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Integrated Management of Weeds in Direct-Seeded Rice in Cambodia

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Abstract: The objective of this work was to determine the value of improved establishment methods and herbicide applications as alternatives to high seeding rates to improve weed suppression in rice. Field experiments were carried out in 2010 and 2011 to determine optimal seeding rates and seeding methods with and without weed competition in wet-seeded rice. Under wet seeding conditions, drum seeding at 80 kg ha^{-1} was the most profitable treatment for both weed-free and unweeded rice. Although pre-emergence herbicides are beginning to be adopted in wet-seeded rice, they are seldom used in dry direct-seeded rice in Cambodia. Experiments were carried out in 2018 and 2019 to test crop tolerance and the efficacy of butachlor, oxadiazon, pendimethalin and pretilachlor applied post-sowing and pre-emergence to dry direct-seeded rice. Oxadiazon and butachlor, with the option for a post-emergence herbicide, provided effective weed control and a high grain yield in dry direct-seeded rice. Pretilachlor did not effectively control weeds under dry seeding conditions. Although pendimethalin exhibited good weed control, crop damage was a risk in poorly prepared seedbeds which typify Cambodian rice systems. With an effective integrated weed management strategy, it might be possible to safely reduce seeding rates below 80 kg ha^{-1} using drum or drill seeding machines.

Keywords: direct-seeded rice; seeding rates; selective herbicides; integrated weed management; agricultural mechanisation; economic analysis

1. Introduction

Agriculture accounts for 22% of Cambodia's Gross Domestic Product (GDP) [1], and rice is by far the most important commodity, making up around half of the agricultural GDP. The total area of agricultural production in Cambodia was 4 million ha in 2016 [2] and of this there was 3 million ha (75%) of rice. Cambodia produced 10.7 million tonnes of paddy in 2018 [3] and a domestic surplus of 5.6 million tonnes (54%).

The climate of North-West Cambodia is affected by the South-East Asia Monsoon, characterised by distinct wet and dry seasons [4]. The Veal Bek Chan weather station in Battambang Province (13°5′23.81″ N, 103°12′49.12″ E) has an average annual rainfall of 1258 mm and an average temperature of 28.0 °C. The hottest month is April with an average maximum temperature of 36.1 °C. January is the coolest month with an average minimum temperature of 19.3 °C.

Land preparation in lowland rice systems begins as early as March, depending on whether there is sufficient rain to soften the soil for ploughing. Primary tillage is mainly conducted with contracted four-wheel tractor disc ploughs by 97% of farmers. Seventy-three percent of primary tillage is conducted in the absence of water in the field. Secondary tillage is mostly conducted using a two-wheel tractor owned by the farmer (85%), usually two weeks after primary tillage [5].

The predominant method of rice establishment is dry direct seeding rice (DDSR) in the early wet season (EWS) and wet direct seeding rice (WDSR) in the main wet season (MWS) (Figure 1).

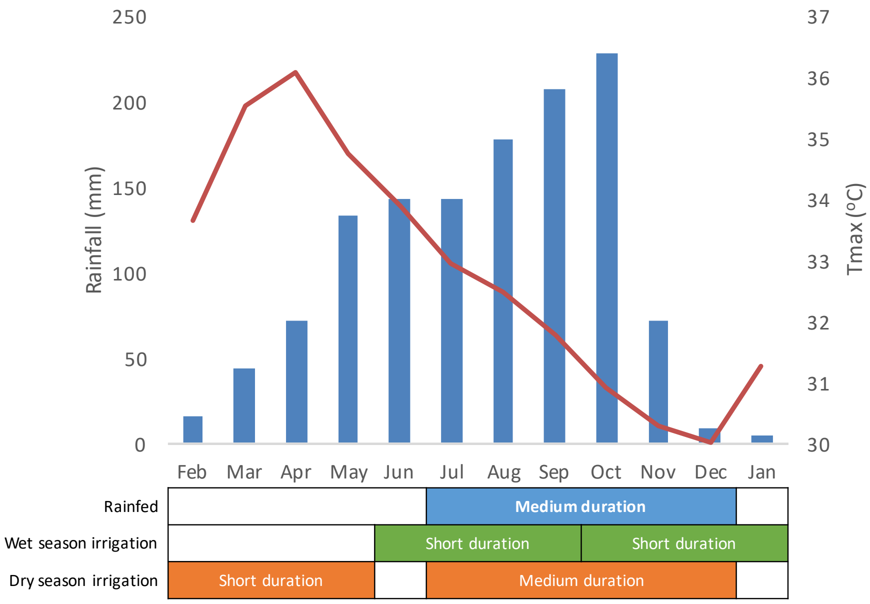


Figure 1. Battambang climate and seasonal rice production cycles (blue columns represent monthly rainfall and the red line represents maximum temperature (°C)).

The preference is for wet seeding in irrigated areas [5]. For DDSR, a dry seed is hand broadcast onto a prepared seed bed and incorporated by harrowing. For WDSR, the seed is pre-germinated and broadcast into puddled fields. Where two short-duration rice crops are grown in the wet season, the second crop is wet-seeded after 1 to 2 passes with a rotavator.

In recent years, there has been significant out-migration of labour from rural areas in Cambodia and this has resulted in rapid mechanisation to maintain production and productivity [6]. In North-West Cambodia, 97% of primary tillage for rice is now conducted with four-wheel tractors [5] and almost 100% of harvesting is now mechanised [7]. In addition, because of the labour shortage, transplanting rice has been replaced by hand broadcasting at seeding rates of 80–300 kg ha^{-1} in Battambang Province [7]. Eighty-eight percent of farmers keep their own seeds for sowing and these seeds contain an average of 482 weed seeds kg^{-1} [7]. Only 18% of rice farmers now practice hand-weeding and 100% of farmers use herbicides [5].

Farmers use high seeding rates to compensate for poor seed quality, poor crop emergence and to compensate for granivory by rodents, birds and insects. The use of high seeding rates also suppresses weed competition [8] but this seed is likely to be heavily contaminated with weed seeds [7], thus potentially exacerbating the weed problem.

Significant shifts in weed species' compositions have occurred after the shift from transplanting to direct-seeded rice in other Asian countries [9]. In areas of Cambodia where direct seeding has been practised for a number of years, grass weeds such as *Echinochloa* spp. and *Leptochloa chinensis* have become more prevalent and are proving difficult to control in direct-seeded rice [10]. In 2016, almost 100% of rice crops in Battambang and Takeo provinces were hand broadcast with only 2 to 3% of farmers still transplanting [7]. Direct seeding is also associated with a reduced access to water management for weed control. Aquatic weeds such as *Monochoria vaginalis* and *Marsilea minuta* were more prevalent in transplanted rice systems [10]. Submerged and floating weed species have become less prevalent with the shift to direct seeding of rice [5].

