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Mechanised dry seeding is an adaptation strategy for managing climate risks and reducing labour costs in rainfed rice production in lowland Lao PDR

A.M. Laing[a,*], C.H. Roth[b], L. Chialue[c], D.S. Gaydon[a], C.M. Grünbühel[d], T. Inthavong[e], V. Phengvichith[e], J. Schiller[f,1], Sipaseuth[e], K. Thiravong[g], L.J. Williams[b]

[a] CSIRO Agriculture and Food, Brisbane, Australia
[b] CSIRO Land & Water, Brisbane, Australia
[c] National University of Laos, Vientiane, Lao Democratic People's Republic
[d] Stockholm Environment Institute – Asia Centre, Bangkok, Thailand
[e] National Agriculture and Forestry Research Institute, Vientiane, Lao Democratic People's Republic
[f] Formerly of The University of Queensland, Brisbane, Australia
[g] Provincial Agriculture and Forestry Office, Savannakhet, Lao Democratic People's Republic

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ABSTRACT

Rainfed rice production in Lao PDR is critical to national food security; under traditional transplanting methods farmers are exposed to climate risks at both the onset and the conclusion of the wet season. Production of the annual crop has a high labour requirement especially during transplanting and harvesting. We engaged with smallholder farmers to investigate the feasibility of one form of dry seeding of rice, i.e. mechanised dry drill seeding, which in this paper we refer to as "dry seeding". We hypothesised that dry seeded rice crops will be established earlier in the wet season and will produce a comparable yield while requiring less water and labour than transplanted rice. Field trials, supported by scenario modelling using the APSIM model, indicated average dry seeded rice yields are comparable to average transplanted yields over the longer term but with reduced risk of crop failure, under both current (1971–2011) and near-future (2021–2040) climates, for two common soil types. Net overall labour savings reduce the cost of rice production under mechanised dry seeding, better positioning households against fluctuations in labour costs and rice prices. Mechanised dry seeding requires different crop management to traditional methods and will not be appropriate for all farmers. Performance of DSR under future climate scenarios is projected to be as good as or better than under current climate conditions.

1. Introduction

Lao PDR is experiencing rapid social change in agriculture with the rise in alternative income streams from non-farm, (relatively) high-earning income opportunities for rural households (Cramb et al., 2015; Manivong et al., 2014). Largely this change is experienced in rural areas where traditional incomes are derived from work which is both menial and poorly paid. Most rural households still aim to produce sufficient rice annually to ensure food security (Cramb et al., 2015; Manivong et al., 2014; Newby et al., 2013) and for many households remittances from younger members working in regional cities are used to hire labourers at key times in the cropping calendar to ensure household food security (Manivong et al., 2014). As access to household labour through the growing season has reduced (due to temporary or permanent migration), the demand for hired labour has increased and thus the cost of hiring workers for transplanting, weeding and other labour-intensive tasks has also increased. Farming households are keen to maintain current rice yields while reducing the costs of production, in particular labour costs. Farmers perceive little benefit in increasing production above that necessary for domestic consumption as input costs are relatively high and rice prices volatile and uncertain (Newby et al., 2013).

Lowland Lao PDR has a climate with highly variable short-term fluctuations (e.g. flooding along the Mekong River basin, and intra- and inter-season drought; Lacombe et al., 2012) and little institutional or community capacity to adapt to these risks (Roth and Grünbühel, 2012). In Lao PDR almost all rice is grown on the lowland plains in the annual wet season (May to November), under rainfed conditions, using traditional methods of puddling and transplanting (Sengxua et al., 2017; Inthavong et al., 2011b; Linquist et al., 2006). This high dependence on rainfed rice production, combined with likely projections for

* Corresponding author at: 306 Carmody Road, St Lucia, QLD, 4067, Australia.
E-mail address: alison.laing@csiro.au (A.M. Laing).
[1] Deceased

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current or increasing variability in the timing, onset and/or duration of the wet season rains (Lacombe et al., 2012; Roth and Grünbühel, 2012), leaves Lao PDR vulnerable to reduced and more risky rice production. There are conflicting reports estimating the impacts of future climates on rice production in Lao PDR: Mainuddin et al. (2011) suggest that average rice yields in Southeast Asia may remain stable or increase, while other work (Snidvongs et al., 2003; Parry et al., 2004; Wassmann et al., 2009) forecasts less positive outcomes in future yields across the region.

Strategies which help farmers better manage risk under current patterns of climate variability are likely to also assist them transition the production system under future climates (Howden et al., 2010, 2007). A challenge for researchers is to identify the strategies which will best assist farmers: one option often considered is improved seasonal climate forecasting, which enables farmers to better target their management decisions to the likely upcoming seasonal conditions. Lacombe et al. (2012) conducted a detailed statistical analysis of rainfall data in the region covering the southern Lao rice production zone over a period of up to 60 years (1951–2010). They derived 37 variables from daily rainfall records and examined the main climate features that affect rainfed agriculture and farmers' livelihoods, including the onset, duration, cessation and intensity of rainfall through the wet season. Lacombe et al. determined that observed rainfall trends across Savannakhet Province are heterogeneous and variable across temporal and spatial scales. They found little correlation between wet season onset and cumulative rainfall over all or part (e.g. the first 30 days) of the wet season, and no correlation between wet season onset and the wet season retreat. These observations of high season-to-season rainfall variability, lack of predictive ability before or during a wet season, and subsequent challenges to rice production are in line with those observed previously (e.g. Hijioka et al., 2014; Fukai and Ouk, 2012; Basnayake et al., 2006). Hence, it has been concluded that current seasonal climate forecasting technology has little value for farmers in Lao PDR.

An alternative strategy is to change traditional management options to increase flexibility and permit better alignment of rice crops to seasonal conditions as they unfold. Fukai et al. (1998), working in irrigated dry season rice production systems, demonstrated that mechanised dry drill seeding of rice (DSR; referred to as 'dry seeding' in the remainder of the paper) enables flexibility in the timing of rice establishment for the southern Lao rice production area. There has been little subsequent work to extend DSR into rainfed wet season production systems in Lao PDR.

In traditional rainfed transplanted rice (PTR), farmers rely on monsoonal rains to produce a single wet season rice crop annually. Between two and four nursery crops are sown at staggered intervals approximately two weeks apart from late April to early June, on premonsoon showers. Once the nursery is established and sufficient rain has fallen to saturate soils, farmers plough, puddle, and prepare their main paddies. When monsoon rains arrive, in late June or July, the most viable seedlings are transplanted into bunded paddies. Rice is transplanted into standing water, which also suppresses weeds and into which fertiliser is broadcast. If rainfall is insufficient or late, crop yields are negatively affected by delayed transplanting of older-seedlings, poorly-timed fertiliser applications, and increased risk of drought stress at the end of the growing season (Linquist et al., 2006).

In contrast to PTR, the mechanised DSR practice tested here involves sowing directly into tilled, unpuddled soil using a tractor-mounted seeder: farmers take advantage of the same early-season rains which germinate and sustain their seedling nurseries to germinate and grow paddy rice. Because the rice is planted *in situ* in the paddies from where it will be harvested, standing water is not necessary during the growing season (weeds must be well managed by alternative means). Physiologically, mechanised DSR is better protected against early and/or intermittent drought as root systems develop sooner and more robustly (Sudhir-Yadav et al., 2014): crops are thus better able to withstand short term rainfall deficits. In lower terraces, early-sown rice plants are taller earlier in the wet season and better able to withstand short-term flooding events. Mechanised dry seeding is much faster than transplanting: to establish one hectare takes approximately one person-day with a seeder compared with about 20 person days to transplant (Pheng Sengxua pers. comm., Fukai and Ouk, 2012). DSR crops mature earlier in the season than PTR crops, and although they might therefore appear less at risk of terminal drought stress, the situation in reality is less clear. Due to the puddling process, soils under PTR crops will have lower saturated percolation rates than the same soils under DSR (puddled soil percolation rates are around 50% that of non-puddled soils: Gathala et al., 2011), and consequently surface water is retained longer as ponding in PTR systems. This means that although DSR crops finish earlier, ponded water may also disappear earlier. Conversely, PTR crops finish later but any rainfall will maintain and pond for longer.

