), propanil + clomazone (9%) and bensulfuron + quinclorac (2%) (Table 8). Types of herbicides used for weed control varied with the commune and type of DSR method. Pyribenzoxim was widely (64%) used in Ta Kream whereas in Preaek Norint it was used by only 5% farmers and in other communes, 20–27% farmers used this herbicide. Propanil + clomazone (pre-mix) was used by 18–20% farmers in Ta Kream and Preaek Norint but no surveyed farmer use this herbicide in OuMal and Phnum Sampov. Except in Ta Kream, bensulfuron + quinclorac (pre-mix) was not used in any of the communes. Bispyribac-sodium was used less in Ta Kream (18%) but in other its used ranged from 29 to 32% in Ou Mal and Phnum Sampov to 55% in Preaek Norint. 2, 4-D was used widely in all the communes. Quinclorac + pyrazosulfuron + fenoxaprop (pre-mix) use varied as follows: Phnum Sampov and Preaek Norint (35–38%) > Ta Kream (23%) > Ou Mal (12%).

Pyribenxozim, propanil + clomazone, and bensulfuron + quinclorac were more associated with wet-seeding (Table 8). Herbicides such as bispyribac-sodium, 2, 4-D, and quinclorac + pyrazosulfuron + fenoxaprop were used equally in both dry and wet-seeding. Majority of farmers used higher doses than recommended. For example, 70% of farmers who used bispyribac are using at 50 g ai ha^{-1}, whereas the recommended dose is 20–30 g ai ha^{-1}. Similarly, pyribenzoxim is applied at either lower or higher dose than recommended. For example, 40% of farmers using pyribenzoxim used at 50 g ai ha^{-1}, 33% farmers used at 25 g ai ha^{-1} and remaining used at a range from 8.0 g to 17.5 g ai ha^{-1}. The application rate of 2,4-D also varied a lot among farmers.

The median time for the first herbicide application was 25 DAS and 30 DAS for the second application. About 35% farmers apply their first herbicide around 30 DAS and 23% 22% farmers apply their second herbicide >40 DAS (data not shown). Majority of farmers (88%) did not drain their field prior to post-emergence herbicide application and only 12% of farmers drained their fields prior to herbicide application (Table 7). These results suggest that there is lack of knowledge on the use of right doses, right time of application and right method of application (application technology).

The majority of the farmers (75%) relied on the advice of input dealers for the choice of herbicide (Table 7). Other sources of information for the surveyed farmers were other fellow farmers (46%), chemical companies (8%), and herbicide label (19%). Only 30% of farmers were happy with the performance of herbicides but none could specify weeds not controlled or why they were not happy.

Ninety-eight percent of farmers used power backpack sprayers and 2% used battery powered sprayers (Table 7). Farmers were asked if they calibrated sprayers and 96% said no, however for these types of sprayers, farmers apply a specified volume per hectare and that could be the reason that farmers are not calibrating their sprayer prior to application. About 29% of farmers did not know what kind of nozzle they used for spraying, whereas 23% of farmers were using the hollow cone nozzle type which is not recommended for herbicide application. The remaining farmers used cut/flood (41%) and flat fan (6%) type nozzles. The majority of farmers used sprayers with a boom fitted with more than one nozzle with an average of five and maximum of seven nozzles per boom.

The majority of farmers (53%) said they changed herbicides every year, 18% changed herbicides every 2 years, 14% seasonally and 14% did not change herbicides. When asked whether herbicide use increased over time most farmers said they were increasing their use of herbicides (93%) while 5% said herbicide use was not changing and 2% said herbicide use was decreasing. Most farmers (94%) said they were aware of pesticide exposure risks. However, the use of personal

Table 6
Farmer ranking of weed species invading their rice fields in different commune, and under different rice establishment methods and rice environments (%) (N = 100).

Weed	Commune					Establishment method		Rice environment	
	Ou Mal	Phnum Sampov	Preaek Norint	Ta Kreem	Overall	Dry-seeding	Wet-seeding	Irrigated	Rainfed lowland
	%								
Alternanthera sessilis	8	0	0	0	2	4	0	0	3
Ammannia spp	0	0	8	0	2	2	2	0	3
Commelina spp	0	0	4	0	1	1	0	0	1
Cynodon dactylon	0	4	8	0	3	2	4	0	4
Cyperus difformis	8	0	8	8	6	2	**10**	11	4
Cyperus iria	**56**	**32**	**28**	**48**	**41**	**47**	**35**	43	40
Cyperus rotundus	4	**12**	4	8	7	8	6	4	8
Dactyloctenium aegyptium	4	**12**	4	0	5	4	6	0	7
Eclipta prostrata	**28**	4	0	0	8	**12**	4	0	11
Echinochloa crus galli	**44**	**44**	**48**	**88**	**56**	**47**	**65**	82	46
Echinochloa colona	8	8	**24**	**12**	13	12	14	14	13
Eleusine indica	4	**28**	4	4	10	12	8	11	10
Fimbristylis miliacea	**64**	**80**	**80**	**68**	**73**	**73**	**73**	68	75
Ischaemum rugosum	**16**	**20**	12	4	13	**18**	8	7	15
Ipomoea aquatica	8	8	**20**	0	9	14	4	0	13
Leptochloa chinensis	**28**	8	**40**	**72**	**37**	18	**57**	68	25
Ludwigia hyssopifolia	12	0	4	4	5	4	6	4	6
Marsilia spp.	8	0	0	0	2	4	0	0	3
Oryza sativa	**68**	**84**	**60**	8	**55**	65	45	21	68
Saggitaria	0	0	4	0	1	0	2	0	1
Sphenoclea zeylanica	0	4	12	4	5	4	6	0	7
Paspalum scrobiculatum	**20**	0	0	4	6	8	4	7	6

Table 7
Weed control practices and knowledge on spray techniques and safety used by farmers (%) (N = 100).