Weeds are a bigger problem for DDSR compared to transplanting because they germinate and emerge at the same time as the rice and are therefore more competitive under DDSR conditions [8]. Cambodian farmers rely primarily on post-emergence herbicides for weed control and have not adopted pre-emergence herbicides because these usually require machine planting to enable the placement of the rice seed below the herbicide layer. The use of a seed drill opens up the opportunity to use post-sowing pre-emergence herbicides for DDSR. Herbicides registered in Cambodia that can be used post-sowing pre-emergence in rice include oxadiazon, butachlor and pendimethalin. Pretilachlor with fenclorim safener is used in WDSR. A much wider range of post-emergence herbicide options are also registered.

The five most important weeds in rice identified by farmers in Battambang Province were *Fimbristylis miliacea*, *Echinochloa crus-galli*, *Oryza sativa* f. *spontanea* (weedy rice), *Cyperus iria* and *L. chinensis* [5]. According to farmers, other weed species of importance were *Echinochloa colona*, *Ischaemum rugosum*, and *Eleusine indica*; also 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*.

Most of the farmers (72%) who hand-weed do so once per crop cycle and only 28% hand-weed their field twice. 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%).

Farmer interviews suggest that there is lack of farmer knowledge on the use of correct herbicides, application rates, time of application and correct method of application of herbicides [5]. The majority of farmers (75%) rely on the advice of input dealers for the choice of herbicide. Other sources of information for the surveyed farmers are other farmers (46%), chemical companies (8%), and the herbicide label (19%).

The objectives of this work were to:

- Determine the costs and benefits of establishment methods and seeding rates for weed management in rice and to provide recommendations for best-practice rice seeding methods and seeding rates.
- Evaluate pre-emergence herbicides in drill-planted dry direct-seeded rice as an alternative to high seeding rates to improve weed suppression in rice.
- Outline an integrated weed management (IWM) strategy for DDSR applicable to rice production systems in North-West Cambodia.

2. Materials and Methods

2.1. Seeding Method and Seeding Rate

Twenty experiments were carried out in Kampong Speu, Kampong Thom, Kampot, Prey Veng and Takeo provinces in southern Cambodia to determine the effect of varying the seeding method and seeding rate of rice for the suppression of weeds under Cambodian conditions. Ten experiments were carried out in the wet season of 2010 and 10 in the dry season of 2011.

Land was prepared by ploughing three times and followed by one harrowing. The soil type was Prateah Lang which has a sandy topsoil less than 40 cm deep over a subsoil that has a loamy or clayey texture [11]. Fertilizer inputs were cattle manure at 3 t ha^{-1}, urea at 50 kg ha^{-1}, diammonium phosphate at 25 kg ha^{-1} and muriate of potash at 25 kg ha^{-1}.

The experimental design was a split plot with three replicates. The main plots were +/− weed control and subplots (3 by 5 m) were the seeding method and seeding rate. The weed control treatment for the broadcast and drum seeder was a combination of post-emergence herbicide bispyribac-sodium

25 g a.i. ha^{-1} applied 8–10 days after sowing (DAS) and hand-weeding. The weed control for transplanted treatments was the pre-emergence herbicide, pretilachlor + fenclorim, applied at 300 g a.i. ha^{-1} 2–3 DAS plus hand-weeding. In the farmer practice treatment, farmer practice was followed for weed control which was hand-weeding one time per crop cycle in Kampot, but in Kampong Thom, Kampong Speu, Prey Veng and Takeo provinces farmers followed the experimental protocol described above. The seeding rate treatments were wet-seed broadcast. Weed biomass was determined 60 DAS in three randomly placed 50 × 50 cm quadrats. Weed samples from each plot dried were oven-dried for two days at 70 °C before being weighed.

Subplots were five seeding rates and five planting methods:

2.1.1. Seeding Rate

- broadcast at 60 kg ha^{-1} (BC 60)
- broadcast at 100 kg ha^{-1} (BC 100)
- broadcast at 150 kg ha^{-1} (BC 150)
- broadcast at 200 kg ha^{-1} (BC 200)
- broadcast at 250 kg ha^{-1} (BC 250).

2.1.2. Seeding Method

- farmer practice broadcast at 180 kg ha^{-1} (FP 180)
- drum seeder at 60 kg ha^{-1} (DS 60)
- drum seeder at 80 kg ha^{-1} (DS 80)
- transplanting one 10-day-old seedling/hill and spacing of 25 by 25 cm (TP 25)
- transplanting 2–3 20-day-old seedlings/hill and spacing of 20 by 20 cm (TP 20).

2.2. *Pre-Emergence Herbicide Experiments*

Experiments to evaluate herbicides applied post-sowing pre-emergence for weed control in rice were carried out during the wet seasons of 2018 and 2019 at the Don Bosco Agro Technical School (13°04′38″ N; 103°10′24″ E) in Battambang Province, North-West Cambodia. The soil type was Toul Samrong which has a clayey or loamy topsoil that forms wide cracks that penetrate deeper than 5 cm into the soil over a clayey or loamy subsoil [11].

The pre-emergence herbicides tested were butachlor, oxadiazon, pendimethalin and pretilachlor. The post-emergence herbicide used was bispyribac-sodium (Table 1). Herbicides were applied in a water volume of 350 L ha^{-1} using an electric-powered knapsack sprayer.

Table 1. Herbicides and rates of application.

Chemical Name	Product Name	Concentration	Product Rate (L ha^{-1})	Active Ingredient Rate (g ha^{-1})
Butachlor	Kago 62 EC [1]	620 g/L	1.5	930
Oxadiazon	Ronstar 25 EC	250 g/L	1.0	250
Pendimethalin	Kmean Smau 500 EC	500 g/L	1.5	750
Pretilachlor + Fenclorim	Sofit 300 EC	300 + 100 g/L	1.5	450
Bispyribac-sodium	Nominee 10 SC [2]	10 g/L	0.2	2

[1] Emulsifiable Concentrate; [2] Suspended Concentrate.

In 2018, the experimental design was a split-plot with rice seeding rates of 40 and 80 kg ha^{-1} as main plots and pre-emergence herbicides as subplots in four replicates. In 2019, the design was a split plot with the post-emergence herbicide, bispyribac-sodium, as main plots and pre-emergence herbicides as subplots. The subplot size in 2018 was 5 by 12 m and 2.5 by 10 m in 2019.