Williams et al. (2015) document the diversity in livelihoods in southern Lao PDR. While DSR is a feasible establishment practice for farming households in irrigated systems, it has not been previously determined if DSR will meet the needs and goals of households in rainfed wet season rice production systems. Management strategies which address multiple production objectives are attractive to farmers and more likely to be adopted than those which only address a single objective (Roth and Grünbühel, 2012). Mechanised DSR which, compared to PTR, facilitates earlier-season planting, faster physiological development and reduced water demand has the potential to reduce farmers' exposure to the high rainfall variability (Lantican et al., 1999).

Accordingly, this study aims to examine if DSR: i) is a technically feasible establishment strategy to manage climate risk (in other words, does it reduce the frequency of crop failures or poor crop yields in dry years); ii) is sufficiently attractive to farming households to encourage them to adopt this technology; and iii) is likely to assist farmers manage future climate risks. Our approach integrates agronomic and social research by combining participatory farmer engagement, on-farm trials, and cropping systems modelling to make comparisons between DSR and PTR for the farming communities in which they are based. While this research was conducted in lowland Lao PDR, we suggest the results are broadly applicable across rainfed lowland rice production areas in developing countries facing agronomic challenges as a result of climate change and labour shortages.

2. Materials and methods

2.1. Study sites

Research was conducted in two districts, Outhoumphone and Champhone, in western Savannakhet Province, Lao PDR (Fig. 1). These districts are representative of the lowland, rainfed rice-growing plains from which almost 80% of the country's rice is produced (Linquist et al., 2006; Roth and Grünbühel, 2012). Rainfall in this region is highly variable year to year (Basnayake et al., 2006; Lacombe et al., 2012). Farms in Champhone district are relatively low-lying and subject to flooding during the wet season, but are endowed with deeper sandy loam soils. Farms in Outhoumphone are located on drier, more undulating toposequences with shallow loamy sands, often underlain by laterites, making these sites more drought prone.

2.2. Analysis of planting window

Daily rainfall data from seven observation stations within Savannakhet Province were analysed for spatial and temporal trends to identify earliest possible sowing windows, using the methods and definitions described in Lacombe et al. (2012), noting that the earliest sowing window occurrence is the commencement of the wet season in any particular year and any sowing window is followed by a 30-day nursery period (see Fig. 1 for station locations). Two stations (Seno and

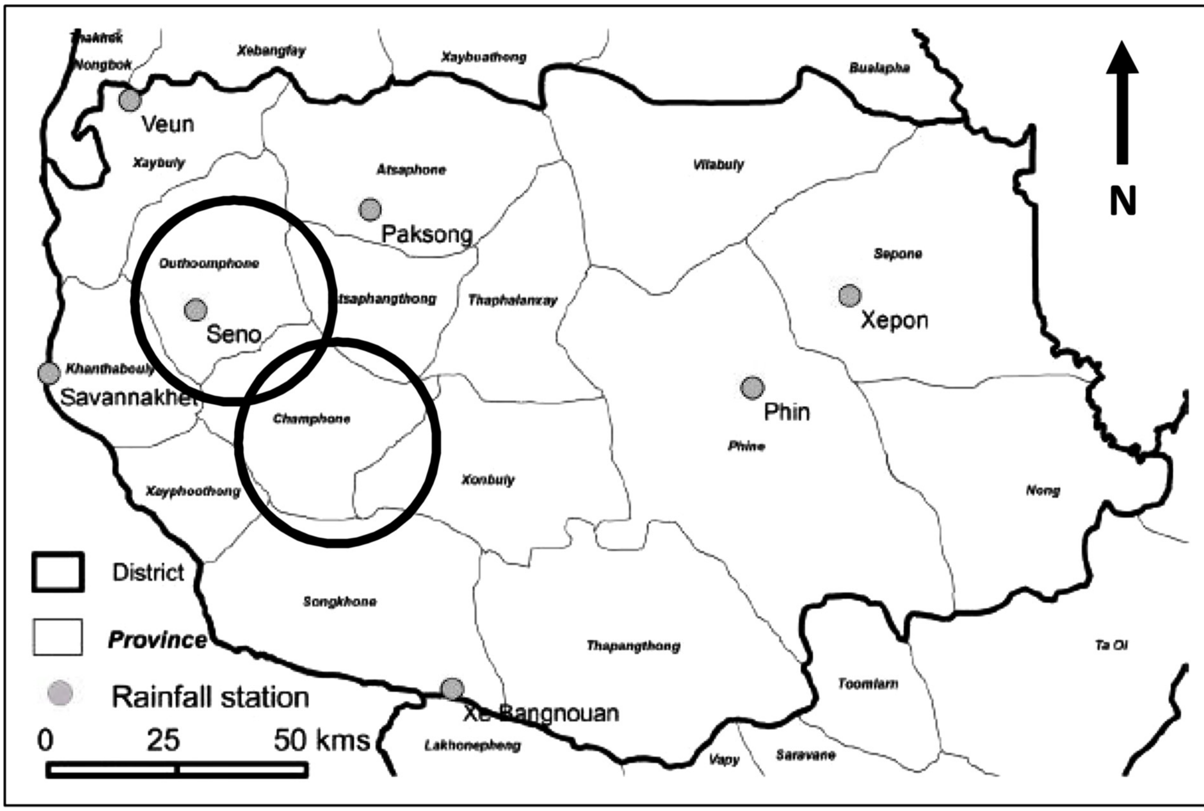

Fig. 1. Rainfall observation stations and location of Outhoumphone and Champhone districts (circled) within Savannakhet Province.

Savannakhet) had datasets of more than 40 years and were used for the main analysis, while the other stations with shorter records (< 20 years) were used to verify variability trends and help fill data gaps. Any missing data were infilled through multiple linear regressions using best correlated stations (R^2 > 0.6 and significance level > 99% according to the F-test). Regression models were fitted with monthly cumulative rainfall and used to interpolate daily time series where observed data were missing. Correlations between averaged 1-year time series of daily rainfall (R^2 > 0.6 and significance level > 99% according to the F-test) suggest that the distribution of rainy days is uniform among the time series used in the regression models (Lacombe et al., 2012).

Table 1
Details of on-farm experiments in 2013 and 2014 (PTR: puddled transplanted rice; DSR: dry seeded rice; GAP: good agricultural practice; FP: farmer practice).

Year	Treatments	District	Village	Number of farmers
2013	T1: PTR	Outhoumphone	Phin Neua	9
	T2: DSR		Phin Thai	3
			Nonsavang	6
			Sibounheuang	3
		Champhone	Tuad	9
			Taleo	9
			Sivilay	9
			Vangmao	3
2014	T1: PTR + GAP	Outhoumphone	Phin Neua	3
	T2: DSR + GAP	Champhone	Tuad	3
	T3: DSR + herbicide		Alan Wattana	3
	T4: DSR + FP			
	T5: PTR + FP (Phin Neua only)			

2.3. On-farm experiments

In 2013 and 2014, on-farm experiments were conducted to compare the performance of two establishment methods: traditional puddled transplanted rice (PTR) and mechanised dry seeded rice (DSR). An overview of the treatments, locations and number of trials is provided in Table 1.

