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Combine harvesting efficiency as affected by rice field size and other factors and its implication for adoption of combine contracting service

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ABSTRACT

Small combine harvesters have become popular in SE Asia recently, but small rice fields appear to limit its field operation and hence its wide adoption by smallholders. Combine harvesting efficiency, the area of paddy field harvested per unit time, was determined for 6 seasons in Central Lao PDR for over 400 fields varying in size and toposequence position, rice varieties grown, crop establishment methods and crop conditions particularly lodging at harvest. Combine harvesting efficiency was commonly about 3 ha/day in small fields of less than 1000 m² and increased with the increase in field size up to 5 ha/day in the size of about 2000–3000 m², but not beyond this range. Lower efficiency was also found in wet season than dry season, and also crops established from broadcasting compared with transplanting and drill seeding, at least partly because broadcasted crops tended to lodge more often than crops established from other methods. Photoperiod sensitive, long duration varieties grown in lower field positions also tended to have lower combine efficiency. Using the data obtained in this work, net return of combine adoption to farmers was estimated for different combine charge fees and yield levels. Increasing combine harvesting efficiency by 50% with increased field size would increase the net income of combine harvesting contractors by around 50% at current charges, allowing them to reduce the combine harvesting fees they charge. This would aid the adoption of combine harvesting services.

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Combine efficiency; field size; lodging; broadcasting; net income

1. Introduction

In some SE Asian countries, many young people have moved out of rural areas, causing labour shortage and increased cost of employing labourers (e.g. for LaoPDR). Thus traditional use of labourers for hand harvesting of rice is not practical any more in some areas, and also the increased labour cost has increased the cost of production, reducing competitiveness of rice in international markets against neighbouring countries. Mechanization may help minimize the labour shortage problem and also improve the rice grain quality. Hand harvesting has been a common practice in the region. With the increased labour cost for hand harvesting, combine harvesting has become an attractive option in many locations in SE Asia. Without spending the time for hand cutting, collecting, sun-drying in the field and carrying dried paddy to a threshing service, the farmer who uses combine harvesting can reduce the cost of growing rice substantially and increase labour productivity. Combine contracting services have commenced recently in Khammouan and Vientiane

provinces in Laos where the present field work was conducted. Bunna et al. (2018) showed that yield harvested by combine is similar to that harvested by hand, as grain loss at harvesting in the field may be slightly higher, but this is compensated for smaller grain loss in postharvest operations of threshing and transport. They also showed that head rice yield, the ratio of whole grain weight after milling to the rough rice weight, may be somewhat lower in combine harvested crops, which may be related to grain drying methods employed following different harvesting methods in their experiments. Vongxayya et al. (2019) also showed only a small difference in head rice yield between the combine and hand harvesting, depending on variety and season. Thus grain yield and quality are little affected by harvesting methods, and advantage of combine harvesting and hence its adoption would largely depend on the fees combine contractors charge. Thus if combine harvesting efficiency, the area that a combine can harvest for a given time period, is improved and combine contractors make extra profit, there is good chance that the combine fees become lower.

The Government of Lao PDR is promoting mechanization to improve labour productivity and grain quality, especially for dry season (DS) rice production. The mechanization includes land preparation, crop establishment methods such as the use of transplanter and seed drill, harvesting using combine harvester and artificial dryer to dry grain particularly combine harvested grain where sun drying may be difficult for DS crops. One limitation for introduction of mechanized rice production is small size of rice fields in Laos as in neighbouring countries, and this appears an impediment for efficient use of machinery. The small paddy size is due to farmer's use of draft animal for land levelling and preparation, and hand transplanting and harvesting. Often a farm may have a total rice area of 1 ha or more, but the area is commonly divided to many paddy fields. Kunihiro (2013) mentioned an association between mechanization and farm size, and advantage of mechanized rice production is shown in larger farms. While farm size may be difficult to alter without a large-scale land reform programme, field size could be modified more readily within a farm if increased field size is shown to benefit farmers. In wheat cropping in Jordan, variable cost of producing the crop was shown to be higher in smaller fields (Jabarin & Epplin, 1994).