The calendar of operations for the herbicide experiments in 2018 and 2019 is given in Table 2. In both years, the short-duration rice variety, Sen Kra Oub, was used after treatment with Cruiser Plus 312.5 FS (thiamethoxam + difenoconazole + fludioxonil) and sown with a machine seed drill in 25 cm rows at 40 and 80 kg ha^{-1} in 2018 and at 75 kg ha^{-1} in 2019. Diammonium phosphate at 50 kg ha^{-1} and muriate of potash at 25 kg ha^{-1} were applied by hand at sowing. Fertiliser topdressing, with urea (50 kg ha^{-1}) and muriate of potash (25 kg ha^{-1}), was applied at around 50 DAS.

Table 2. Calendar of operations for herbicide experiments in 2018 and 2019.

Operation	2018	2019
Glyphosate at 4 L ha^{-1}	12 June	17 June
Rotary tillage	19 June	23 June
Seed treatment, planting, basal fertiliser application	20 June	24 June
Application of pre-emergence herbicides	22 June	25 June
Rice establishment and weed counts	29 June	12 July
Application of post-emergence herbicide	Not applicable	22 July
Weed counts, ground cover	21 July	29 July
Fertiliser topdressing	11 August	15 August
Weed biomass	1 September	10 September
Harvest (2 by 1 m^2 quadrats per plot)	22 October	11 October

2.3. Sampling Procedures in 2018 and 2019

The plant density of rice and weeds (grasses, broadleaves, sedges) was determined from three 60 by 60 cm quadrats per plot. At rice physiological maturity, samples for the determination of yield components were taken from three 60 by 60 cm quadrats in each plot. After counting panicles, two subsamples of three panicles were taken for counts of spikelets per panicle. The paddy moisture content was recorded and the 100 grain weight was determined from two samples per plot. Following sampling for yield components, whole plots were harvested for the determination of rice paddy yield and weed biomass. The paddy yield was corrected to 14% moisture content.

2.4. Statistical Analyses

Data were statistically analysed using the IBM SPSS® statistical package version 22. For the seeding rate and seeding method experiments, after the initial analysis of variance, the significant treatment effects were examined using nine predetermined orthogonal single-degree-of-freedom contrasts for the weed biomass and paddy yield variables (Table 3).

Table 3. Coefficients for orthogonal contrasts used in the single-degree-of–freedom analysis of variance for seeding rate/seeding methods.

Orthogonal Contrast	Seeding Rate					Seeding Method				
	BC 60	BC 100	BC 150	BC 200	BC 250	FP 180	DS 60	DS 80	TP 20	TP 25
Linear	−2	−1	0	1	2	0	0	0	0	0
Quadratic	2	−1	−2	−1	2	0	0	0	0	0
Cubic	−1	2	0	−2	1	0	0	0	0	0
Quartic	1	−4	6	−4	1	0	0	0	0	0
DS 80 vs. DS 60	0	0	0	0	0	0	1	−1	0	0
TP 20 vs. TP 25	0	0	0	0	0	0	0	0	1	−1
FP 180 vs. DS 80	0	0	0	0	0	1	−1	0	0	0
DS 80 vs. TP 20	0	0	0	0	0	0	0	1	−1	0
FP 180 vs. TP 20	0	0	0	0	0	1	0	0	−1	0

The variance increased with the mean for weed density and biomass data. Therefore, a logarithmic transformation, ln (y + 1), was performed on these dependent variable data [12]. Duncan's multiple range test [13] was used to identify the subsets of means found not to be significantly different for the pre-emergence herbicide treatments in the 2018 and 2019 experiments.

2.5. Economic Analyses

Partial budgets were prepared to calculate the total costs that vary and the net benefits for relevant treatment comparisons in all experiments [14]. Assumptions for the marginal analysis were: value of seed kept for sowing (USD)—USD 0.25 kg^{-1}; labour cost was $5US per person-per day where transplanting required 20 person-days ha^{-1}; drum seeder, 4 person-days ha^{-1}; broadcasting 3 person-days ha^{-1}. The price of paddy was set at USD 250 t^{-1} (price for Sen Kra Oub variety, April 2020). Pretilachlor + fenclorim costed USD 17.50 ha^{-1} and bispyribac-sodium costed USD 20 ha^{-1} and the cost of application was USD 4.88 ha^{-1}. The Marginal Rate of Return (MRR), the difference in net benefits divided by the difference in costs that vary, was calculated for relevant treatment comparisons [14].

3. Results

3.1. Seeding Method and Seeding Rate

The main effects for season (S), seeding method/rate (T) and weeds (W) were all highly significant for the weed biomass and paddy yield. The only significant interactions were for S * W and T * W for weed biomass and T * W for paddy yield (Table 4).

Table 4. Analysis of variance for weed biomass and paddy yield for seeding rate ad seeding method options.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F Ratio	Probability
		Weed Biomass			
Season	1	29.9135	29.9135	106.68	0.000
Seeding method/rate	9	21.8072	2.42302	7.34	0.000
Linear	1	0.11623	0.11623	0.41	NS [1]
Quadratic	1	3.31827	3.31827	11.83	0.001
Cubic	1	1.66267	1.66267	5.93	0.014
Quartic	1	0.06880	0.06880	0.25	NS
DS 80 vs. DS 60	1	1.20217	1.20217	4.29	0.036
TP 20 vs. TP 25	1	3.67708	3.67708	13.11	0.000
FP 180 vs. DS 80	1	10.1725	10.1725	36.28	0.000
DS 80 vs. TP 20	1	0.05300	0.05300	0.19	NS
FP 180 vs. TP 20	1	8.75705	8.75705	31.23	0.000
Weeds	1	513.726	513.726	1832.04	0.000
Season × Seeding	9	2.42984	0.26998	0.96	NS
Season × Weeds	1	29.5836	29.5836	105.50	0.000
Seeding × Weeds	9	21.6973	2.41081	8.60	0.000
Season * Seeding × Weeds	9	2.28655	2.28655	0.91	NS
		Paddy Yield			
Season	1	11.6793	11.6793	15.30	0.000
Seeding method/rate	9	33.3630	3.70701	4.82	0.000
Linear	1	5.86101	5.86101	7.68	0.006
Quadratic	1	3.56353	3.56353	4.67	0.029
Cubic	1	3.74471	3.74471	4.90	0.026
Quartic	1	0.60147	0.60147	0.79	NS
Ds 80 vs. DS 60	1	5.99950	5.99950	7.86	0.005
TP 20 vs. TP 25	1	11.3980	11.3980	14.93	0.000
FP 180 vs. DS 80	1	2.67029	2.67029	3.50	NS
DS 80 vs. TP 20	1	0.31319	0.31319	0.41	NS
FP 180 vs. TP 20	1	1.15448	1.15448	1.51	0.217
Weeds	1	102.724	102.724	133.47	0.000
Season × Seeding	9	4.43231	0.49248	0.65	NS
Season × Weeds	1	0.38161	0.38161	0.50	NS
Seeding × Weeds	9	16.0676	1.78529	2.32	0.014
Season × Seeding × Weeds	9	5.98394	0.66488	0.87	NS

[1] NS = not significant.