For both seasons, each farmer was an experimental replicate, testing all treatment options on reasonably homogenous soil in fields averaging 400–500 m^2. A stepwise approach was taken to field trials. In 2013 the focus was an initial comparison of the two establishment methods (PTR vs DSR), at multiple locations (involving 51 farmers from eight villages; four in each district). For most farmers this was their first opportunity to access and test a DSR seeder; results from this season (not presented here) demonstrated that rice could be successfully produced under DSR in the trial sites in Savannakhet. While results were reliable enough to provide proof of concept, the heterogeneity of rice varieties used by farmers, and the challenges of conducting participatory on-farm research resulted in a lack of consistency in the output data. Hence, in 2014, on-farm trials involved a smaller number of participants (nine farmers across three villages) and were more rigorously monitored. In 2014 trials we tested different levels of crop management and interactions with PTR and DSR. This resulted in five different treatments (Table 1), with a greater emphasis being placed on timely manual weed management, particularly during land preparation and in the early stages after sowing. The main addition in 2014 was the introduction to both PTR and DSR treatments of Good Agricultural Practice (GAP) guidelines as recommended by the Lao government's National Agricultural and Forestry Research Institute (NAFRI). GAP comprises: higher rates of nitrogen than farmers typically use (75 kg N ha^{-1} split into one basal and two in-crop applications); two pre-planting ploughings (ten days apart for weed management); and early manual weed removal from paddies as necessary. Additionally we tested chemical management of weeds with a DSR treatment to which a sulfonylurea herbicide (Goadi) was applied post-emergence at a rate of 5 g $3L^{-1}$. These treatments contrast with traditional farmer practice (FP) where: farmers apply lower rates of nitrogen (approximately 10 kg

N ha^{-1} at sowing); paddy fields are ploughed once before puddling; and ponded water is the primary mechanism for weed suppression. Three farmers in each of three villages (one in Outhoumphone and two in Champhone districts) participated in the 2014 trials; each farmer was treated as an experimental replicate. All farmers used new TDK8 seed provided by NAFRI.

The dry seeder tested in 2013 was a simple Thai-built model mounted onto the prevalent two-wheel tractors. It employed four sets of discs to open furrows in moist soil into which seed is dropped; there were no press-wheels. Wet season rainfall was low in 2013 and farmers reported difficulty applying fertiliser early in the season (it is broadcast into standing water in paddies). Hence, in 2014 a locally produced seeder with tines instead of discs was developed and used, enabling the incorporation of fertiliser into the soil at sowing. This modified seeder was also lighter and more easily manoeuvrable.

2.4. Analysis of costs and labour required for production

We conducted both cost of production (COP) and simple gross margin (GM) analyses on the results of field trials to compare the performance of PTR and DSR. As much of the rice grown is for home consumption, COP may be the more meaningful measure of the value of a treatment option to farmers than GM. Data on inputs used, their costs, and the person days required to complete different activities under both transplanting and mechanised dry seeding (e.g. land preparation, weeding, harvesting, post-harvest processing) were recorded through the 2014 growing season. COP includes all inputs required to produce a crop (labour, seed, chemicals) while GM is the marketable value (i.e. yield x farm gate rice price) less the COP.

As the costs and benefits of rice growing are very dependent on rice and labour prices, we augmented the GM analysis with a spreadsheet-based sensitivity analysis of changes in rice price and labour costs: comparing a present-day baseline gross margin with variations of up to +/- 20% in rice price and 50 per cent and 100 per cent increases in daily labour costs. The baseline was calculated using current estimates of labour costs (50,000 LAK day^{-1}; approximately USD \$6 day^{-1}) and farm gate rice prices (2200 LAK kg^{-1}; approximately USD \$0.3 kg^{-1}). In all gross margin sensitivity analyses weeds were assumed to be well controlled.

2.5. Participatory engagement with farming communities

Initial engagement with farmers in Outhoumphone and Champhone in 2012 indicated their strong interest in DSR, primarily because of its potential to save labour. We extended farmer engagement in 2013 to supplement the experimental and modelling approaches with social research, to more systematically capture farmer perspectives on the attractiveness and feasibility of DSR, as well as eliciting farmers' collaboration in setting up and conducting the trials.

In April 2013 farmers participated in interviews and in semi-structured focus group discussions following NAFRI-provided agronomic training in the use of the dry seeder. Thirty self-selected farmers, approximately half those who participated in the agronomic training, formed into three focus groups which represented six of the eight villages in which on-farm testing of DSR was scheduled. The aims of the discussions were i) to get farmer feedback on training, especially training related to DSR techniques, ii) to gauge farmers' attitudes to, and interest in, using DSR to establish (some of) their crop, and iii) to understand farmers' perceptions of constraints and likely benefits of applying the DSR management practices discussed in the training.

In July 2013, 20 farmers from eight villages (five in Champhone and three in Outhoumphone) in which DSR was being tested were interviewed, separately. In December 2013, six of the eight villages visited in July (three in each district) were revisited. In each village groups of 10 to 15 farmers self-selected to participate in focus group discussions conducted to document farmers' experiences with and attitudes towards DSR after one growing season.

All interviews and focus group discussions were conducted in Lao and followed a common structure. In all activities farmers who were engaged in on-farm testing voluntarily chose to participate in discussions and/or interviews. While no formal attempt was made to continue engaging with the same farmers throughout the growing season, the majority of farmers who chose to interact with researchers participated in all three discussions.

2.6. Simulation modelling

The APSIM cropping systems model (Holzworth et al., 2014; Keating et al., 2003) was used to compare long-term rice production under transplanting and mechanised dry seeding. APSIM has modules for simulating rice crops, (APSIM-Oryza, based on Oryza2000: Bouman and van Laar, 2006), and for ponded soil conditions (Gaydon et al., 2012a, 2012b) and has been comprehensively tested and validated in a range of South and Southeast Asian rice growing environments and management practices (Poulton et al., 2016; Balwinder-Singh et al., 2016; Gaydon et al., 2017). APSIM requires four categories of inputs - soil parameters, crop coefficients, climate data, and farmer management rules.

The APSIM-Oryza model does not simulate the processes of germination and emergence for DSR, making instead the assumption that the crop emerges on the day it is planted. As this does not happen in reality, we have assumed that emergence occurs after a fixed period (seven days from the first sowing opportunity) to allow for germination-emergence processes. We believe that employing a fixed period for emergence is valid, since DSR sowing occurred here into moist soil and germination processes began immediately without lag. Simulated DSR plant densities were estimated from those achieved in established field trials. These estimations implicitly included a certain percentage of seedlings which had died, as APSIM-Oryza is unable to simulate in-field stand thinning (i.e. reduction in plants per square metre) due to drought or pests. APSIM was, however, able to simulate the death of the DSR crop due to drought in early growth stages: this is captured in the crop risk figures presented. For the very young DSR crops, seedling death due to submergence is a risk which may be realised when heavy rains cause ponding and inundation of the young plants past a certain threshold number of days. We captured this risk by including an APSIM-Manager rule for all simulations which compared the variable 'height' (representing rice crop height) with 'pond_depth' on a daily basis. When 'pond_depth' was greater than 'height' for more than seven successive days, the crop was killed and a crop failure registered.