In addition, most of the rainfed lowland rice field is located in sloped land (Inthavong et al., 2011), where small field size with rather tall levee is required for holding standing water, and often different varieties are grown at different toposequence positions in the wet season (WS). Some fields are hand transplanted but broadcasting has become common in recent years in the Mekong region (Fukai & Ouk, 2012), while seed drills and drum seeders are gaining popularity in Central Laos (Sengxua et al., 2018). In the WS, crops are rainfed and can be photoperiod sensitive varieties while in DS, photoperiod insensitive varieties are grown under irrigation. Thus rainfed lowland rice fields in the region are quite variable, and the machinery operation efficiency may vary accordingly. This study is aimed to determine factors, particularly field size, affecting combine harvesting efficiency, i.e. combine field capacity, using a large number of paddy fields in Central Lao PDR.

2. Materials and methods

2.1. Combine harvesting efficiency

The work reported here was conducted for six seasons (three wet and three DSs); in the first three seasons in Khammouan and Bolikhamxay provinces where some fields were enlarged, and in the last three seasons in Vientiane province and Vientiane capital.

A Kubota DC70 combine harvester was used to determine harvesting efficiency (field capacity or work rate). The field size was determined and the time required for the combine to complete harvesting was recorded for each field, harvesting efficiency calculated as hectares per day. Across six seasons, combine harvesting efficiency was calculated from the time spent harvesting in the field without including the time required for transfer of combine from one field to next. This could be a very short time of a minute or so, if the fields are adjacent to each other, but which could be a long time if the fields are a long distance apart. The efficiency is calculated assuming combine works harvesting in the fields for 8 h a day.

A total of 56 rice fields with a combined area of 15 ha were produced after enlarging smaller fields in 3 villages in 2014; 26 fields in Pakpung village, Bolikhamxai province, and 18 fields in Hatkhamhien village, Xebangfai district, and 12 fields in PakEtue village, Nongbok district, Khammouane province. In each village, about 5 ha of fields that were originally less than 1000 m² was enlarged and levelled by four-wheel tractor. The size of each enlarged field ranged from 1020 to 8560 m² depending on the slope and toposequence. In the sloping areas, topsoil was removed from higher to lower positions to enlarge the field, and this soil movement affected the performance of the subsequent rice crops in the first season where soil fertility was not improved.

In the first three seasons, beside the three villages where field enlargement took place, combine harvesting efficiency was also determined in other villages in Khammouan Province, with or without field enlargement. In Navangthong village, where farmers enlarged and levelled their fields by themselves, amalgamated field size ranged from 3100 to 9400 m², and in Tung village, where the original field size was retained, it ranged from 225 to 700 m².

In DS2014/15, 75 fields totalling 14.3 ha and belonging to 24 farmers in 7 villages were harvested. In WS2015, 62 fields totalling 9.5 ha belonging to 6 farmers in 5 villages were harvested while in DS 2015/16, 76 fields totalling 9.7 ha belonging to 11 farmers in 2 villages were harvested. Farmers had planted rice with different methods in the villages, including hand transplanting and use of a transplanter and direct seeding by broadcasting and using a seed drill or drum seeder (see Xangsayasane et al., 2019b for crop establishment methods), and combine harvesting efficiency determined. Some crops were lodged severely at the time of harvesting and the lodging was recorded when the majority of plants in the field were bent in such way that panicles were close to the soil surface. Paddy rice

harvested by combine was dried to reduce moisture content by sun drying or flatbed dryer.

Similar methods were used for estimating combine harvesting efficiency for the other three seasons (WS2016, DS2016/17 and DS2017) in Vientiane province. In season 4, we harvested paddy fields in Ekxang village where some fields had been amalgamated by farmers but most were more typical small fields. In this village, all fields were established by broadcasting except three fields which were drill planted. There were also upper and lower toposequence fields as common in rainfed lowland fields in Laos, and these two groups of fields were harvested at different times. The upper fields totalling 50 fields were planted with quicker maturing photoperiod insensitive varieties and harvested earlier on 18–21 October 2016, while the remaining 75 fields in lower toposequence position were planted with photoperiod sensitive varieties and harvested on 11–20 November 2016. Combine efficiency was tested also in seasons 5 and 6 in 2017 near Rice Research Centre (RRC), Vientiane capital, where paddy fields had been levelled and enlarged earlier. The fields used in these seasons were for seed production and crops were managed by RRC staff. In WS2017, photoperiod sensitive KDML105 variety was planted in the fields where combine efficiency was examined. In this season, also fuel requirement for combine to harvest each paddy was determined.