The dry season paddy yield (3089 kg ha^{-1}) was significantly greater than the wet season paddy yield (2892 kg ha^{-1}). For the seeding rate main effect, the weed biomass was greatest for the broadcast 60 kg ha^{-1} treatment (1742 kg ha^{-1}) and this is consistent with the lower paddy yield (2526 kg ha^{-1}) in said treatment in the presence of weeds (Table 5).

Table 5. Effect of seeding method and rate on weed biomass and paddy yield (t ha^{-1}).

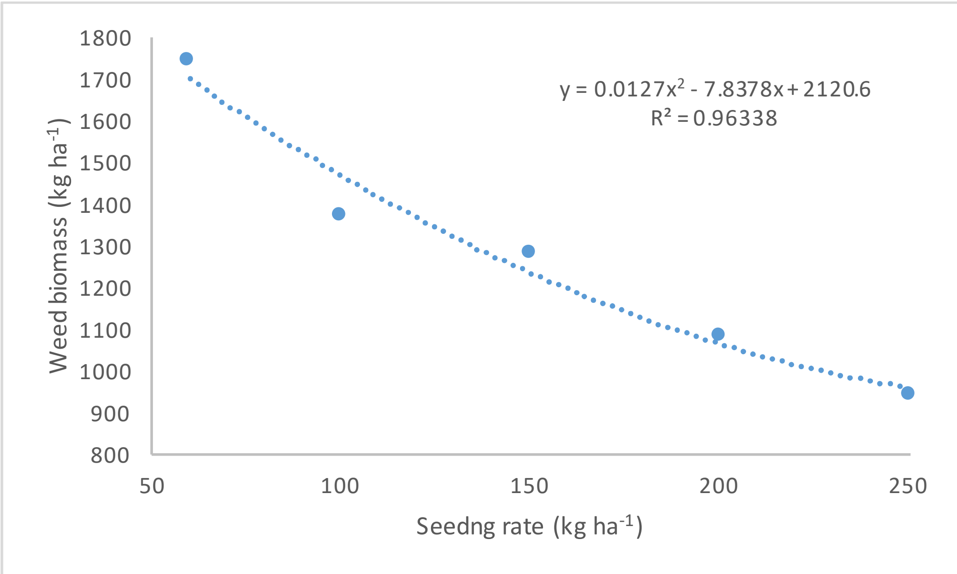
Treatment	Weed Biomass (kg ha^{-1})	Yield (kg ha^{-1})	
		Non-Weedy	Weedy
Seeding Rate			
BC 60	1742	2996	2526
BC 100	1371	3162	2647
BC 150	1279	3239	2683
BC 200	1079	3079	2837
BC 250	942	2996	2759
Seeding Method			
FP 180	919	3273	2671
DS 60	1683	3176	2490
DS 80	1459	3450	2704
TP 20	1188	3644	2893
TP 25	1434	3819	2772
LSD [1] 0.05	206	314	314

[1] LSD = Least significant difference.

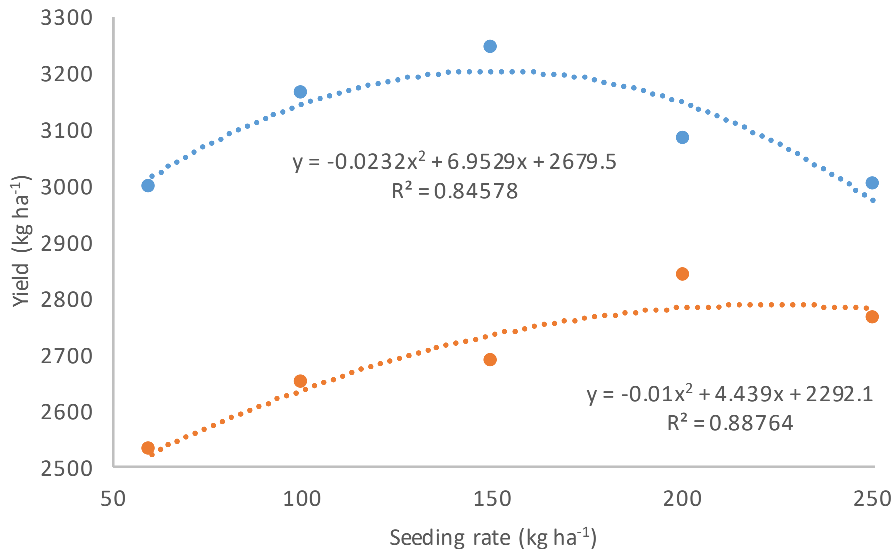
For broadcast seeding rates, there was a significant quadratic trend for both weed biomass and yield. With single-degree-of-freedom contrasts, the weed biomass was significantly greater for TP 25 compared to TP 20 and weed biomass was significantly greater in the DS 80 treatment compared to FP 180. The yield for DS 80 was significantly greater than that for DS 60.

The weed (W) main effect was significant with 1310 kg ha^{-1} of weed biomass in the weedy treatment. Weed competition reduced the paddy yield from 3283 to 2698 kg ha^{-1} (18%). There was no significant S × T interaction for weed biomass or paddy yield. There was a significant S × W interaction for weed biomass with more biomass in the weedy treatment in the wet season (1624 kg ha^{-1}) and less in the dry season (995 kg ha^{-1}). The T × W interaction was significant for weed biomass with the lowest weed biomass (919 kg ha^{-1}) in the farmer practice treatment, hand-broadcast at 180 kg ha^{-1}.

Increasing the seeding rate from 60 to 250 kg ha^{-1} reduced weed biomass by 46%, from 1742 to 942 kg ha^{-1} (Figure 2a). Without weeds, paddy yields increased with seeding rates up to 150 kg ha^{-1} but in the presence of weeds, paddy yields increased with seeding rates up to 200 kg ha^{-1} (Figure 2b).