2.6.1. Soils data

Two soils were simulated: in both there is an arable top layer over an impermeable layer. In the first soil the arable layer is relatively deep and thus has a greater plant available water capacity. In the second soil the arable layer is relatively shallow and thus has a lower plant available water capacity. The 'deeper' soil represents mid to low positions in the toposequence while the 'shallower' soil represents higher positions in the toposequence. (Tables 2 and 3). These soils are representative of most of the low-lying, slightly undulating plains in which rice is grown in the Outhoumphone and Champhone districts of Savannakhet Province (Pheng Sengxua, pers. comm.). In both soils a puddled hardpan layer was simulated in transplanting simulations; this layer is less permeable (i.e. has a lower Ks) under PTR than the comparable layer in mechanised dry seeding simulations, in which the soil is no longer compacted each year with transplanting. Additionally, in transplanting simulations only, physiological development, including above and below ground biomass production, is temporarily impeded after transplanting. Soil texture, bulk density and soil porosity were obtained from sampling the study sites and these parameters were then used to extract soil water retention and conductivity parameters from literature for similar soils in NE Thailand (Williamson et al., 1989; Tsubo et al., 2006,

Table 2
Soil characterisation data used in the soil with a shallow arable layer between hardpan and impermeable layer (representative of the upper toposequence).

Depth (mm)	Sand (%)	Silt (%)	Clay (%)	OC[a] (Total %)	Ks under PTR (mm day^{-1})	Ks under DSR (mm day^{-1})	BD (g cm^{-1})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	SWCON	KL
0-200	70	20	10		30	30	1.50	0.25	0.48	0.56	0.30	0.80
200-300	70	20	10		10	20	1.64	0.27	0.50	0.56	0.30	0.60
300-500	65	25	10		50	50	1.68	0.35	0.38	0.56	0.30	0.60
500-1500	60	20	20		1	1	1.60	0.27	0.33	0.56	0.10	0.40

[a] OC: organic carbon; Ks: rate at which water moves through fully saturated soil; BD: bulk density; LL: volumetric soil water content at limit of water extraction of rice (wilting point); DUL: volumetric soil water content after drainage has ceased (field capacity); SAT: volumetric water content at saturation; SWCON: fraction of soil water between DUL and SAT which drains per day; KL: water extraction efficiency coefficient.

2007; Inthavong et al., 2011a). Key nutrient data (C, N) were provided by soil scientists from NAFRI (Pheng Sengxua, pers. comm.). We assumed that the saturated percolation rate (K_s) of the soils differed between steady-state treatments of PTR and DSR due to compaction of the plough-pan layer (200–300 mm). Figures used required roughly a doubling of K_s in the DSR system (Gathala et al., 2011): the values used for each system and soil are detailed in Tables 2 and 3.

2.6.2. Crop data

A rice variety was parameterised in APSIM to represent a modern improved variety of Lao glutinous rice, TDK8, using data obtained in the field trials (crop production data, plus dates of key phenological stages) following the standard approach to calibration and validation described in Gaydon et al. (2017). The calibration and validation undertaken in this current study is part of the dataset detailed in Gaydon et al. (2017), hence is not reproduced here. TDK8 is common across Savannakhet Province and was one of the most popular varieties used by farmers in all field trials. Phenology and management data were collected through the 2014 growing season for use in APSIM model calibration and validation.

2.6.3. Climate data

Daily climate parameters (maximum and minimum temperatures, rainfall, and sunshine hours) were obtained for the Savannakhet station (1971–2011). Other climate stations either had insufficient duration or incomplete datasets, so the simulations only used the Savannakhet climate station data. In the first series of simulations, we used long-term historical climate data to evaluate whether DSR offers an advantage over PTR in reducing the impact of early-season or within-season drought under current climate conditions. Next we assessed the performance of PTR and DSR under future climates. For this purpose, climate projections were derived using the Linear Mixed Effect State Space model (LMESS; Kokic et al., 2011) which combines output from global circulation models (GCMs) with small scale climate observations to produce statistically robust projections of climate for current and future time periods. The LMESS method of generating data retains relationships between climate variables such as rainfall, temperature and solar radiation which are critical to crop simulation modelling. Using the LMESS method, data from two contrasting GCMs, GFDL GCM 2.1 (GFDL; Delworth et al., 2006) and ECHAM 5 (ECHAM; Roeckner et al., 2003), under the A2 SRES emissions scenario (IPCC, 2000: approximately equivalent to representative concentration pathway RCP6; Moss et al., 2008) were combined with climate observations from Savannakhet station to generate future climate projections over the period 2021 to 2040. Data from GFDL represent a relatively more extreme future climate where tropical rainfall is likely to be higher (and possibly more intense) than present day; data from ECHAM represent a relatively milder future climate. Both GCMs capture key climate interactions in Southeast Asia well (Philip Kokic, pers. comm.).

Relative to the present day, average annual rainfall for the twenty year period centred on 2030 is forecast to increase by 27% under ECHAM and by 32% under GFDL (Table 4). The forecast increase in annual rainfall in the two 2030 climates, above the present day distribution, is considerably greater than the forecast difference in average rainfall between the two future climate projections. Small decreases in average annual maximum temperatures are forecast under ECHAM and GFDL (−0.1 and −0.3 °C, respectively) while increases in average annual minimum temperatures of + 1.0 °C (ECHAM) and + 1.1 °C (GFDL) are forecast. These changes in temperature are unlikely to have significant effects on rice growth or performance. In general, forecasts of future climate variables, particularly rainfall, in Southeast Asia are highly uncertain: the projected changes in rainfall and temperature we generated exhibit the same trend observed by Lacombe et al. (2013) and Li et al., (2016), who project a wetter future climate for central parts of the Mekong Basin. They are also well within current likely future climate bounds for Southeast Asia (Hijioka et al., 2014).

2.6.4. Scenarios simulated

For both soil types and for present and future climates, eight rice management scenarios have been simulated (Table 5). The baseline scenario (S1) represents farmers' current risk averse (low input) management practice: a single rainfed PTR TDK8 crop is established every wet season. In the PTR simulations the crop is transplanted the first time water ponds on the soil surface for three consecutive days; the nursery is sown 30 days before transplanting. Most farmers use small amounts of nitrogen fertiliser which are incorporated into the soil at sowing: 7 kg N ha^{-1} and 0.5 t ha^{-1} farmyard manure were added in all low-nitrogen scenarios. NAFRI recommends applying higher fertiliser rates to rice crops. In all higher-nitrogen scenarios an application of 11 kg N ha^{-1} was applied at sowing with 0.5 t ha^{-1} farmyard manure;

Table 3
Soil characterisation data used in the soil with a deep arable layer between the hardpan and the impermeable layer (representative of the mid to low toposequence).

Depth (mm)	Sand (%)	Silt (%)	Clay (%)	OC[a] (Total %)	Ks under PTR (mm day^{-1})	Ks under DSR (mm day^{-1})	BD (g cm^{-1})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	SWCON	KL
0-200	70	20	10	0.6	30	30	1.50	0.10	0.38	0.51	0.30	0.80
200-300	70	20	10	0.24	10	20	1.64	0.20	0.41	0.51	0.30	0.60
300-1000	65	25	10	0.30	50	50	1.68	0.28	0.38	0.51	0.30	0.60
1000-1500	60	20	20	0.22	1	1	1.60	0.29	0.33	0.51	0.10	0.40

[a] OC: organic carbon; Ks: rate at which water moves through fully saturated soil; BD: bulk density; LL: volumetric soil water content at limit of water extraction of rice (wilting point); DUL: volumetric soil water content after drainage has ceased (field capacity); SAT: volumetric water content at saturation; SWCON: fraction of soil water between DUL and SAT which drains per day; KL: water extraction efficiency coefficient.

Table 4
Changes in key average annual climate variables for rice production between present day (PD; 1971–2011) and future (2030; 2021–2040) projected time periods using climate data generated by the LMESS method (Kokic et al., 2011).