Yield was determined after 14% moisture content adjustment. The yield does not include any grain lost during the harvesting process.

Economic analysis was conducted using the input and output information obtained mostly from the present work. The yields of 3230 and 2280 kg/ha obtained for the first three seasons and the fourth season, respectively, were used and farm gate price of USD0.3/kg and hence gross incomes to the farmer of USD969 and 684/ha, respectively, were assumed. Combine harvesting efficiency of 3.5 ha/day for small size paddy fields and 5 ha/day for large size paddy fields obtained in the present work were used to determine the effect of increased combine harvesting efficiency on daily return to combine contractor. The daily return was estimated as the difference between revenue and operational costs, without including combine depreciation and maintenance costs. Revenue was calculated as 20% and 10% of the total crop value; 20% is common in Laos, but lower fees have been offered more recently. The daily fuel cost was estimated to be the same at USD50 for harvesting the 3.5 ha small fields and 5 ha large fields as the fuel efficiency improved with the increase in field size. Input costs other than harvesting of USD214/ha are assumed for broadcasting

crops, and the costs for seed, fertilizer, irrigation and weeding (hired labour) are included. Net return to farmers was calculated on area basis and also on labour resource basis (labour productivity). Family labour is the labour provided by family members working at the farm, commonly two adults. The labour requirement for crops at different yield levels was assumed to be the same. In order to compare net return to farmers between combine and hand harvesting, hand harvesting is estimated to require 36 labourer-days. Commonly they are hired, and it is assumed here that 2 family members and 34 hired labourers harvest the crop. As a comparison, also net return to the farmers is calculated for the case of harvesting the crop by the family members alone.

2.2. Combine harvesting grain loss

Yield loss estimation from combine harvesting was conducted in farmers' fields in five villages in two provinces in Laos. In DS2014/15, total of 8 sites collected data on yield loss and in DS2015/15, total of 21 sites determined yield loss. Grain loss was determined by randomly collecting grain on the soil surface in 1 m² soon after the area was combine-harvested.

3. Results

3.1. The first three seasons in Khammouan and Bolikhamxay

The results of first three seasons of experiments (DS2014/15, WS2015, DS2015/16) conducted in Khammouan and Bolikhamxay provinces shows that the combine efficiency as measured by the area of rice field harvested in one day was low at 3.0 ha/day for small paddies less than 1000 m², and the efficiency increased with field size. The maximum efficiency of about 5 ha/day was obtained in the field size of 2000–3000 m², and no further efficiency gain was found over 3000 m² (Figure 1). The time required to harvest a typical 1.9 ha farm (including moving between fields) was compared between small size fields of 500–1000 m² and the optimal size of 2000–3000 m². The combine could harvest the 1.9 ha farm with the large fields in about 3 h, while it would take more than 5 h in the more traditional farm with small fields. The yield was generally not affected by field size; the mean yield was 3.23 t/ha for the 213 fields in the 3 seasons studied.

The method of crop establishment also affected combine efficiency; among the three main establishment methods of broadcasting, hand transplanting and transplanter used in the three experiments, crops