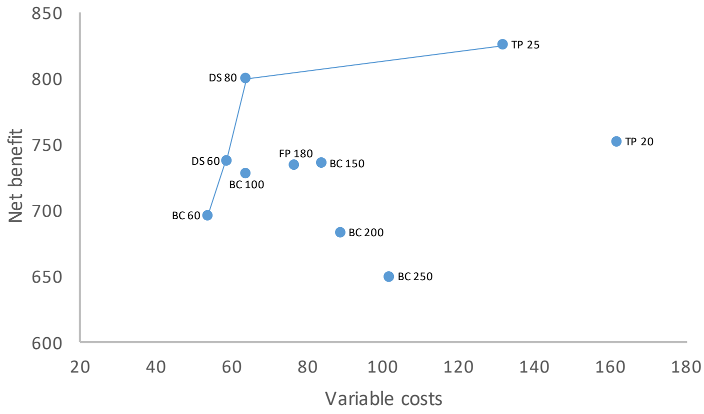
(**a**)



(**b**)

Figure 2. (**a**) Effect of seeding rate on weed biomass. (**b**) Effect of seeding rate on rice paddy yield under conditions of weed-free (blue) and weedy (red).

The minimum rate of return acceptable to farmers is generally expected to be between 50 and 100% [14]. A dominance analysis was carried out by first listing the treatments in order of increasing costs that vary for the seeding method and seeding rate. The relationship between the costs that vary and net benefits for the non-dominated treatments is shown in the net benefit curves (Figure 3). Treatments that have net benefits less than or equal to those of a treatment with lower costs that vary are said to be dominated. Treatments that are not dominated are connected with lines. Without weeds (Figure 3a), the dominance analysis eliminated all treatments except BC 60, DS 60 (8.04), DS 80 (12.66) and TP 25 (0.37) from consideration because of the dominated net benefits (Marginal Rate of Return (MRR) in brackets). In the presence of weeds (Figure 3b), all treatments were dominated except BC 60, DS 80 (3.46) and BC 200 (0.33). The DS 80 treatment gave the highest MRR with and without the presence of weeds.



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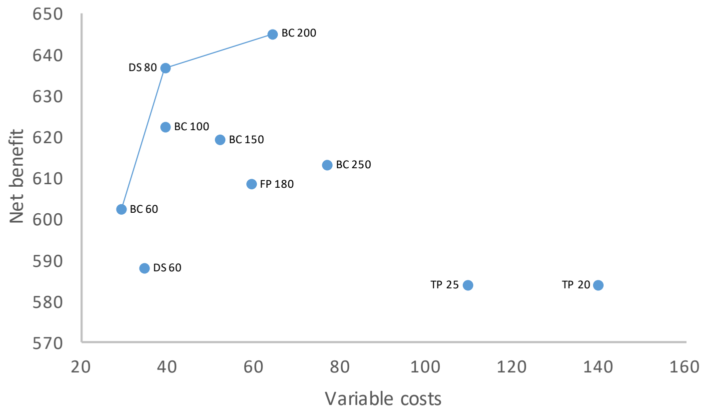


(**b**)

Figure 3. (**a**) Net benefit curve for rice seeding rates and methods without weed competition (USD). (**b**) Net benefit curves for rice seeding rates and methods with weed competition (USD).

3.2. Pre-Emergence Herbicides

The rainfall recorded during the crop growth period was 607 mm in 2018 and 538 mm in 2019 (Figure 4). The average for this period is 655 mm and the lower amount received in 2019 was largely due to a low rainfall in June.

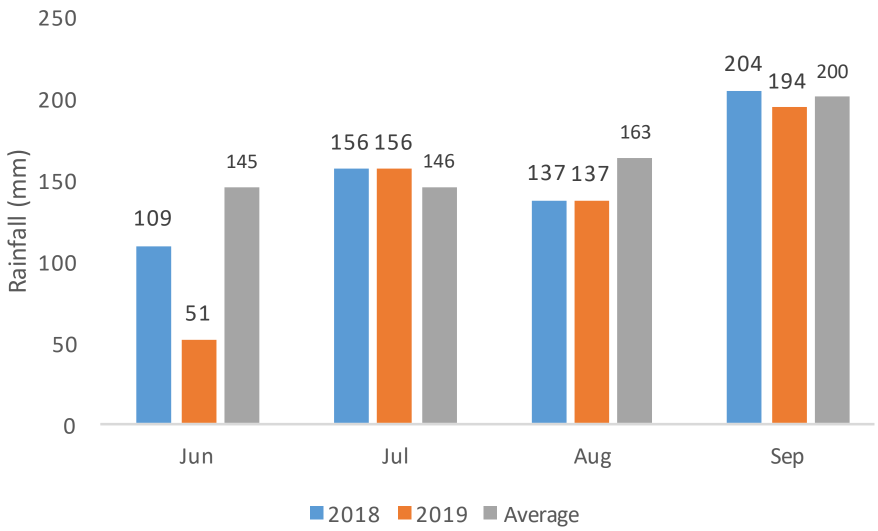
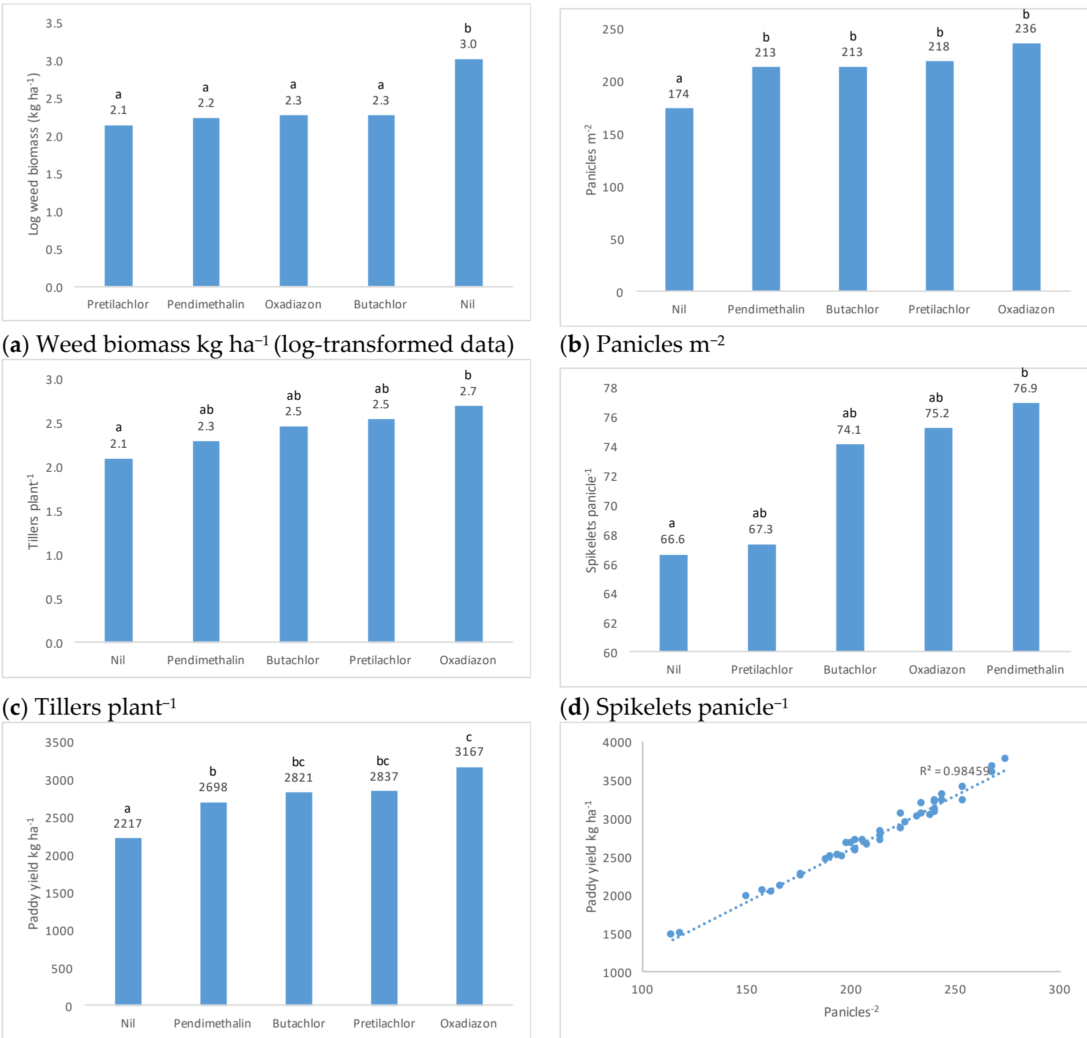