Variable	1971-2011	ECHAM (change from PD)	GFDL (change from PD)
Cumulative annual rainfall (mm)	1476.6	1876.4 (+27%)	1946.4 (+32%)
Annual maximum temperature (°C)	31.3	31.2 (−0.1 °C)	31.0 (−0.3 °C)
Annual minimum temperature (°C)	21.2	22.1 (+ 1.0 °C)	22.2 (+ 1.1 °C)

this was followed by two top dressing events, of 30 kg N ha^{-1} each, which were applied at 28 and 55 days after transplanting for PTR simulations and at 22 and 42 days after sowing for dry seeding simulations.

Other management options examined through scenarios were: i) the effect of short-term early-season supplementary irrigation in PTR systems; and DSR with a sowing rule under which rice is established either ii) earlier (i.e. into a drier soil once 25 mm rain has been received after 15 April) or iii) later (into a wetter soil once 40 mm rain has been received after 15 April) in the growing season. Where supplementary irrigation is applied it is done so in the first two months after sowing (i.e. in the nursery and for the first month after transplanting) when no rainfall or irrigation water has been received by the crop in the previous seven consecutive days. This option, tested through simulation modelling, enables us to examine the benefit, or otherwise, of early-season supplementary irrigation. As current opportunities to access sufficient water in a timely manner to enable supplementary irrigation are limited for most farmers in Outhoumphone and Champhone districts, often due to limited and/or aging irrigation infrastructure, we have not examined options for extended irrigation such as late-season irrigation.

All the listed management rules were coded into the APSIM-Manager, emulating farmer decision making. APSIM v7.5 was parameterised and calibrated using data described above and subsequently validated using independent field trial data (Gaydon et al., 2017) and sensibility testing based on expert opinion.

3. Results

3.1. Rainfall variability and planting window

The results of the rainfall variability analysis conducted for Savannakhet are presented in Fig. 2 and show that the average 41-year (1971–2011) cumulative rainfall over every 30 day period from a given (potential rice sowing) date increases with time from 1 April (Julian day 91) until approximately 11 May (Julian day 131), after which cumulative 30 day rainfall plateaus through June. This trend is consistent across the seven rainfall datasets examined (data not shown). From late June onwards the average cumulative 30 day rainfall again increases over time.

Fig. 2 illustrates the cumulative rainfall over the extent of the potential 30-day sowing-and-nursery window, from early-sown nurseries at the beginning of April to those late-sown in mid-July. The maximum and minimum cumulative 30 day rainfall amounts shown in Fig. 2 also illustrate the high degree of rainfall variability inherent in this region (Basnayake et al., 2006), however average rainfall in the early May to late June period (Julian day range 121 to 181) is up to 200 mm, which is sufficient to establish a dry seeded rice crop but insufficient for ponding and thus transplanting.

In terms of soil moisture, average historical rainfall translates to three distinct stages (Fig. 3). Stage 1 (1 April to early May; Julian day range 91–130) is when a gradual wetting up of the soil occurs. Stage 2 (early May to June; Julian day range 130–171) is the stage where one can expect the soil to be moist enough to support plant growth, but not consistently wet enough for ponding to occur. With the renewed increase in average annual rainfall in Stage 3 (from June to late September; Julian day range 171–263), sufficient rainfall accumulates so that soil saturation and ponding are likely. Fig. 3 illustrates average long-term (1971–2011) ponding simulated under PTR and DSR for both the deep and shallow soils.

3.2. On-farm experiments: inputs applied, yields obtained and labour requirements

Farmers used proximate dates to sow crops, both in the main paddy for DSR and in the nursery for PTR. In both 2013 and 2014 transplanting was delayed on many farms by between two and four weeks due to an insufficiency of rainfall to form ponds in paddies. In contrast, DSR was sown in a timely manner on early-season rains.

Yields are comparable in PTR and DSR systems with GAP (where weeds are well controlled and relatively high rates of fertiliser are applied). In 2014 on-farm testing, farmers achieved average yields of 3.3 t ha^{-1} under both PTR and DSR, in treatments where weeds were well managed manually and additional nitrogen fertiliser was applied, i.e. T1 (PTR + GAP) and T2 (DSR + GAP) (Table 6). In the transplanted system with traditional farmer practice, T5 (PTR + FP), fertiliser rates were lower and average yields were consequently reduced to 2.0 t ha^{-1}. Comparable yields (average 3.3 t ha^{-1}) were obtained across treatment T3 (DSR + herbicide) and treatments T1 and T2, where weeds were manually controlled. In DSR where weeds are poorly managed (T4: DSR + FP) average yields (2.3 t ha^{-1}) are reduced relative to PTR and DSR systems with GAP (T1 and T2).

As expected, the addition of nitrogen fertiliser increases yields above those achieved under traditional farmer practice (i.e. comparing T1 with T5 and T2 with T4 in Table 6). It is well documented that rainfed lowland Lao production systems are nutrient deficient (Haefele et al., 2010; Fukai and Ouk, 2012).

Farmers in 2014 on-farm trials took, on average, 31 person-days per hectare to establish a transplanted crop and 8 person days per hectare to establish a dry seeded crop (Table 7). In the PTR systems 11 person days per hectare were required to control weeds. This increased to 16 person days per hectare under DSR where weeds were well managed (through thorough land preparation and timely manual intervention through the growing season), and to 32 person days per hectare in a DSR system where weed management followed traditional farmer practice rather than early intervention. Overall, including the additional labour required for weeding under a well-managed DSR system relative to transplanting, the total labour required to produce a crop is lower under DSR (52 person days per hectare) than PTR (73 person days per hectare).

3.3. Cost of production and gross margin analyses

The cost of production (COP) under a well-managed DSR system (DSR + GAP) is comparable to that under a traditional PTR system (PTR + FP) and lower than that under a well-managed PTR system (PTR + GAP). Under the traditional PTR system (with low fertiliser inputs and ad hoc weed control) the cost of production is USD $515 ha^{-1} (Table 7). When the PTR system is well managed COP increases to USD $676 ha^{-1}, due to additional input (fertiliser) and higher manual weeding costs, while under a DSR system with GAP the cost of production is USD $515 ha^{-1}.

Average COP and yields are key factors in gross margin (GM) calculations: the DSR + GAP system, with a combination of relatively low COP and relatively high average yields has an average GM which is more attractive than all other options except the DSR with herbicide system (which is not attractive to farmers for cultural and social reasons). The gross margin in a traditional PTR system (with low fertiliser inputs) is USD $69 ha^{-1}; this is lower than gross margins achieved in

Table 5
Scenarios examined with APSIM.