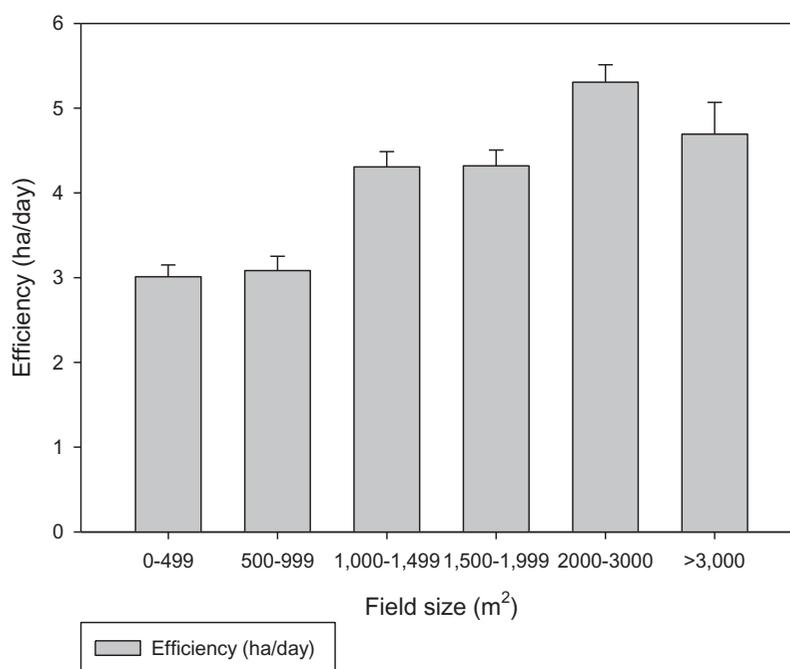


Figure 1. Mean combine harvesting efficiency (ha/day) and standard error for different field sizes (m²) as measured in three seasons in Khammouan and Bolikhamxay, Laos. Error bars indicate SE.

established from broadcasting resulted in less efficient combine harvesting than transplanted crops (Table 1). This was the case even though the fields established by broadcasting were considerably larger which would increase combine efficiency. Thus when fields were selected so that the mean size was about 2000 m² across all crop establishment methods, the difference became greater; the combine efficiency of the broadcast crop was about 21% lower than hand transplanted crop. At least part of this inefficiency was associated with the tendency of broadcast crops to lodge. Of the 65 crops established from broadcasting, 17 lodged,

while no lodging occurred in transplanted crops. The combine efficiency for lodged crops was almost halved compared with non-lodged broadcast crops, but this was partly due to larger fields of non-lodged crops (Table 1). When comparison was made for similar sized fields, the mean efficiency of lodged crops was 38% lower than that of non-lodged crops.

3.2. The last three seasons in Vientiane

The results obtained in the seasons 4–6 in Vientiane confirmed the results in seasons 1–3 in Khammouan

Table 1. Effects of crop establishment method on combine efficiency and lodging effect for (a) all fields, (b) a subset of similar sized fields and (c) a subset of broadcast crops.

Establishment method	Number of fields	Mean field size (m ²)	Mean efficiency (ha/day)
(a) All fields (n = 179)			
Broadcasting	65	2000	3.57 (0.16)
Hand transplanting	50	1451	4.01 (0.19)
Transplanter	64	1008	3.89 (0.29)
(b) Similar-sized fields (n = 123)			
Broadcasting	65	2000	3.57 (0.16)
Hand transplanting	32	2008	4.53 (0.30)
Transplanter	26	1977	4.49 (0.30)
(c) Broadcast crops			
	Number of fields	Mean field size (m ²)	Combine efficiency (ha/day)
All field (n = 65)			
Lodged	17	782	2.16 (0.20)
Non-lodged	48	2399	4.03 (0.15)
	20	768	3.49 (0.22)

Mean field sizes are also shown.

and Bolikhamxay in that combine efficiency increased with the field size (Table 2). However, there was a sharp contrast in the crops planted in the upper and lower fields in Ekxang village in Vientiane province in WS2016. Thus the upper fields were generally smaller with mean size of 987 m² and the crops were harvested earlier (all by 21 October) and combine efficiency was higher for a given field size class than the lower fields which were generally larger in size with mean of 2709 m² and harvested during 11–20 November.

In the last two seasons (DS2016/17 and WS2017), analysis of combine harvesting efficiency was conducted using mostly enlarged fields near RRC (Table 2). For any given field size group, combine harvesting efficiency in these seasons was similar to that obtained in Ekxang in WS2016, but as the field size was generally larger in the RRC area, mean size in DS and WS being 3383 and 3192 m², respectively, the efficiency was >30% higher. In the last season when the fuel use was monitored, fuel use efficiency increased from around 0.6 to over 1.0 ha/10 L with increase in field size.