Parameter	%	Parameter	%
Herbicide used for weed control		Source of information on herbicide use	
Yes	100	*Input dealer*	75
No	0	*Other farmers*	46
Type of herbicide use		*Chemical companies*	8
Pre-emergence	0	*Herbicide label*	19
Post-emergence	100	Type of sprayer used	
Hand weeding for weed control		*Power back pack*	98
Yes	18	*Battery operated*	2
No	82	Nozzle type used	
Number of hand weeding		*Hollow Cone type*	23
One	72	*Cut/flood jet*	41
Two	28	*Flat fan*	6
		Did not know	29
Do you drain standing water prior to POST application		Types of spray boom	
Yes	12	*Single nozzle*	14
No	88	*Multiple nozzle*	86
Satisfied with herbicide efficacy			
Yes	30	Are you aware of pesticide exposure risks?	
No	70	*Yes*	94
Sprayer calibration prior to use		*No*	6
Yes	4	Herbicide use	
No	96	*Increasing*	93
Do you change herbicide?		*Decreasing*	2
Yes	86	*No change*	5
No	14		

protective equipment (PPE) was at a low level of sophistication: face-mask (76%), hat (73%), long shirt (67%), and gloves (54%). Only 10% of farmers wore boots and none used gas masks or aprons.

About 83% of farmers thought that some weed species were developing herbicide resistance. However, no farmers were able to nominate a weed species that was no longer controlled by a particular herbicide. The main reason for use of herbicides cited was efficacy (74%) but the cost of labor for hand weeding was mentioned by 29% of farmers. The main weed management issues cited by farmers were the high cost of labor and herbicides (68%), lack of knowledge (62%) and misuse of herbicides (45%).

3.9. Weed seed contamination in paddy seed samples

All the seed samples (100%) were contaminated with weed seeds. Seeds of 34 weed species, representing 12 families, were identified in paddy seed samples (Table 9). The most important families were Poaceae (9 species), Cyperaceae (8 species) and Fabaceae (4 species). Thirteen small-seeded species were present in the form of spikelets (e.g. *Fimbristylis* spp.) or capsules (e.g. *Lindernia antipoda*). Species with small seeds that separate from the spikelets or panicles such as *L. chinensis* were not found.

The most common weed seed contaminants found in paddy seed samples were *O. sativa* f *spontanea* (awnless biotype) (92%), *Fimbristylis miliacea* (50%), *E. crus-galli* (42%), *E. colona* (33%), *O. sativa* f. *spontanea* (awned biotype) (28%), *L. antipoda* (23%), *I. rugosum* (22%), *Cyanotis axillaris* (21%), *Melochia corchorifolia* (20%), and *Paspalum scrobiculatum* (12%) (Table 9). In one kg of farmer-kept seeds, a mean of 570 ± 72 seeds of weedy rice (both awnless and awned biotypes) were detected. Similarly, a mean of 190 ± 40 seeds of *Echinochloa* species per kg of paddy seeds were found. The mean number of weed seeds/propagules of all weed species was 1,072 ± 106 kg^{-1}, which is equivalent to, 192,960 seeds ha^{-1} assuming a field is sown with a seed rate of 180 kg ha^{-1}.

Awned and awnless weedy rice biotypes did not vary significantly between communes (Fig. 3A). *E. crus-galli, F. miliacea* and *E. colona* were the most frequently occurring contaminants under the more intensive production systems in Ta Kream and Preaek Norint communes. The weed composition under drier and less intensive conditions in Ou Mal commune was characterized by a greater frequency of *M. corchorifolia*, *C. axillaris* and *I. rugosum* (Fig. 3a). The weeds listed by farmers as infesting their fields showed a similar pattern to the weed seeds found in farmer-kept paddy seed samples with *Echinochloa* spp. associated

Table 8
Major herbicides used for weed control in different communes and crop establishment methods in Battambang province of northwest Cambodia[a].

Parameter	N	Bensulfuron + Quinclorac	Bispyribac-sodium	Propanil + Clomazone	Pyrinbenzoxim	2,4-D	Quinclorac + Pyrazosulfuron + Fenoxaprop	Quinclorac + Pyrazosulfuron
Commune								
Ou Mal	*25*	0	32	0	20	92	12	0
Phnum Sampov	*24*	0	29	0	21	71	38	4
Preaek Norint	*20*	0	55	20	5	65	35	0
Ta Kreem	*22*	9	14	18	64	73	23	0
Average	*91*	2	32	9	27	76	26	1
CE method								
Dry-seeding	*47*	0	28	4	17	79	28	0
Wet-seeding	*44*	5	36	14	39	73	25	2

[a] Herbicide use was same in both dry and wet-season.

Table 9
Frequency (%) of seeds of weed species found in paddy seed samples in order of importance and average number of weed seeds of these contaminant in one kg of farmers' kept seed samples; combined from four provinces in Battambang (n = 100).

Family	Weed species	Freq. (%)	Seeds (kg^{-1})	Form[a]
Poaceae	*Oryza sativa* f. *spontanea* (awnless)	92	543.93	S
Cyperaceae	*Fimbristylis miliacea* (L.) Vahl	50	83.00	P
Poaceae	*Echinochloa crus galli* (L.) Beauv.	42	103.03	S
Poaceae	*Echinochloa colona* (L.) Link	33	86.60	S
Poaceae	*Oryza sativa* f. *spontanea* (awned)	28	25.40	S
Linderniaceae	*Lindernia antipoda* (L.) Alston	23	36.90	P
Poaceae	*Ischaemum rugosum* Salisb.	22	18.27	S
Commelinaceae	*Cyanotis axillaris* (L.) D. Don ex Sweet	21	13.20	S
Malvaceae	*Melochia corchorifolia* L.	20	48.47	S
Poaceae	*Paspalum scrobiculatum* L.	12	10.93	S
Cyperaceae	*Fimbristylis dichotoma* (L.) Vahl	10	5.03	P
Poaceae	*Pennisetum pedicellatum* L.	9	12.43	S
Poaceae	*Panicum repens* L.	7	6.23	S
Fabaceae	*Aeschynomene americana* L.	7	4.13	S
Cyperaceae	*Cyperus iria* L.	7	0.70	P
Malvaceae	*Pentapetes phoenicea* L.	6	2.87	S
Phyllanthaceae	*Phyllanthus virgatus* G. Forster	5	7.53	P
Cyperaceae	*Fimbristylis ovata* (Burm. F) J. Kern	5	1.53	P
Cyperaceae	*Scleria lithosperma* (L.) Swartz	4	4.67	S
Poaceae	*Digitaria bicornis* (Lam.) Roemer & J.A. Schultes ex Loud.	4	3.10	S
Boraginaceae	*Heliotropum indicum* L.	4	2.10	S
Asteraceae	*Actinoscirpus grossus* (L.f.) Goetgh. & D. A. Simpson	4	2.43	P
Phyllanthaceae	*Phyllanthus urinaria* L.	4	1.10	P
Xyridaceae	*Xyris indica* L.	4	0.53	P
Cyperaceae	*Cyperus difformis* L.	3	0.30	P
Asteraceae	*Eclipta prostrata* (L.) L	2	7.57	S
Fabaceae	*Aeschynomene aspera* L.	2	2.00	S
Asteraceae	*Chromolaena odorata* L. R.M.King & H.Rob.	2	0.33	S
Onagraceae	*Ludwigia octovalvis* (Jacq.) P.H.Raven	2	0.20	P
Convolvulaceae	*Ipomoea obscura* (L.) Ker Gawler	1	0.33	S
Fabaceae	*Aeschynomene indica* L.	1	0.10	S
Fabaceae	*Alysicarpus monilifer* (L.) DC	1	0.10	S
Cyperaceae	*Schoenoplectus juncoides* Roxburgh	1	0.33	P
Cyperaceae	*Schoenoplectus supinus* (L.) Palla	1	0.23	P