Scenario	Establishment	Sowing rules	Fertiliser	Water	Description
S1: PTR_0 N_RF	Transplanting	Nursery established 30 days before the first time water ponds for 3 consecutive days One tillage event 3 days before sowing Transplant 30 days after sowing	7 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing	Rainfed	Farmer practice common throughout Savannakhet Province
S2: PTR_+N_RF	Transplanting	Nursery established 30 days before the first time water ponds for 3 consecutive days One tillage event 3 days before sowing Transplant 30 days after sowing	11 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing, 60 kg N ha^{-1} applied as two top dressings	Rainfed	Increased nitrogen, as recommended by NAFRI
S3: PTR_0 N_irri	Transplanting	Nursery established 30 days before the first time water ponds for 3 consecutive days One tillage event 3 days before sowing Transplant 30 days after sowing	7 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing	Rainfed except in first two months after sowing when early-season irrigation events of 50 mm were applied where no rainfall/irrigation received in previous 7 days	Farmer practice with supplementary irrigation
S4: PTR_+N_irri	Transplanting	Nursery established 30 days before the first time water ponds for 3 consecutive days One tillage event 3 days before sowing Transplant 30 days after sowing	11 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing, 60 kg N ha^{-1} applied as two top dressings	Rainfed except in first two months after sowing when early-season irrigation events of 50 mm were applied where no rainfall/irrigation received in previous 7 days	Supplementary irrigation and NAFRI-recommended N rates
S5: DSR_0 N_dry	Dry seeding	Tilling commences first time 25 mm rain received within 3 days, after 15 April Two tillage events 10 days apart Sowing 3 days after second tillage	7 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing	Rainfed	Early sowing (into a drier soil) and farmers' traditional N rates
S6: DSR_+N_dry	Dry seeding	Tilling commences first time 25 mm rain received within 3 days, after 15 April Two tillage events 10 days apart Sowing 3 days after second tillage	11 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing, 60 kg N ha^{-1} applied as two top dressings	Rainfed	Early sowing (into a drier soil) and NAFRI-recommended N rates
S7: DSR_0 N_wet	Dry direct seeding	Tillage commences first time 40 mm rain received within 5 days, after 15 April Two tillage events 14 days apart Sowing 3 days after second tillage	7 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing	Rainfed	Later sowing (into a wetter soil) and farmers' traditional N rates
S8: DSR_+N_wet	Dry direct seeding	Tillage commences first time 40 mm rain received within 5 days, after 15 April Two tillage events 14 days apart Sowing 3 days after second tillage	11 kg N ha^{-1} + 0.5 t ha^{-1} farmyard manure applied at sowing, 60 kg N ha^{-1} applied as two top dressings	Rainfed	Later sowing (into a wetter soil) and NAFRI-recommended N rates

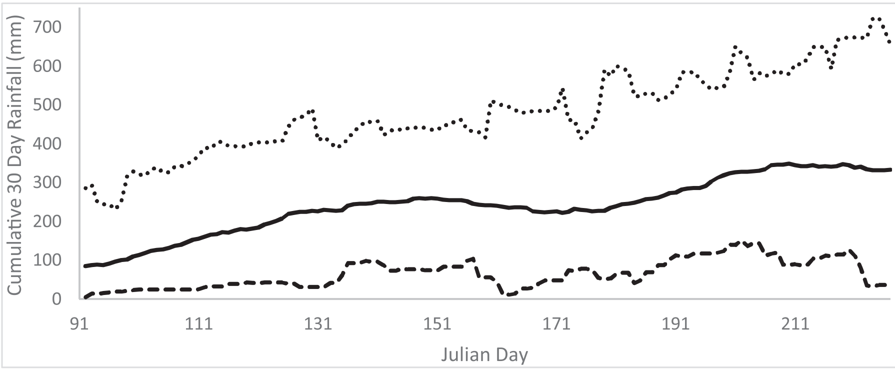

Fig. 2. Average 30 day cumulative rainfall (solid line) through the extent of the potential sowing-and-nursery window, from early-sown nurseries established on 1 April (Julian day 91) and those late sown in mid-July with a nursery extending to 15 August (Julian day 227) over 41 years (1971–2011) at Savannakhet. The maximum (dotted) and minimum (dashed) 30 day cumulative rainfall amounts recorded on each day over the 41 year period are also shown.

both PTR and DSR systems where GAP is applied (Table 7). The reduction in labour at establishment in a DSR system reduces input costs and results in increased gross margins. In DSR, where weeds are well managed, a gross margin of USD \$385 ha^{-1} can be achieved, compared to USD \$252 ha^{-1} for PTR where weeds are well managed, and USD \$173 ha^{-1} for DSR where weeds are not well managed.

Under the baseline current labour costs (USD \$6 day^{-1}) and rice price (USD \$0.3 kg^{-1}) average gross margins are positive under PTR (USD \$209 ha^{-1}) and higher under DSR (USD \$356 ha^{-1}) (Fig. 4). Gross margins are negative for labour costs of both USD \$9 day^{-1} (i.e. 50% wage increase) and USD \$12 day^{-1} (i.e. 100% wage increase) where rice prices remain current or decrease. Under labour costs of USD \$9 day^{-1} positive gross margins are achieved when rice prices are increased above current levels. For a labour cost of USD \$12 day^{-1} there is no rice price examined for which gross margins are positive for transplanted rice.

Table 6
Yield results comparing PTR and DSR on farmers' fields, Savannakhet Province, 2014.

Treatment	Average yield (t ha^{-1})[a]	Number of farms
T1: PTR + GAP	3.3 (0.24)	9
T2: DSR + GAP	3.3 (0.27)	9
T3: DSR + herbicide	3.3 (0.26)	9
T4: DSR + FP	2.3 (0.19)	9
T5: PTR + FP	2.0 (0.11)	3

[a] Standard deviations of yield are shown in parentheses.

In contrast, under DSR positive gross margins are achieved when labour cost is USD \$9 day^{-1} for all rice prices examined. For a labour cost of USD \$12 day^{-1} positive gross margins are achieved when rice prices are at current baseline levels or higher.