The choice of variety in relation to the position in the toposequence affected combine harvesting rate as demonstrated in WS2016 (Table 3). Varieties XBF1, XBF2 and VTE450-2 which were released recently from the Lao rice breeding programme were all planted in the upper fields and harvested early. These had high yields and high combine harvesting efficiency, despite the generally small field size.

The late-maturing crops in the lower paddies were harvested much later and had lower yields (1.78 t/ha compared with 3.23 t/ha in the upper fields), but they took longer to harvest by combine (3.0 ha/day compared

Table 3. Combine efficiency and grain yield of rice varieties planted in upper and lower fields in Ekxang village, Vientiane, Laos, WS2016.

Variety	Number of fields	Mean field size (m ²)	Mean combine efficiency (ha/day)	Mean yield (kg/ha)
Upper fields				
TDK9	8	652	2.93 (0.17)	2906 (263)
VTE450-2	24	768	3.82 (0.18)	3110 (261)
XBF1	3	1111	3.92 (0.24)	3272 (385)
XBF2	8	1021	3.55 (0.42)	3251 (392)
TDK12	5	990	3.43 (0.36)	2411 (185)
Lower fields				
KDML105	42	2952	3.28 (0.17)	1702 (53)
RD6	19	2568	2.75 (0.15)	1582 (54)
TDK4	14	2171	2.49 (0.26)	2308 (77)

with 3.6 ha/day in the upper fields). These crops in the lower fields also lodged more frequently (25 out of 75 crops harvested compared with 3 out of 50 crops in the upper fields). However, even in the fields with no lodging, the efficiency of combine harvesting was less in the lower fields. This was likely related to the larger biomass of the taller, long-duration, photoperiod-sensitive varieties.

3.3. Seasonal effect in combine harvesting efficiency

The results of first 4 seasons conducted on 338 farmers' fields suggest that harvesting is more efficient in DS than in WS (Table 4). Mean combine harvesting efficiency was less than 3.5 ha/day in WS while it was more than 4 ha/day in DS despite mean field size being tended to be larger in WS. Combine harvesting in the WS was less efficient, perhaps because fields tended to be boggy and the crops larger in size. The

Table 2. Combine harvesting efficiency for WS2016 (upper and lower fields), DS2016/17 and WS2017 in Vientiane.

Field size (m ²)	WS2016 (Ekxang) Upper fields		WS2016 (Ekxang) Lower fields		Fuel efficiency (ha/10 L)
	Number of fields	Combine efficiency (ha/day)	Number of fields	Combine efficiency (ha/day)	
<500	13	2.63 (0.18)	1	1.53 (-)	
500–1000	23	3.78 (0.12)	11	2.33 (0.24)	
1000–1500	7	4.08 (0.10)	15	2.54 (0.24)	
1500–2000	2	4.09 (0.13)	10	2.85 (0.26)	
2000–3000	2	4.83 (0.31)	12	3.35 (0.21)	
>3000	3	4.27 (0.35)	26	3.46 (0.23)	
All	50	3.61	75	3.00	
Average size (m ²)	987		2709		
Field size (m ²)	DS2016/17 (near RRC)		WS2017 (near RRC)		Fuel efficiency (ha/10 L)
	Number of fields	Combine efficiency (ha/day)	Number of fields	Combine efficiency (ha/day)	
<500	0	–	0	–	
500–1000	2	3.30 (1.16)	3	3.97 (0.13)	0.63
1000–1500	4	4.26 (0.76)	3	4.20 (0.08)	0.58
1500–2000	6	4.41 (0.66)	5	4.64 (0.06)	0.82
2000–3000	12	5.01 (0.28)	3	5.00 (0.23)	0.78
>3000	21	5.21 (0.35)	8	5.76 (0.14)	1.09
All	45	4.89 (0.21)	22	4.98	0.85
Average size (m ²)	3383		3192		

Combine efficiency obtained in upper and lower fields are shown separately in WS2016.

Table 4. The mean field size and combine harvesting efficiency determined in six seasons in Central Laos.