Figure 4. Rainfall during the crop growth period.

3.2.1. Herbicide Experiments, 2018

In 2018, pre-emergence herbicides significantly affected the weed biomass, panicles m^{-2}, tillers plant^{-1}, spikelets panicle^{-1} and paddy yield (Figure 5). The seeding rate significantly affected plants m^{-2}, panicles m^{-2}, the weed biomass and paddy yield. There were no significant interactions between the herbicide and seeding rate.



(**a**) Weed biomass kg ha^{-1} (log-transformed data) (**b**) Panicles m^{-2}

(**c**) Tillers plant^{-1} (**d**) Spikelets panicle^{-1}

(**e**) Paddy yield (kg ha^{-1}) at 14% moisture content (**f**) Relationship between panicles m^{-2} and paddy yield (kg ha^{-1})

Figure 5. Effect of pre-emergence herbicides on rice yield components in 2018 (means that share the same letter are not significantly different).

Pre-emergence herbicides had no significant effect on rice plants m^{-2} or on 100 seed weight (g). Pre-emergence herbicides significantly reduced weed biomass with no significant differences between herbicides (Figure 5a). Pre-emergence herbicides resulted in significantly greater panicles m^{-2} (Figure 5b), oxadiazon resulted in more tillers plant^{-1} compared to nil herbicide (Figure 5c) and pendimethalin resulted in more spikelets panicle^{-1} (Figure 5d), which is consistent with reduced panicles m^{-2} (not significant). All pre-emergence herbicides produced greater paddy yields compared to the nil herbicide treatment. An application of oxadiazon resulted in the highest yield (3167 kg ha^{-1}) and this was significantly greater than the paddy yield for the nil treatment (2217 kg ha^{-1}) as well as the pendimethalin treatment (2698 kg ha^{-1}) (Figure 5e). Panicles m^{-2} was the main predictor of paddy yield (Figure 5f).

Increasing seeding rates from 40 to 80 kg ha^{-1} resulted in a significant increase in established plants from 76 to 104 plants m^{-2} and increased panicles m^{-2} from 193 to 229 (Table 6).

Table 6. Effect of seeding rate on rice yield components in 2018.

Seeding Rate (kg ha^{-1})	Plants m^{-2}	Panicles m^{-2}	Tillers per Plant	Yield 14% (kg ha^{-1})
40	76	193	2.6	2503
80	104	229	2.2	2993
Standard error	3.4	6.5	0.1	86.3

Although the number of tillers per plant was greater for the 40 kg ha^{-1} seeding rate (2.6) compared to the 80 kg ha^{-1} seeding rate (2.2), 3.0 tillers per plant would be required to produce the same number of fertile panicles m^{-2} as the 80 kg ha^{-1} seeding rate. Therefore, the lower paddy yield for the 40 kg ha^{-1} seeding rate (2503 kg ha^{-1}) compared to the 80 kg ha^{-1} seeding rate (2993 kg ha^{-1}) was due to the inability of the variety (Sen Kra Oub) to compensate for seeding rate by producing more tillers (Table 6).

3.2.2. Herbicide Experiments, 2019

Pre-emergence herbicides significantly affected weed density at 17 DAS and paddy yield while the post-emergence herbicide significantly affected weed density at 34 DAS and 100 grain weight (g). There were no significant interactions between pre- and post-emergence herbicides (Table 7).

Table 7. Significant treatment effects in 2019.

Treatment	Rice Plants m^{-2}	Weed Density 12 July m^{-2}	Weed Density 29 July m^{-2}	Panicles m^{-2}	Tillers per Plant	Spikelets per Panicle	100 Grain Weight (g)	Weed Biomass (kg ha^{-1})	Yield (kg ha^{-1})
Pre-emergence herbicide	NS	0.00	0.00	NS	NS	NS	NS	0.01	0.01
Post-emergence herbicide	NS	NS	0.00	NS	NS	NS	0.02	NS	NS
Pre * Post	NS	NS	NS	NS	NS	NS	NS	NS	NS

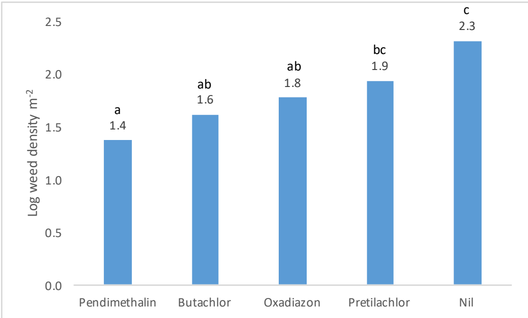
All pre-emergence herbicide treatments significantly reduced weed density at 17 DAS compared to the nil herbicide treatment (Figure 6a). Weeds were counted again at 34 DAS, seven days after the post-emergence herbicide application, but there was no significant change in the result (Figure 6b). The only pre-emergence herbicide to significantly reduce weed biomass at 78 DAS was pendimethalin.