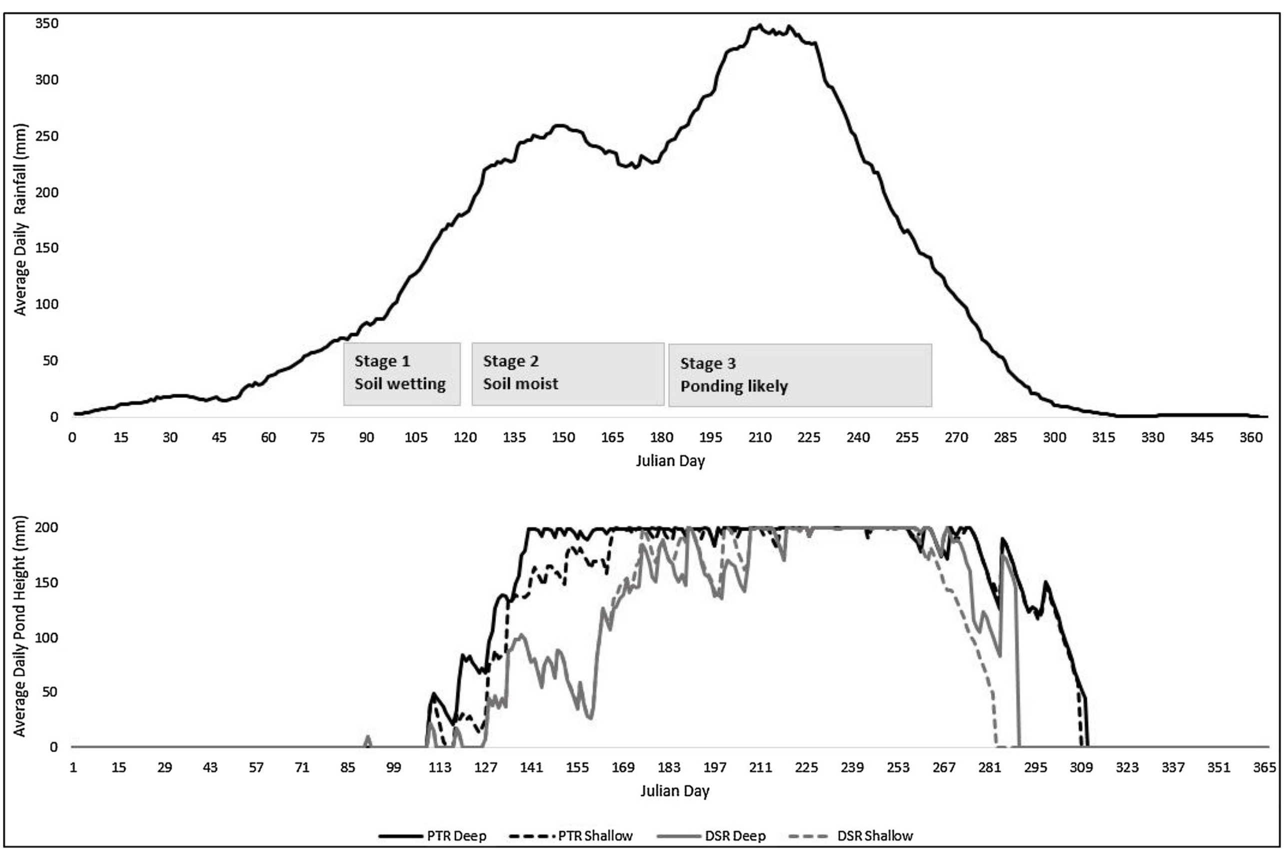

Fig. 3. Top: average annual rainfall for the 41 year (1971–2011) data record at Savannakhet, with the three soil wetting stages (described in the text) overlaid; Bottom: simulated average long term (1971–2011) daily ponding under PTR and DSR for the deeper and shallower soil types, between 1 January (Julian day 1) to 31 December (Julian day 365). Note that ponding is capped at 200 mm as this is the maximum height of the paddy bund.

Table 7
Average labour requirements, cost of production and gross margins calculated for PTR and DSR using data from 2014 on-farm trials.

Treatment	Average yield (t ha^{-1})	Total labour required[a] (person days ha^{-1})	Cost of production (USD[b] ha^{-1})	Gross margin (USD ha^{-1})
T1: PTR + GAP	3.3	73	684	252
T2: DSR + GAP	3.3	52	520	385
T3: DSR + herbi	3.4	40	461	448
T4: DSR + FP	2.3	68	617	173
T5: PTR + FP[c]	2.2	66	521	69

[a] Includes labour for establishment, weeding, fertiliser application, harvesting and for post-harvest processing.
[b] At time of writing (May 2018) 1 USD = 8316 LAK.
[c] PTR + FP data are from Phin Neua (three farms) only. In other treatments data are from nine farms.

3.4. Farmers' perceptions of DSR

Throughout the participatory engagement undertaken in 2013, farmers consistently reported an interest in DSR, primarily because of the potential for maintaining rice yields while reducing the labour required for production. Through the engagement activities, farmers' opinions on the suitability DSR for all households and for all toposequences became more nuanced as their understanding of the different management challenges associated with this establishment method deepened.

Over 90% of farmers who participated in focus group discussions on DSR in April 2013 stated they were interested in the machinery and eager to experiment with it on their farms in the 2013 wet season.

At discussions in December 2013, following harvest, farmers showed a greater awareness of challenges implicit in this unfamiliar technology, in particular around weed management and timely access to machinery, however most farmers did not consider these challenges insuperable; the potential production benefits, in terms of reduced labour requirements, were highly attractive and outweighed the risks associated with trialling new practices. Many farmers stated that they expected there would be an ongoing learning curve to adjust to DSR but that it would be worth persisting with. Farmers had begun to think about DSR into the future, and in large part the issues they raised were about accessing and using machines of their own. Those farmers who were more resource-constrained (in terms of land, labour, capital, and early-season supplementary irrigation) and thus more risk averse were less interested in testing DSR, particularly when relying on their own resources in future, than farmers who had (relatively) greater resilience.

3.5. APSIM modelling: examining DSR under current climate and management conditions

The APSIM model was validated against observed independent (not used in model calibration) field trial data and sensibility testing from expert agronomists and soil scientists. This validation is summarised in Gaydon et al. (2017).

Results of the APSIM modelling suggest that, over the 41 year historical climate record (1971–2011), traditional transplanted rice management with low nitrogen inputs (Scenario 1: PTR_0 N_RF) results in a high chance (> 90% probability) of either some crop failure (0 t/ha) or poor yields (< 0.5 t/ha) as a consequence of water stress (Fig. 5). This is more pronounced on shallow soils (Fig. 5a and Table 8), with predictions of 5% total crop failure (0 t ha^{-1}) and yields of less than 0.5 t ha^{-1} in 12% of years. On the deep soil (Fig. 5b and Table 9) total crop failure reduces to 2%.

The range of sowing dates is smaller under DSR, where sowing over the 41 years occurred in a 46-day range between 29 April and 14 June, than under PTR, where sowing occurred in a 118-day range between 26 March and 22 July. Sowing under DSR is also, generally, earlier in the season than under PTR (Fig. 6). Reflecting the more consistent, earlier sowing opportunities, DSR harvest occurs across the 41 years over a 50-day interval between 25 August and 14 October, while PTR harvest occurs over a 122-day interval between 30 July and 29 November.

Early-season supplementary irrigation (Scenario 3: PTR_0 N_irri and Scenario 4: PTR_+N_irri), which was applied if needed only in the first two months after rice sowing, has the potential to significantly reduce the risk of crop failure in both soil types, primarily by reducing the effects of early season drought during rice establishment. The benefit of early-season supplementary irrigation is more pronounced on shallow soils, particularly in poor years. In terms of overall yield response, increasing nitrogen applied (Scenario 2: PTR_+N_RF and Scenario 4: PTR_+N_irri) has a considerable impact on yields, with median simulated yields increasing over Scenario 1 (PTR_0 N_RF) and Scenario 3 (PTR_0 N_irri) by 1.5-1.7 t ha^{-1}.

Relative to transplanting, DSR reduces the climate risk of crop failure or low yields (Fig. 7 and Tables 8 and 9). The risk-reduction benefit achieved with DSR is comparable to that of applying early-season supplementary irrigation to a transplanted crop: for example, on the drier soil the percentage of years in which yields are below 0.5 t ha^{-1} reduces from 12% in a PTR crop to i) 0% in PTR with early-season supplementary irrigation, ii) 2% in a DSR crop with a drier sowing rule, and iii) 0% in a DSR crop with a wetter sowing rule (Table 8). Similar climate risk reductions are also observed in the wetter soil (Table 9). As with transplanting, increased fertiliser rates under DSR (Scenario 6: DSR_+N_dry and Scenario 8: DSR_+N_wet) lead to median yield increases of about 1.7 to 1.9 t ha^{-1} over low nitrogen scenarios (Scenario 5: DSR_0 N_dry and Scenario 7: DSR_0 N_wet), but with less risk of crop failure than in transplanting (Figs. 5 and 7).

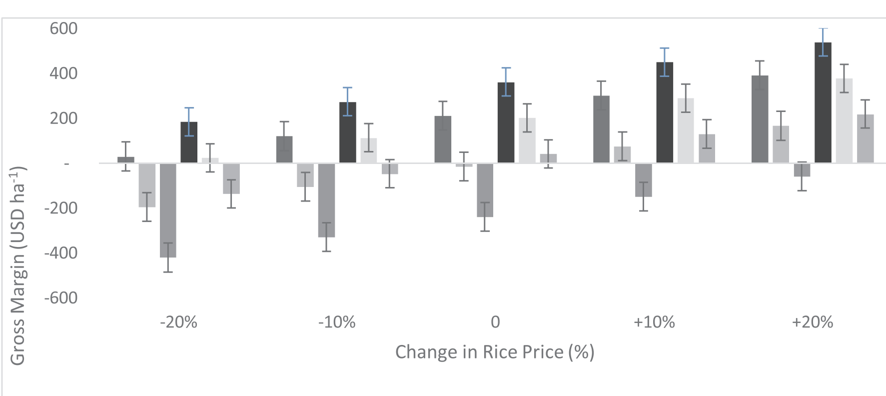

Fig. 4. Gross margins (USD-equivalent per hectare) under transplanted (PTR) and mechanised dry seeded (DSR) rice establishment methods where rice price varies by up to +/-20%, for labour costs of USD \$6 day^{-1} (baseline labour cost), USD \$9 day^{-1} (+50% on baseline), or USD \$12 day^{-1} (+100% on baseline). In both establishment methods weeds are well controlled without the use of chemicals.