Seasons	Number of fields harvested	Field size (m ²)	Combine efficiency (ha/day)
DS2014/15	75	1715	4.17
WS2015	62	1506	3.45
DS2015/16	76	1280	4.06
WS2016	125	2021	3.24
DS2016/17	45	3383	4.89
WS2017	22	3192	4.98

season effect did not exist in 2017 where comparison was made in mostly enlarged fields near the research station and the crop was for seed production and managed by station staff members.

3.4. Grain loss during combine harvesting

Yield loss from combine harvesting varied from 0.1% to 5.1% of the total yield in DS2014/15 and DS2015/16. Establishment methods did not appear to affect the yield loss percentage. The mean yield loss was about 1.5%, which should be acceptable by the industry. The loss depends on several factors, but a higher combine speed would generally increase grain loss. As combine harvesting does not involve separate threshing and handling of grain as in manual harvesting, the loss found here should be considered to be less than the expected loss from hand-harvested crops.

3.5. Effects on the combine contracting business

Economic analysis shows a large effect of paddy field size on the contractor's daily return, assuming a per-tonne

charge (Table 5). Thus, in the case of the typical fee in Laos (USD194/ha or 20%), the daily return would increase with increased field size by almost USD291 or 51% with the high yield level, and USD205 or 55% at the lower yield level. In the case of the low fee of 10% of the grain harvested as in Cambodia where the contract harvesting industry is more mature, the daily return would increase with increased field size by USD145 or 63% at the high yield level and USD103 or 78% at the low yield level. In both cases, the improved combine harvesting efficiency resulting from enlarged paddy fields will increase the contractor's profit greatly, both enhancing the viability of the combine-harvesting service and lowering harvesting fees (assuming adequate competition).

3.6. Benefit of combine harvesting services to farmers

The financial gain of adoption of combine harvesting service and associated labour cost is shown in Table 6. Yield level considered here is 3230 kg/ha which was mean yield in the first three seasons in Khammouan

Table 5. Daily return to combine contractor from yield levels of 3230 and 2280 kg/ha, small and large paddy fields, and two fee charge rates of 10% and 20%.

Combine efficiency	Yield 3230 kg/ha				Yield 2280 kg/ha			
	3.5 ha/day		5 ha/day		3.5 ha/day		5 ha/day	
Fees	10%	20%	10%	20%	10%	20%	10%	20%
Revenue/day	339	679	484	970	239	479	342	684
Labour (\$10 × 5.7)	57	57	57	57	57	57	57	57
Fuel/day	50	50	50	50	50	50	50	50
Daily return	232	572	377	863	132	372	235	577

Table 6. Budgeted net returns to farmers for hand- and combine-harvested rice for the yield of (a) 3230 kg/ha and (b) 2280 kg/ha.

Measure	Units	Hand-harvesting		Combine-harvesting	
		Family labour	Hired labour	10% fee	20% fee
(a) Yield 3230 kg/ha					
Yield	kg/ha	3230	3230	3230	3230
Farm gate price	USD/kg	0.3	0.3	0.3	0.3
Gross income	USD/ha	969	969	969	969
Input cost (not including harvesting and family labour)	USD/ha	214	214	214	214
Contract-harvesting fee	USD/ha	0	0	96.9	193.8
Hand-harvesting cost (USD 7/day)	USD/ha	0	238	0	0
Threshing fee (5% of paddy)	USD/ha	48	48	0	0
Net return per ha	USD/ha	707	469	658	561
Total family labour input (from land preparation to harvesting)	days/ha	102	68	68	68
Net return per day of family labour	USD/day	6.79	6.89	9.68	8.25
(b) Yield 2280 kg/ha					
Yield	kg/ha	2280	2280	2280	2280
Farm gate price	USD/kg	0.3	0.3	0.3	0.3
Gross income	USD/ha	684	684	684	684
Input cost (not including harvesting and family labour)	USD/ha	214	214	214	214
Contract-harvesting fee	USD/ha	0	0	68.4	136.8
Hand-harvesting cost (USD 7/day)	USD/ha	0	238	0	0
Threshing fee (5% of paddy)	USD/ha	34	34	0	0
Net return per ha	USD/ha	436	198	402	333
Total family labour input (from land preparation to harvesting)	days/ha	104	68	68	68
Net return per day of family labour	USD/day	4.19	2.91	5.91	4.90