[a] S = seed; P = propagule (capsule, spikelet etc).

with Ta Kream, *Fimbristylis* spp. with Preaek Norint and broadleaf species (e.g. *Eclipta prostrata*) with Ou Mal (Fig. 3 B).

Seeds of weedy rice (*O. sativa* f *spontanea*) were found in 92% of paddy seed samples but only 55% of farmers listed this species as occurring in their fields (Fig. 4). Farmers did not list weed species such as *L. antipoda*, *C. axillaris*, *M. corchorifolia* as their important weeds but they were found in their paddy seed samples. The grass, *P. scrobiculatum*, was found in farmer-kept seed samples but not listed by farmers. *F. dichotoma* was not listed by farmers but it is likely they didn't distinguish this species from *F. miliacea*. Weed species including *C. iria* and *L. chinensis* were considered important weeds by farmers (Table 6, Fig. 4) but these species were not found in paddy seed samples (Table 9 and Fig. 4).

The top 10 weed contaminants in paddy seed samples in 2017, a wet year, was compared with 2016, a dry year (Fig. 5). *O. sativa* f. *spontanea* (awnless weedy rice) was by far the most frequent weed seed contaminant in the harvested paddy in both 2016 (95%) and 2017 (92%). The weed species that were more frequent in the wet year were *F. miliacea*, *Echinochloa* spp., and *L. antipoda*. The species that were more frequent in the dry year were *I. rugosum*, *M. corchorifolia,* and *P. scrobiculatum*.

When farmers were interviewed to determine their knowledge about weedy rice, 94% of farmers said they were aware and 67% said they had weedy rice in their fields and of these, 50% described weedy rice as a minor problem and 17% described it as a severe problem (Table 10). This implies that almost 27% of farmers were apparently not aware they had weedy rice in their fields as 95% of samples were contaminated with weedy rice.

Regarding cleaning methods for seed kept for sowing, 24% of farmers did not clean their kept seeds prior to sowing, however, 76% of farmers did clean their seed. Among the seed cleaning practices, winnowing was used by 34% of farmers, floatation by 28% of farmers and 14% of farmers used both winnowing and floatation. No farmers used a sieving method for cleaning paddy seeds (Table 10).

4. Discussion

4.1. Household survey of rice farmers on agronomic practices, weed problems, management, and knowledge

In all the study sites, rice was established by DSR using manual broadcasting by 100% of the farmers with an average seeding rate of 181 kg ha^{-1} (Table 3). Martin et al. (2017) in their survey study conducted in Battambang and Takeo province of Cambodia also found that 97% farmers were practicing DSR using a similar seed rate. The majority of the farmers used their own saved seeds or seed purchased from neighbouring farmers (82–83%) for planting rice in both dry and wet season and only 8–13% farmers bought seeds from a seed company (Table 4). These results are similar to the findings of Martin et al. (2017). Chin (2001) reported a similar situation in Vietnam, where 81% of farmers use their own saved seeds for rice sowing and only < 5% farmers buy certified seeds.

Some of the possible reasons for using a high seed rate are as follows: (1) broadcast method instead of mechanized seeding, (2) using own-saved seeds rather than certified seeds, which have high probability of poor quality with low germination rate, (3) compensating the potential losses in the field including predation, poor germination and seed/seedling mortality due to inundation caused by untimely rain (Kumar and Ladha, 2011), and (4) to suppress weeds (Chauhan, 2013). The risk of seed predation by birds or rodents could be high in wet-DSR because pre-germinated seeds are sown on the soil surface. In India, a seed rate of 20–25 kg ha^{-1} is recommended for mechanized dry-DSR (Kumar and Ladha, 2011). Wang et al. (2014) in China also found that when wet-DSR was sown with a mechanical row hill seeder, a seed rate of 20–25 kg ha^{-1} generated yields higher than broadcast DSR and similar to puddled transplanted rice. These results suggest that there is huge scope for reducing seeding rate and potentially seed cost by using mechanized seeding. However, low seed rates under DSR systems should be accompanied with effective integrated weed management to avoid competition from weeds.

All the paddy seed samples of farmer-kept seeds were contaminated with weed seeds. Based on initial experimentation, the seeding rate in Battambang can be reduced to 45 kg ha^{-1} if rice is drill-seeded (W Zwick pers. Comm. cited in Martin et al., 2017). A low seed rate would enable farmers to afford good quality seed free from weed seeds, as a high seed rate is an important bottleneck for adoption of good quality seeds. Martin et al. (2017) estimated that the cost of drill-seeding with quality seed free from weed [more expensive (US$ 0.75 kg^{-1}) than farmers saved seed (US $ 0.25 kg^{-1})] is similar to hand broadcast DSR with the current seed rate. However, this would reduce weed problem in the long-run by reducing introduction of weed seeds through contaminated paddy seeds.