There were significantly more panicles m^{-2} in the oxadiazon and butachlor treatments compared with the nil pre-emergence herbicide treatment (Figure 6d). Butachlor was the only pre-emergence herbicide to significantly increase paddy yield compared to the nil herbicide (Figure 6e). There was a significant relationship between the panicles m^{-2} and paddy yield in 2019 but not as strong as it was in 2018 (Figure 6f).

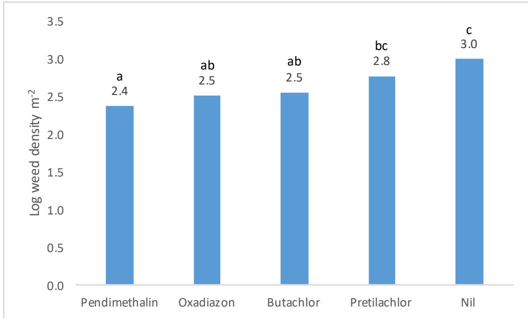
Although the post-emergence herbicide, bispyribac-sodium, more than halved weed density (Table 8) it only resulted in an increase in paddy yield of 232 kg ha^{-1} (5%) compared to the yield increase from the application of butachlor of 990 kg ha^{-1} (26%).

Table 8. Effect of post-emergence herbicide on rice yield components in 2019.

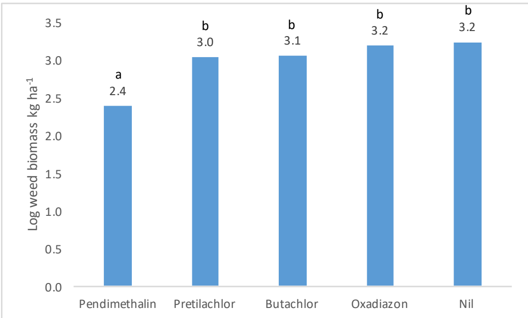
Herbicide Treatment	Weed Density on 29 July m^{-2}	100 Grain Weight (g)	Yield 14% (kg ha^{-1})
Nil	811	3.34	4255
Plus	355	3.12	4457
Standard error	88	0.026	Not significant



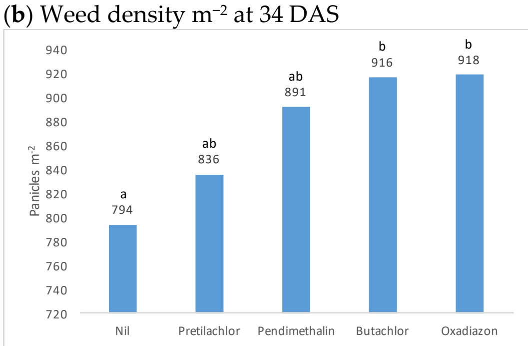
(**a**) Weed density m^{-2} at 17 DAS



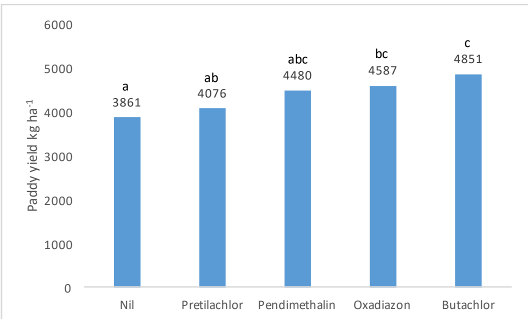
(**b**) Weed density m^{-2} at 34 DAS



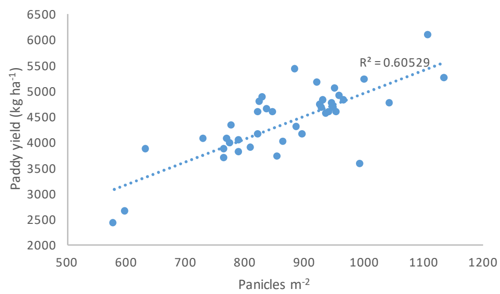
(**c**) Weed biomass kg ha^{-1} at 78 DAS [1] (log-transformed data)



(**d**) Panicles m^{-2}



(**e**) Paddy yield kg ha^{-1}



(**f**) Relationship between panicles m^{-2} and paddy yield (kg ha^{-1})

Figure 6. Effect of pre-emergence herbicides on yield components in 2019 (means that share the same letter are not significantly different).

3.2.3. Economic Analysis of Herbicide Experiments

The partial budget to compare the MRR for pre-emergence herbicide vs. increasing the seeding rate in 2018 is presented in Table 9 and the partial budget to compare pre- and post-emergence herbicides in 2019 is presented in Table 10. Income was based on a paddy price of USD 250 t^{-1}. Only the costs that varied between treatments were included: the cost of herbicide application was assumed to be USD 12 ha^{-1}; oxadiazon and bispyribac-sodium, USD 20 ha^{-1}; farm kept seed for sowing, USD 0.25 kg^{-1}.

Table 9. Marginal rates of return (MRR) for increasing seeding rates vs. herbicide for weed suppression in 2018.

Herbicide	Seeding Rate (kg ha^{-1})	Paddy Yield (kg ha^{-1})	Income (USD ha^{-1})	V-Costs (USD ha^{-1})	Net Benefit (USD ha^{-1})	Marginal Costs	Marginal Returns	MRR
Nil	40	2057	514	10	504			
Nil	80	2377	594	20	574	10	70	7
Oxadiazon	40	2835	709	42	667	22	93	4
Oxadiazon	80	3500	875	52	823	10	156	16

Table 10. Marginal rates of return (MRR) for increasing seeding rates vs. herbicide for weed suppression in 2019.

Pre-Em Herbicide	Post-Em Herbicide	Paddy Yield (kg ha^{-1})	Income (USD ha^{-1})	V-Costs (USD ha^{-1})	Net Benefit (USD ha^{-1})	Marginal Costs	Marginal Returns	MRR
Nil	Nil	3673	918	0	918			
Nil	Bispyribac	4049	1012	32	980	32	62	2
Oxadiazon	Nil	4247	1062	32	1030	32	50	2
Oxadiazon	Bispyribac	4928	1232	64	1168	32	138	4

In 2018, increasing the seeding rate from 40 to 80 kg ha^{-1} gave a Marginal Rate of Return (MRR) of 7. The pre-emergence herbicide oxadiazon gave a MRR of 4 and the combination of pre-emergence herbicide and a seeding rate of 80 kg ha^{-1} gave the best result with a MRR of 16 (Table 9). In 2019, the application of pre- or post-emergence herbicide alone gave an MRR of 2 whereas pre- plus post-emergence herbicide gave the best result with an MRR of 4 (Table 10).