and Bolikhamxay, and 2280 kg/ha which was the mean yield in season 4 in Ekxang village, Vientiane province. Two hand harvesting cases are one done by family labour and the other by hired workers; the latter is common in recent times. Combine harvesting fees are either 10% or 20% of the rice harvested; 20% was common in Central Laos, but the fees have been reduced in some areas where combine service has become common. Farm gate price varies for glutinous and non-glutinous rice and fluctuate seasonally, but USD0.3/kg is used here.

For the yield level of 3230 kg/ha, the net return per ha is 40% higher with combine harvesting (with a fee of 10%) than with hand-harvesting using hired labour. The financial benefit is smaller if the fees are 20% but is still 20% higher than hand-harvesting with hired labour. The high net return for hand-harvesting with family labour is because the calculation ignores the opportunity cost of family labour. The net return to family labour was 41% higher with combine harvesting. When the yield level is reduced to 2280 kg/ha, the gross income and net return are reduced greatly. However, relative advantage of combine contracting service is increased under these cases.

4. Discussion

4.1. Combine harvesting efficiency

4.1.1. Field size

Yield was generally not affected by field size, and the benefit of large field size was mostly due to increased efficiency of machinery operation. This is in agreement with the finding of Kunihiro (2013) that mechanization is often associated with farm size. Optimum paddy field size for maximum combine efficiency was found to be around 2000–3000 m² and existing small paddies could be amalgamated to this size or new paddies developed at this size for improved combine harvesting efficiency. Thus it appears that 3–5 paddies/ha may be the optimal size for rainfed lowland rice in Central Laos. Fuel use efficiency was also found to increase in larger paddy fields. The advantage of larger field size may also apply to other field operations such as land preparation and mechanized planting. In addition, farmers in the villages where the work was conducted believed water was saved with enlarged fields, perhaps also as a result of land levelling and the time spent in water management was also reduced with the reduction in the number of levees. Often the implication of enlarged paddies is the change of establishment method, as hand transplanting may not be practical any more in such a large field.

Field enlargement methods require attention, as removal of top soils and exposing subsoil could have severe adverse effect on growth of crops planted in the enlarged fields. Thus, the optimum size as well as the shape of enlarged field would depend on the topography of the area. The general principle would be to make paddy fields along contours, and generally long narrow paddies may be created on sloped fields. The number of turns at corners is reduced with narrower paddies, and this increases combine harvesting efficiency. The slope of land is critical, and if top soils of only 10 cm depth is to be removed, 2% slope would result in 5 m wide paddies. If slope is greater than this, a proper method of removing top soils first and levelling subsoil before putting the top soil back to the field needs to be considered. Unless this procedure is followed, the subsoil will be exposed and plant growth might be severely affected at least in the first year after the field enlargement. After the soil is moved, the land needs to be levelled as Rickman et al. (2001) have shown the unevenly levelled field to reduce crop yield in rainfed lowland rice in Cambodia. Information on rice field arrangement for efficient machinery operation can be found in extension materials from south eastern Australia (Plunckett et al., 2018).

Some farmers have recently amalgamated fields to produce larger size fields, realizing that larger fields are more efficient for various machinery operations including combine harvester in the field. Khammouan Provincial Government has recently promoted the field amalgamation by providing credits, and this some farmers are taking advantage of the Government scheme (Fukai et al., 2019).

4.1.2. Other factors

Generally higher combine harvesting efficiency found in season 5 and 6 was related to the fact that they were generally large levelled fields and that these fields were used for seed production and fields were maintained well. From the work in seasons 1–3, broadcasting was found to be less efficient compared to transplanting or drill planted crops, due to incidence of lodging as well as more biomass (Naklang et al., 1996). For similar reasons of more biomass and boggy fields, WS crops were found to be less efficient. This reduced efficiency in the WS corresponds to combine contractors charging higher fees in the WS than in DS in Cambodia (USD100/ha cf. USD70/ha in the DS). In field conditions where low combine harvesting efficiency is expected, combine contractors may make per-hour charge rather than per-ha charge.