The predominant soil type in Battambang province is Toul Samroung (White et al., 1997). This soil is characterized by brown or gray clayey or loamy topsoil that develops moderate to large cracks on drying. The fertilizer recommendation for rice for this soil type is N:P:K: 86:30:10 kg ha^{-1} (Blair and Blair, 2014). However, results showed that

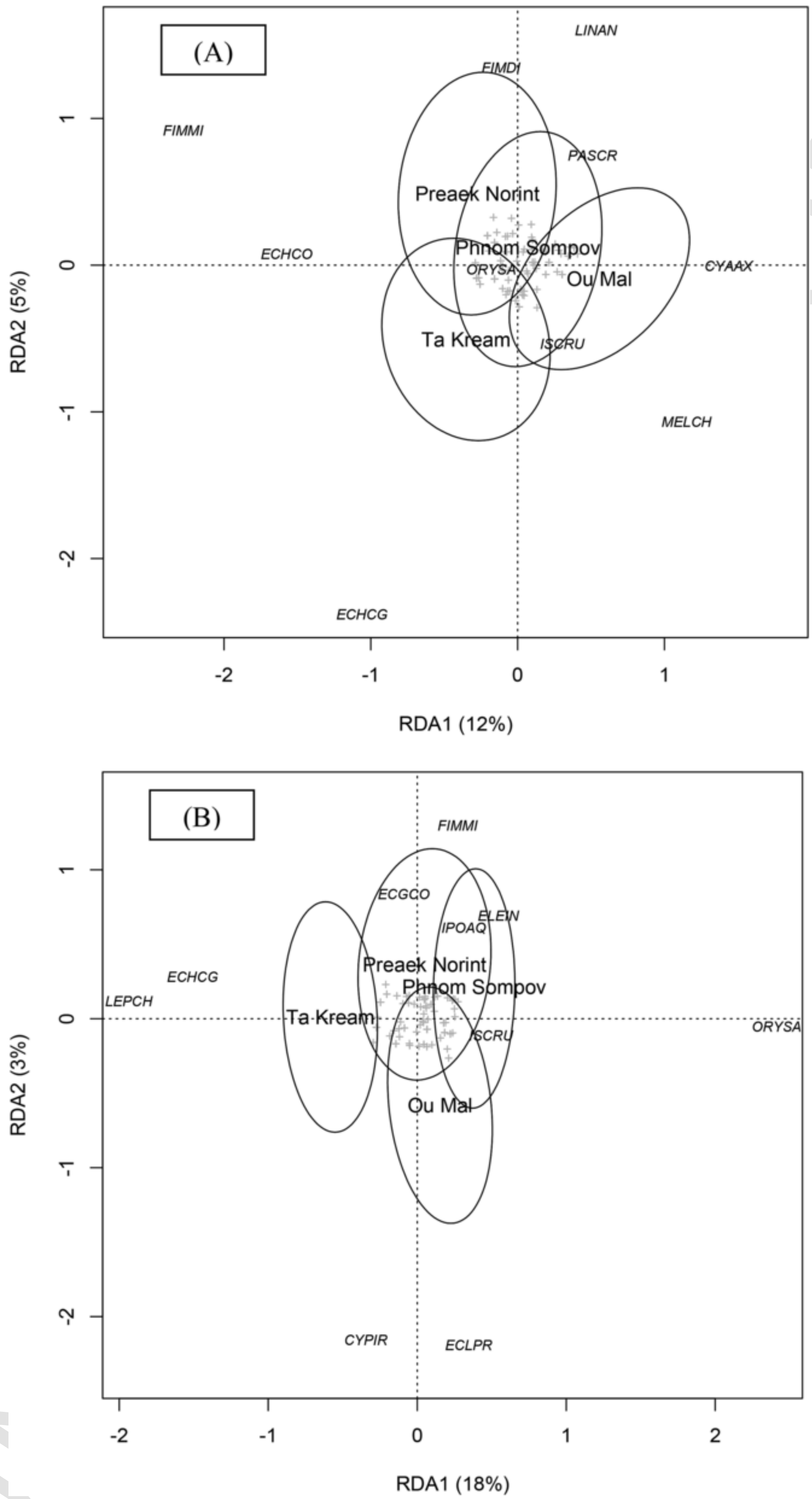

Fig. 3. Redundancy analysis (RDA) of weed species diversity of contaminants in paddy seed samples (A) and of weed species as reported by farmers in their fields (B), in relation to commune location in Battambang province.Weed abbreviations: ORYSA = *Oryza sativa* (weedy rice); ECLPR = *Eclipta prostrata*; CYPIR = *Cyperus iria*; LEPCH = *Leptochloa chinensis*; ECHCG = *Echinochloa crus-galli*; ECHCO = *Echinochloa colona*; FIMMI = *Fimbristylis miliacea*; FIMDI = *Fimbristylis dichotoma*; ISHRU = *Ischaemum rugosum*; ELEIN = *Eleusine indica*; IPOAQ = *Ipomoea aquatic*; MELCH = *Melochia corchorifolia;* CYAAX = *Cyanotis axillaris; PASCR* = *Paspalum scrobiculatum*; LINAN = *Lindernia* spp.

fertilizer used by farmers in both wet and dry season was well below the recommended rate: 50, 63, and 60% lower than recommended rates of N, P, and K, respectively. The top 10% high yielding farmers who are using high fertilizer were using adequate N (88 kg N ha^{-1}) but P and K was 23 and 50% below the recommended rate, respectively. The combination of high seed rate and fertilizer application below rec-

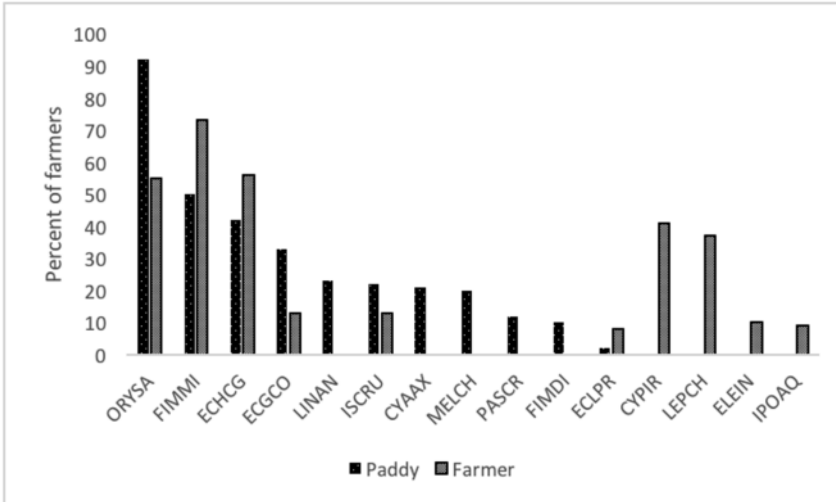

Fig. 4. Weed species frequency (a) contaminants in paddy seed samples and (b) farmer ranking of weed species in their fields in four communes in Battambang province. Refer Fig. 3 for weed abbreviations.