4. Discussion

Integrated Pest Management (IPM) has been successfully demonstrated for rice in Cambodia since 1993 [15]. However, its dissemination and sustained adoption among farmers have not met similar success. There is evidence that mutual socio-technical dependencies predispose farmers to be locked into pesticide use in preference to the adoption of IPM [16]. In the case of weed management in rice, farmers rely predominantly on input sellers for advice and there is a strong bias for dependence on post-emergence herbicides [5]. Options available for the integrated management of weeds in direct-seeded rice include: the stale seedbed technique; crop residue mulching; reduced or no-tillage; use of weed-free crop seed; high seeding rates; improved herbicide application and timing; machinery hygiene.

The average weed-free yield in the seeding method and seeding rate experiments was 3.29 t ha^{-1}, which is well below a potential of 6–7 t ha^{-1} [17]. Therefore, biotic and abiotic factors other than the applied treatments are likely to have been limiting. It is possible that, under higher yielding conditions, higher seeding rates could give economic returns for suppressing weeds. There was a quadratic relationship between the seeding rate and paddy yield for both non-weedy and weedy treatments. Without weeds, the yield peaked at a seeding rate of 150 kg ha^{-1}, whereas with weeds the highest yield was with a seeding rate of 200–250 kg ha^{-1}. However, when the cost of seed was taken into account, increasing the seeding rate above 100 kg ha^{-1} in a weed-free crop could not be justified. Similarly, increasing the seeding rate to 200 kg ha^{-1} could only be marginally justified in a weedy crop. However, the net benefit for the non-weedy treatment at 150 kg ha^{-1} was USD 733 ha^{-1} compared to the weedy treatment at 200 kg ha^{-1} (USD 644) giving a shortfall of USD 89. This suggests that the money spent on extra seed might be better spent on alternative weed control methods, including herbicide use. Under weed-free conditions, the response in paddy yield is flat for seeding rates ranging from 15 to 125 kg ha^{-1} in the absence of weeds [18]. However, a quadratic model predicted optimal seeding rates of 48–80 kg ha^{-1} [18]. After a marginal analysis of costs and returns, this study found that all broadcast seeding rates were dominated both with and without weeds and that the drum seeder at 80 kg ha^{-1} was the most cost-effective treatment with and without weeds in a wet-seeded direct seeding situation. This study suggests that increasing the seeding rate alone is not a cost-effective method to reduce paddy yield losses from weeds and that an integrated approach to weed management should be adopted [19]. For better weed management in wet-seeded rice, drum seeding at 80 kg ha^{-1} could be combined with: reduced inversion tillage plus stale-seedbed; the use of weed-free seed for sowing; pre- and post-emergence herbicides. With an effective integrated weed management strategy, it might be possible to safely reduce seeding rates below 80 kg ha^{-1} with drum or drill seeding machines.

In the 2018 seeding rate and pre-emergence herbicide experiment, the paddy yield, at a seeding rate of 80 kg ha^{-1} (2993 kg ha^{-1}), was significantly greater than it was for a seeding rate of 40 kg ha^{-1} (2503 kg ha^{-1}). Even with use of a pre-emergence herbicide, it was still more profitable to use a seeding rate of 80 kg ha^{-1} compared to 40 kg ha^{-1}. In 2019, although the effect of the post-emergence herbicide on the paddy yield was not significant, pre-plus post-emergence was the most profitable option. Pendimethalin was found to effectively control weeds in both years and this benefit was not carried through to significant increases in the paddy yield, which implies the potential of phytotoxicity to rice. This result is consistent with other findings [20] where pendimethalin effectively controlled weeds but reduced paddy yields, especially at higher application rates. Nevertheless, pendimethalin is a potentially valuable post-sowing pre-emergence herbicide for dry direct-seeded rice in North-West Cambodia but further evaluation is required to enable reliable recommendations to be made.

These results are consistent with the need to integrate herbicide use with other weed management strategies, such as increased seeding rates [8]. Furthermore, hand-weeding at the crop flowering stage will reduce the recharge of the weed seed bank and weed seed contamination of the harvested paddy [5]. Rice grain loss with combine harvesting is around 5% (>200 kg ha^{-1}) [21]. Self-sown rice is a significant problem that could be reduced by the stale seedbed technique, reduced tillage and crop residue mulching [8].

In North-West Cambodia, there is an exploitable yield gap of 1.3 t ha^{-1} (40%) in wet-season direct-seeded rice [5]. Weed competition in direct-seeded rice systems can result in rice yield losses of up to 50% and there is considerable scope to reduce the yield gap in direct-seeded rice systems with integrated weed management (IWM) strategies [8]. We propose an IWM strategy for direct-seeded rice (DSR) in North-West Cambodia. The elements of the strategy are:

- Machinery, especially combine harvesters, should be cleaned before movement from field to field and farm to farm. Machines should be adjusted, if possible, to reduce the return of rice seed to the field.
- The stale seedbed technique keeps self-sown rice and weed seeds on the soil surface where numbers can be more easily reduced by germination after rain or eaten by granivores. Emerged weeds are controlled using pre-sowing non-selective herbicides before sowing.
- Crop residue mulching reduces weed emergence and keeps weeds at the soil surface where they can be more easily controlled.
- Avoiding inversion tillage (disc ploughing) reduces the chance of burying weed seeds which acquire dark-induced dormancy. Subsequent cultivation brings buried seeds to the surface where they can germinate and emerge with the crop. Rotary cultivation can reduce the number of dormant weed seeds being brought to the soil surface.
- Seed kept for sowing should be cleaned to remove weed seed contaminants including those of weedy rice (*Oryza sativa* f. *spontanea*).
- Seeding rates can be reduced with drum and drill seeding and this enables weed-free seed to be purchased from reputable seed producers.
- For dry direct-seeded rice, our work suggests that pre-emergence herbicides can improve weed control in combination with post-emergence herbicides (if required) and optimal seeding rates.
- Tall weeds such as *Echinochloa crus galli* and weedy rice can be hand-rogued as the rice begins to flower. These weeds mature around one week earlier than short-duration rice and this practice reduces the contamination of the paddy sample and reduces the recharge of the weed seed bank.

5. Conclusions

Seeding rates in direct-seeded rice can be reduced from 200 to 80 kg ha^{-1} or less with row or drill seeding and improved weed control. The use of post-sowing pre-emergence herbicides such as butachlor or oxadiazon can improve weed control in dry direct-seeded rice in North-West Cambodia. However, further research is required to determine if pendimethalin is also a pre-emergence herbicide option for dry direct-seeded rice in the region.

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writing—review and editing, R.M.; visualization, B.S. and R.M.; supervision. All authors have read and agreed to the published version of the manuscript.

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