The results of season 4 show that taller, late maturing varieties grown in lower fields had lower efficiency. They tended to lodge but also yield was not high. The lower yield in these late-harvested, lower fields may have been partly related to the use of seed that was produced on the farm, as the farmers had not renewed their seed for a long time and had been using saved seed from their own crops for many years. Within quick maturing varieties grown in upper fields, VTE450-2 was most efficient for combine harvesting. The variety was released recently after farmer participatory variety selection programme (Mitchell et al., 2014). A lodging resistant variety when broadcast with high harvest index is required particularly for combine harvesting as broadcasting is getting popular in Central Laos. This should be considered as a high priority for the rice breeding programme.

The combine efficiency estimated above does not include the time required for combine to cross the bund; the combine efficiency for enlarged fields would be further increased as the number of crossings is substantially reduced. However, another factor that would affect combine harvesting efficiency is the distance between the paddies that were to be harvested, affecting travel time. In addition to the size and other factors related to the field conditions reported in the present work, a combine is most efficient when a number of neighbouring fields of large size are harvested in one day.

4.2. Adoption of combine harvesting service

In Central Laos, combine contracting services are increasing rapidly. In Khammouan province, 24 combines are now available compared to 2 in 2014, and in Bolikhamxay, the first combine became available in 2017. These combines are operated by contractors and their services are spreading quickly in these provinces. Combine service fees have become cheaper in Laos, probably due to increased competition among service providers; the fee was often over USD200/ha in 2014 but much lower fees have been charged in the past year.

The combine contracting business in Laos seems currently viable, with possible further improvement. It appears that the combine owner is able to meet the credit repayments, despite the short term of the loan, by charging farmers a relatively high fee. The cost of a standard model combine is about USD35,000, including an initial USD3000 instalment, with a 3-year payback period. With a daily net return over operating costs (fuel and labour) of USD500, a total of 70 working days are required to meet the full repayment, which could be

achieved in about 1 year in Laos. Generally combine maintenance cost is not high in the first year. If competition forces down the fee to the equivalent of 10% of the total product, a longer period would be required to meet the repayment schedule, but the operation is likely to still be viable.

Farmers will also gain financially with adoption of combine services that have become available to them. The benefit will depend on not only the yield and combine fees as shown here but also local wage rate, and drying costs (whether sun-drying in field or artificial drying), and effects on grain quality. The effect of harvesting methods on grain quality may not be large, but often harvesting methods are related to drying method, which would affect grain quality greatly (Vongxayya et al., 2019; Xangsaysane et al., 2019a). As combine harvested rice is already threshed and the rough rice has high moisture content, rough rice is not readily sun-dried on-farm and is often dried artificially. This results in higher head rice yield compared with hand harvested rice where the whole plants (panicles and stems) are commonly sun-dried in the field (Vongxayya et al., 2019).

While there is likely to be significant economic benefit at the farm and community level with the adoption of combine harvesting, these changes are likely to interact with other practices such as mechanized planting, artificial drying, deep-ripping of compacted soils, and the development of new cropping systems. The availability of drying facilities is a limiting factor for the adoption of combine harvester, as combine harvested paddy is difficult to sun-dry on farm particularly for DS crops when the chance of rainfall during the drying is high. Thus, the development of a drying service is a major requirement for wide adoption of combine harvesting. Drying services may be provided by mills or villagers, though it is likely that mills have an advantage in providing this service. Thus it is important to develop grain drying facilities for further adoption of combine contracting services (Xangsayasane et al., 2016).

5. Conclusion

Increasing field size will increase combine harvesting efficiency and benefit combine contractors. Reduction in combine service fees may be achieved with increased combine harvesting efficiency as a result of field size and other factors explored here. This will increase the financial gain to farmers of adopting service. Competition, better post-harvest handling and coordination with millers will aid mechanized rice harvesting so that all parties will get benefit in a longer term. Development of lodging resistant varieties will increase combine harvesting

efficiency and should be considered as a high priority in the rice breeding programme.

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