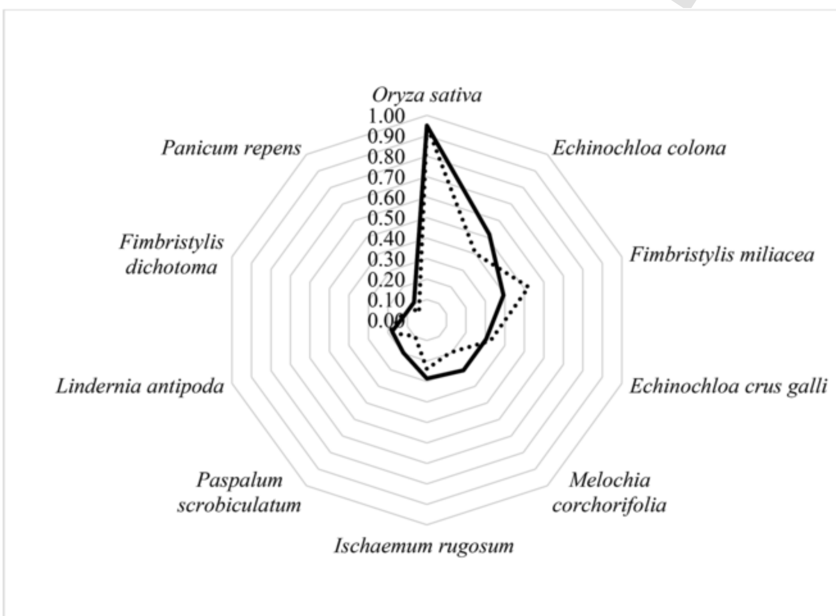

Fig. 5. Frequency (%) of the 10 most common weed seeds found in paddy seed samples in the 2017 wet season (dotted line) in this study compared to the 2016 (solid line) wet season-Note: 2017 was a wet year and 2016 was a dry year.

Table 10
Farmer's knowledge about weedy rice and their seed cleaning practices.

Parameter	%
% farmers familiar with weedy rice	94
% farmers reported weedy rice presence in their field	67
% farmers reported weedy rice a severe problem	17
% farmers reported weedy rice a minor problem	50
% farmers reported no weedy rice problem	33
Seed cleaning prior to seeding	
Yes	76
No	24
Method of seed cleaning	
Sieving	0
Winnowing	34
Floatation	28
Floatation + winnowing	14

ommended rates may further reduce the yield potential as there might be more competition among plants at high plant densities for nutrients. It has been reported that at harvest, N uptake and N translocation declined at higher seeding rates which resulted in lower yield compared to lower seed rates (Mahajan and Chauhan, 2016). Therefore optimal fertilization becomes more important under high seeding rates. Cambodian farmers have identified high price as the main constraint to adoption of inputs such as fertilizer (Anon., 2015). The concept of site-specific nutrient management (SSNM) (Dobermann and White, 1999) is recommended as an extension tool to assist farmer decision making for optimized fertilizer applications. This should include a 'real-time' approach to N management where the timing and rate of N is adjusted to estimated crop needs using recommendations based on readings of canopy greenness (Peng et al., 1996).

The majority of surveyed farmers indicated that weeds were one of the main constraints in their rice cultivation. An exploitable yield gap of 40% ($1.3\,t\,ha^{-1}$) in wet-season and of 30% ($\sim 1.0\,t\,ha^{-1}$) in dry season was estimated from the data collected (Table 2). These results indicate that poor weed control, fertilizer applications below recommended rates, and rainfed conditions (only 33% farms had access to irrigation) could be important contributors to the yield gap. Research is required to quantify the relative effects of integrated weed and fertilizer management, and supplemental irrigation on closing the yield gap. All these conditions (low fertilizer, poor water control) shift crop-weed competition in favor of weeds because of poor crop canopy development. In Cambodia, Ikeda et al. (2008) reported a rice yield loss by up to 46% due to weed competition.

The five most important weed species nominated by farmers were *Fimbristylis* spp., *E. crus-galli*, *O. sativa* f. *spontanea* (weedy rice), *C. iria* and *L. chinensis*. These species typically predominate in DSR rice under conditions of insufficient water supply (Juraimi et al., 2013). Direct seeding results in more difficult to control weeds, especially, weedy rice (Azmi and Baki, 2002). In other areas of Cambodia, where direct-seeding has been carried out for some years, grasses such as *Echinochloa* spp. and *L. chinensis* have also become more prevalent and are proving difficult to control. In contrast to findings of Martin et al. (2017), farmers in this study did not mention submerged and floating weeds (Hydrocharitaceae, Hydrophyllaceae, Marsileaceae, Nymphaeaceae, Pontederiaceae), which suggests that the majority of the rice fields have less access and control of irrigation water compared to the Kamping Puoy Irrigation Area. In a field survey conducted by Castilla et al., 2019) (unpublished) in four provinces of Cambodia including Battambang to assess the pest injuries and weeds incidence in rice fields also reported *Echnochloa* spp, *L. chinensis*, and *C. iria* as dominating weed species in Battambang similar to our study. In contrast to this study, they also reported *Aeschynomene aspera* as another dominant weed species in rice fields in Banan district of Battambang. The seeds of *M. corchorifolia* were found in 20% of farmer-kept seed samples but farmers did not list this as an important weed. Martin et al., (2017) found that farmers did not recognize some common weed species such as *M. corchorifolia*.

One hundred percent of surveyed farmers in Battambang province used herbicides for weed control. Survey results indicate that knowledge gap exists among farmers for selection of the right herbicides and their proper application practices. Farmers used total post-emergence herbicides; none used pre-emergence herbicides. Pre-emergence herbicides (pretilachlor with fenclorim safener for wet-DSR; pendimethalin, oxadiargyl, oxadiazon, and pretilachlor with fenclorim safener for dry-DSR), are highly recommended for achieving effective weed control in wet-DSR and dry-DSR to avoid early weed competition (Chauhan, 2012; Kumar and Ladha, 2011). Authors observed the availability of these herbicides in the local input stores. Furthermore, 15% of farmers used 2, 4-D as the sole herbicide and this would contribute to the grass-dominated weed problem. Generally, it is recommended to drain water in the field prior to post-emergence herbicide application; however, only 12% of farmers drained their fields prior to post-herbicide application. Although multiple-nozzle spray booms are commonly used (86% of farmers), only 7% said they used flat-fan nozzles. Flat-fan nozzles should be used on multiple-nozzle booms as the spray pattern is tapered from the center to the edges to create a uniform coverage through overlapping with adjacent nozzles (Bellinder et al., 2002; Chauhan, 2012). The knowledge of sprayer calibration and application techniques is lacking among farmers. Only 4% of the surveyed farmers calibrate their sprayer prior to herbicide application. However, based on our own personal observation, we found that Cambodian farmers generally sweep the spray boom from side to side, as they walk through the crop, and this might explain why they do not use flat-fan nozzles. Not only does this method result in uneven application, the operator has high exposure to the spray drift. Although 92% of farmers said they were aware of pesticide risks, the choice of personal protective equipment (PPE) indicated that their level of exposure during application is likely to be high considering the way the spray boom is used and use of boots (10%) and gloves (54%) was low. Moreover, power sprayers are widely used which is not recommended for herbicide application because of the high risks of drift associated with these sprayers due to the high pressure. Input dealers (75%) or fellow farmers (46%) were the key sources of information for the surveyed farmers in the selection and use of herbicides for weed control in their rice fields. Together these findings suggest that knowledge gap exists among farmers, as well as local input suppliers, on the selection of herbicides and application techniques.

More than 40 varieties of rice are grown across northwestern Cambodia (Cross et al., 2017). However, in localized areas such as the cluster of communes in this study, only nine varieties were grown (Fig. 2). As with the Cross et al. (2017) survey, the short-duration Sen Kra Oub was the most popular variety in both wet and dry seasons (Fig. 2). The preference for short-duration varieties is consistent with the number of farms with access to irrigation (33%) and 53% of farmers grew rice in the dry season. The local variety, Srov Ngor accounted for 20% but did not feature in the Cross et al. (2017) survey. Other varieties such as Neang Khon, Phka Rumduol, and Riang Chey featured in the Cross et al. (2017) survey.

Farmer's reported yield varied according to commune, rice environment, and rice establishment method. The possible reasons for higher yield in Ta Kream compared to other communes during wet-season could be because rice in Ta Kream was mostly (92%) irrigated, whereas in other communes it was rainfed. The average rice yield of Preaek Norint was statistically similar to Ta Kream during wet-season despite rainfed nature of rice farming and use of low N fertilizer. It could be because (1) 48% of sampled farmers used wet-seeding and this commune has better access of soil and water being in seasonally flooded land leading to flooding of rice fields between September and November which may have enhanced nutrient availability and reduced weed competition, and (2) majority of sampled farmers in Preaek Norint used photo-insensitive varieties as used by high yielding irrigated commune, Ta Kream whereas, in other communes, a significant area was under photosensitive rice varieties which are more sensitive to planting dates. In contrast, the lowest average rice yield of this commune during dry season could be because of use of low N and P fertilizers compared to other communes (e.g. 37 kg N ha^{-1} versus 49–56 kg N ha^{-1} and 4 kg P ha^{-1} versus 12–21 kg P ha^{-1}). The lower yield of Ou Mal compared to other communes could be because Ou Mal has the least access to water and is also on difficult soil type.

The possible reason for higher yields of wet-seeding than dry-seeding in wet season could be because wet-seeding was grown under irrigated conditions whereas dry-seeding was mostly under rainfed lowland environment. However, no difference was observed in dry season mainly because only those farmers who had access to irrigation grew rice during dry season.

4.2. Weed seed contamination level in paddy seed samples

The majority of farmers (100% of samples were contaminated) in Battambang are returning a substantial amount of weed seeds back to their rice fields by using contaminated paddy seeds. Based on the average contamination level (1,072 weed seeds kg^{-1} paddy seed), it equates to 192,960 weed seeds per hectare. Weed seed contamination therefore is an important issue in DSR where farmers use their own saved seeds. Similar findings have been reported elsewhere in Southeast Asia (Rao et al., 2017).

The five most frequent weed species found as contaminants in paddy samples were *O. sativa* f. *spontanea* (92%) *F. miliacea* (50%), *E. colona* (42%), *E. crus galli* (33%), and *I. rugosum* (28%). Farmers also ranked the same species as important in their farm. However, *C. iria* and *L. chinensis* were also ranked as important by farmers but we did not find seeds of these species as major contaminants in paddy seed samples (Tables 6 and 9, Fig. 4). It is possible that *C. iria* sheds seeds before harvest and that the small seeds of *L. chinensis* are removed by the harvesting machine or shattered prior to harvest.

We also observed seasonal variation in the type of weed seed contaminants. The marked differences in the most common weed seeds found in the paddy seed samples in the wet and dry seasons highlight that weather conditions can influence the dominance of weeds in the paddy field in any particular year, which in turn can influence the type of weed seed contaminants in farmers' own saved seeds.

Weedy rice has emerged as a major threat for the DSR system in many Asian countries where transplanted rice has been widely replaced with DSR because of limited options to manage this weed because of its physiological, morphological and phenological similarly to cultivated rice (Kumar and Ladha, 2011; Chauhan, 2013; and Ziska et al., 2015). One of the mechanisms of spread of weedy rice in cultivated rice fields is via seed lot contamination (Rao et al., 2017). Noldin (2000) estimated if paddy seed contaminated with two seeds of weedy rice per kg of rice seeds is sown in a rice field; it can produce 100 kg of weedy rice in three seasons. In Vietnam, where the majority of farmers also use their own saved seed, 314 weedy rice seeds per kg of paddy seeds have been reported (Mai et al., 1998). In our study, weedy rice contamination far exceeded this level with average weedy rice seeds of 544 (awnless) and 25 (awned) in 1 kg of paddy seed. In Thailand, Maneechote et al. (2004) reported a weedy rice contamination level of 4,000 seeds in 1 kg of paddy seed.

Our data suggest that although farmers are familiar with weedy rice (94%) (Table 10), they lack knowledge on weedy rice identification. Of the surveyed farmers, 67% of farmers said weedy rice occurred in their fields but in the seed contamination study we found that 92% of paddy samples were contaminated with awnless weedy rice. Only 37% of samples were contaminated with awned weedy rice. This suggests that farmers might have difficulty identifying weedy rice, especially awnless biotypes. Furthermore, it is unlikely that farmers can remove weedy rice seeds from seed kept for sowing using on-farm seed cleaning techniques. This was confirmed by analysis of freshly harvested paddy samples, farmer-kept seed samples, and seed samples from seed producers from the 2016 crop (Fig. 6). Weedy rice contamination level did not differ between samples of fresh paddy and farmer kept seed for sowing but it was drastically reduced in seed samples collected from seed producers. The average level of weedy rice (red seed) contamination of seed producer and seed company seed was 30 red seeds per 500 g and the minimum standard for certified seed is 5 red seeds for certified seed and 8 red seeds for graded seed (Khun and Soly, 2012).

Our findings highlight the importance of using clean seeds as part of integrated weed management program. Weed problems in Cambodia can be substantially reduced by using certified seeds free from weed seeds or by proper cleaning of their own saved seeds prior to sowing. None of the farmers surveyed used sieving. Sieving can be an effective method of seed cleaning as the size of most of the weed seeds are smaller than rice seeds and therefore these can be easily separated from rice seeds except for those that are of similar size and shape such as weedy rice.

Fig. 6. Weed seed contamination in fresh paddy (n = 27), farmer-kept seeds (n = 29), and producer seeds (n = 28) (Martin Pers. Comm.).

5. Conclusions

From this survey, it is evident that farmers perceived weeds as one of the major factors affecting their rice yields. The lack of awareness on weedy rice is evident from the fact that 92% of paddy seed samples were contaminated with weedy rice and only 67% of farmers were aware that they had weedy rice in their fields. These results suggest that weedy rice is becoming an increasingly problematic weed in DSR fields. Current agronomic practices such as use of high seed rate combined with farmer-saved paddy seeds, with a high level of contamination with weed seeds, have a major impact on weed management because by these practices farmers are accidently returning a substantial amount of weed seed (> 190,000 weed seeds ha^{-1}) back to their field at the time of rice seeding. Preventing or minimizing the spread of weed seeds via contaminants in crop seeds (e.g. by using clean/certified seeds), can be a practical approach to reduce the weed problem in DSR, including that of weedy rice. Overall, data suggest that the yield gap can be partially closed by deploying effective weed management and recommended fertilizer rates.

The results highlight the need for implementation of training and educational programs for farmers and input dealers on IWM, and other best agronomic practices with special emphasis on awareness and management of emerging weed problems such as weedy rice. Information generated in this survey also would assist in the development of actionable outreach material. Future research in the following areas would further strengthen IWM: (1) assessing long-term benefits of certified seeds free from weed seeds to minimize weedy rice and other weed problems and its positive impact on rice grain yield in DSR systems, (2) understanding the knowledge gap and training needs of input dealers, (3) developing innovative IWM approaches for weedy rice and other emerging weed problems, and (4) developing strategies to manage contaminated weed seeds in farmers saved paddy seed (e.g. seed cleaning methods, and modifying harvest and threshing equipment to avoid, or separate, weed seeds from harvested paddy etc).

Acknowledgements

Funding for this research was provided by the United States Agency for International Development under Cooperative Agreement No. AID-OAA-L-15-00001 with Virginia Tech under the Feed the Future Collaborative Research on Integrated Pest Management Innovation Lab (IPM IL). This research was conducted under the sub-grant, Ecologically-based Participatory Integrated Pest Management for rice in Cambodia (EPIC), with the International Rice Research Institute (IRRI), The Philippines as the lead institution for the sub-grant. Contents of the paper are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. The authors are grateful to Faculty of Agriculture and Food Processing, the University of Battambang, and UNICAM project (EU 562006-EPP-1-2015-1-ES-EPPKA2-CBHE-JP), the University of Battambang, for providing laboratory and financial support. We also would like to thank Dr. Touch Van who prepared the maps in Fig. 1, Dr. Rica Joy Flor for her support and guidance to Sokunroth during this study, and Dr. Grant Singleton and Prof. Elvis A. Heinrichs for reviewing and providing critical comments on the manuscript.

References

Anon, 2015. Cambodian Agriculture in Transition: Opportunities and Risks. Economic and Sector Work, Report No. 96308-KH. The International Bank for Reconstruction and Development/The World Bank 1818 H Street, NW, Washington, DC 20433.

Azmi, M., Baki, B.B., 2002. Impact of continuous direct seeding rice culture on weed species diversity in the Malaysian rice ecosystem. In: Proceedings of the Regional

Symposium on Environment and Natural Resources. 10-11 April, 2002. Hotel Renaissance, Kuala Lumpur, Malaysia, vol 1, pp. 61–67.

Blair, G., Blair, N., 2014. Nutrient status of Cambodian soils, rationalisation of fertiliser recommendations and the challenges ahead for Cambodian soil science. Curr. Agric. Res. J. 2, 5–13.

Bellinder, R.R., Miller, A.J., Malik, R.K., Ranjit, J.D., Hobbs, P.R., Brar, L.S., Singh, G., Singh, S., Yadev, A., 2002. Improving herbicide application accuracy in South Asia. Weed Technol. 16, 845–850.

Bouman, B.A.M., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agric. Syst. 93, 43–60.

Chauhan, B.S., 2012. Weed Management in Direct-Seeded Rice Systems. International Rice Research Institute, Los Baños Philippines, 20 pp..

Chauhan, B.S., 2013. Management Strategies for Weedy Rice in Asia. International Rice Research Institute, Los Baños, Philippines, 16 pp..

Chim, C., Buth, B., Ear, S., 2015. Effect of Labour Movement on Agricultural Mechanisation in Cambodia. CDRI Working Paper Series No. 107. Phnom Penh, Cambodia.

Chin, D.V., 2001. Biology and management of barnyardgrass, red sprangletop and weedy rice. Weed Biol. Manag. 1, 37–41.

Cross, R., et al., 2017. CamSID baseline survey results so far. Khmer Rumduol. Meas. No. 2, 4–7 https://aciarcambodiasidproject.files.wordpress.com/2017/07/camsid-newsletter-number-2-final.pdf.

Dobermann, A., White, P.F., 1999. Strategies for nutrient management in irrigated and rainfed lowland rice systems. Nutrient Cycl. Agroecosyst. 53, 1–18.

FAOSTAT, 2017. FAOSTAT Database. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). Retrieved April 24, 2017, from http://www.fao.org/faostat/en/#home.

GRiSP (Global Rice Science Partnership), 2013. Rice almanac. In: fourth ed., In: Ikeda, H., Kamoshita, A., Yamagishi, J., Ouk, M., Lor, B. (Eds.), 2008. Assessment of Management of Direct Seeded Rice Production under Different Water Conditions in Cambodia. Paddy Water Environ, vol 6, International Rice Research Institute, Los Baños (Philippines), pp. 91–103. https://doi.org/10.1007/s10333-007-0103-9, 283 pp..

IFC, 2015. Cambodia rice: export potential and strategies. Cambodia agribusiness series – No. 4. Phnom penh: international finance corporation. 31pp. Available at https://www.ifc.org/wps/wcm/connect/ed10f08049a04cfd8bbcabe54d141794/Cambodia + Market + Survey-Final-2015.pdf?MOD = AJPERES, Accessed on April 1, 2019.

Ikeda, H., Kamoshita, A., Yamagishi, J., Ouk, M., Lor, B., 2008. Assessment of management of direct seeded rice production under different water conditions in Cambodia. Paddy Water Environ. 6, 91–103.

IMF, 2009. Cambodia: Statistical Appendix. Country Report No. 09/48. International Monetary Fund, Washington D.C.

Juraimi, A.S., Uddin, M.K., Anwar, M.P., Mohamed, M.T.M., Ismail, M.R., Man, A., 2013. Sustainable weed management in direct seeded rice culture: a review. Aust. J. Crop. Sci. 7, 989–1002.

Khun, L.H., Soly, S., 2012. National Seed Standards. General Directorate of Agriculture, Ministry of Agriculture Forestry and Fisheries. Royal Government of Cambodia, Phnom Penh, Cambodia.

Kumar, V., Ladha, J.K., 2011. Direct seeding of rice: recent developments and future research needs. Adv. Agron. 111, 297–413.

Kumar, V., Opena, J., Valencia, K., Thi, H.L., Spn, N.H., Donayre, D.K., Janiya, J., Johnson, D.E., 2017. Rice weed management in Southeast Asia. In: Rao, A.N., Matsumoto, H. (Eds.), Weed Management in Rice in the Asian-Pacific Region. Asian-Pacific Weed Science Society (APWSS). The Weed Science Society of Japan, Japan and Indian Society of Weed Science, India, pp. 282–307.

Mahajan, G., Chauhan, B.S., 2016. Performance of dry direct-seeded rice in response to genotype and seeding rate. Agron. J. 108, 257–265.

Mai, V., Chien, H.V., Suong, V.T.T., Thiet, L.V., 1998. Survey and analysis of farmers' seed contamination by weed and weedy rice seeds in South Vietnam, 1997. In: Paper Presented at the International Symposium on Wild and Weedy Rices in Agroecosystems, 10–11 August 1998, Ho Chi Minh City, Vietnam.

Maneechote, C., Jamjod, S., Rerkasem, B., 2004. Invasion of weedy rice in rice fields in Thailand: problems and management. IRRN 29 (2), 20–22.

Martin, R.J., Van Ogtrop, F., Henson, Y., Broeum, K., Rien, R., Srean, P., Tan, D.K.Y., 2017. A survey of weed seed contamination of rice paddy in Cambodia. Weed Res. 57, 333–341.

Martin, R.J., 2017. Weed Research Issues, Challenges, and Opportunities in Cambodia. Crop Prot https://doi.org/10.1016/j.cropro.2017.06.019.

Noldin, J.A., 2000. Red rice status and management in Americas. In: Baki, B.B., Chin, D.V., Mortimer, M. (Eds.), Proceedings of Wild and Weedy Rice in Rice Ecosystems in Asia—A Review. Ho Chi Minh City, Vietnam, 10–11 August 1998. International Rice Research Institute, Los Baño s, Philippines, pp. 21–24.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2016. Vegan: community ecology package. R package version 2.4-0. Available at https://CRAN.R-project.org/package = vegan, Accessed 3 August 2017.

Oerke, E.C., Dehne, H.W., Schönbeck, F., Weber, A., 1999. Crop Production and Crop Protection. Estimated Losses in Major Food and Cash Crops. Elsevier, Amsterdam, 808 pp.

Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Visperas, R.M., Cassman, K.G., 1996. Increased N use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crop. Res. 47, 243–252.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. In: https://www.R-project.org/.

Rao, A.N., Brainard, D.C., Kumar, V., Ladha, J.K., Johnson, D.E., 2017. Preventive weed management in direct-seeded rice: targeting the weed seedbank. Adv. Agron. 144, 45–142.

Stuart, A.M., Pame, A.R.P., Silva, J.V., Dikitanan, R.C., Rutsaert, P., Malabayabas, A.J.B., Lampayan, R.M., Radanielson, A.M., Singleton, G.R., 2016. Yield gaps in rice-based farming systems: insights from local studies and prospects for future analysis. Field Crop. Res. 194, 43–56.

Stuart, A., Pame, A.R., Vithoonjit, D., Lampayan, R.M., 2017. The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. Field Crop. Res. 220, 78–87.

Wang, D., Chen, S., Wang, Z., Ji, C., Xu, C., Zhang, X., Chauhan, B.S., 2014. Optimizing hill seeding density for high-yielding hybrid rice in a single rice cropping system in South China. PLoS One 9 (10), e109417 https://doi.org/10.1371/journal.pone.0109417.

White, P.F., Oberthür, T., Sovuthy, P., 1997. The Soils Used for Rice Production in Cambodia: a Manual for Their Identification and Management. Cambodia IRRI Australia Project, Phnom Penh, Cambodia.

Ziska, L.H., Gealy, D.R., Burgos, N., Caicedo, A.L., Gressel, J., et al., 2015. Weedy (red) rice: an emerging constraint to global rice production. Adv. Agron. 129, 181–228.