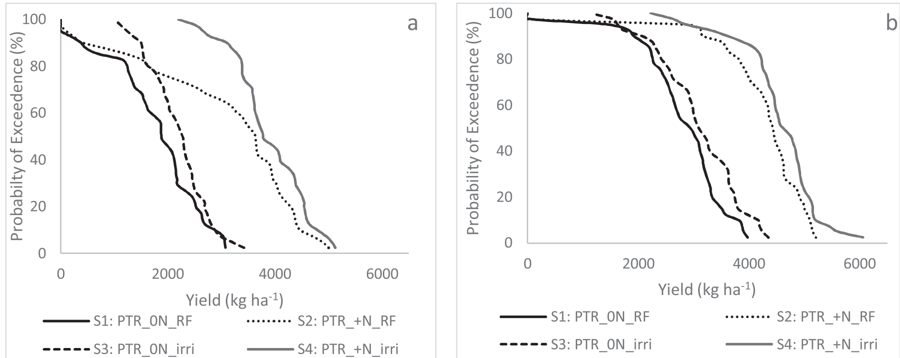

Fig. 5. Probability of exceedance of rice yields (1971–2011; kg ha^{-1}) for puddled transplanted rice (PTR) with low (0 N) and higher (+N) nitrogen fertiliser applications, without (RF) and with (irri) supplementary irrigation, for data between 1971 and 2011, for shallow (a) and deep (b) soils.

Table 8
Yield variability and crop failure rates on the shallow soil for present day, ECHAM and GFDL climates.

Scenario	Present day (1971–2011)			ECHAM (2021–2040)			GFDL (2021–2040)		
	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}
S1: PTR_0 N_RF	2.00	0.0–3.1	12	1.96	0.0–3.3	10	1.81	0.0–3.2	10
S2: PTR_+N_RF	3.64	0.0–5.0	12	3.41	0.0–5.3	10	3.59	0.0–5.1	10
S3: PTR_0 N_irri	2.24	0.8–3.5	0	2.46	1.6–3.1	0	2.31	0.9–3.0	0
S4: PTR_+N_irri	3.97	2.2–5.2	0	4.10	3.0–5.1	0	3.90	2.1–4.9	0
S5: DSR_0 N_dry	2.18	0.4–2.9	2	2.32	1.3–3.7	0	2.55	1.7–3.2	0
S6: DSR_+N_dry	4.02	0.4–5.0	2	4.23	2.5–5.0	0	4.30	2.6–4.9	0
S7: DSR_0 N_wet	2.34	1.1–3.1	0	2.31	1.3–3.6	0	2.41	1.6–3.4	0
S8: DSR_+N_wet	4.00	1.6–4.9	0	4.22	2.4–5.1	0	4.38	2.6–5.0	0

Table 9
Yield variability and failure rates on the deep soil for present day, ECHAM and GFDL climates.

Scenario	Present day (1971-2011)			ECHAM (2021-2040)			GFDL (2021-2040)		
	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}	Median yield (t ha^{-1})	Yield range (t ha^{-1})	% years yield < 0.5 t ha^{-1}
S1: PTR_0 N_RF	2.97	0.0–4.0	5	3.36	0.0–4.3	5	2.88	0.0–4.0	5
S2: PTR_+N_RF	4.42	0.0–5.2	5	4.71	0.0–5.5	5	4.43	0.0–5.3	5
S3: PTR_0 N_irri	3.08	1.2–4.4	0	3.50	1.8–4.3	0	3.09	1.4–4.1	0
S4: PTR_+N_irri	4.59	2.2–6.2	0	4.87	3.5–5.5	0	4.48	3.1–5.4	0
S5: DSR_0 N_dry	2.59	0.4–3.9	2	2.95	1.8–4.4	0	3.00	1.6–4.1	0
S6: DSR_+N_dry	4.47	0.4–5.4	2	4.83	2.8–5.4	0	4.73	3.0–5.3	0
S7: DSR_0 N_wet	2.78	1.3–3.8	0	3.06	1.8–4.5	0	2.90	1.6–4.1	0
S8: DSR_+N_wet	4.52	2.7–5.3	0	4.91	2.7–5.5	0	4.73	3.0–5.4	0

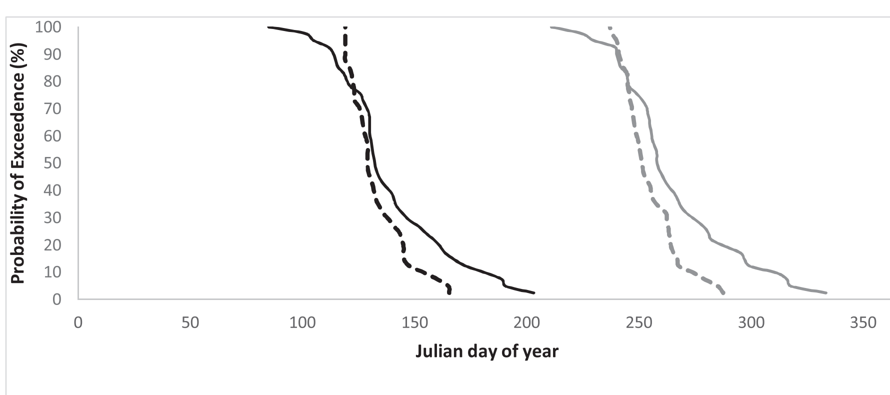

Fig. 6. Probability of exceedence of sowing and harvest dates (1971–2011) for rainfed puddled transplanted rice (PTR) with high N and for mechanised dry seeded rice (DSR) under the drier sowing rule with high N.

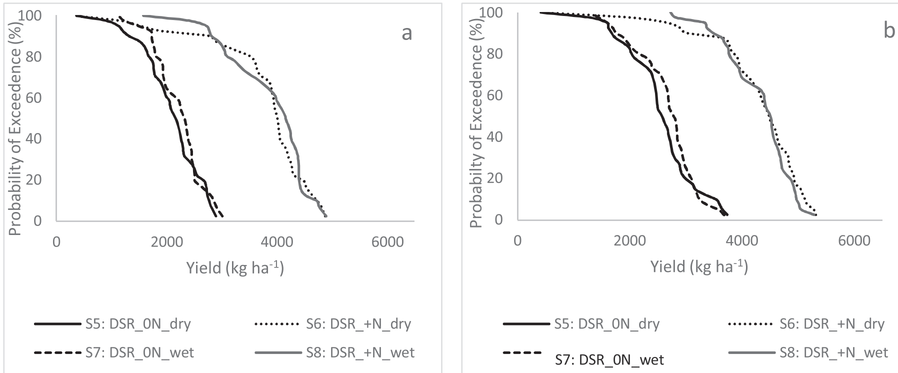

Fig. 7. Probability of exceedance of rice yields (1971–2011; kg ha^{-1}) for mechanised dry seeded rice (DSR) with low (0 N) and higher (+N) nitrogen fertiliser applications, with drier (dry) and wetter (wet) sowing rules, for data between 1971 and 2011, for shallow (a) and deep (b) soils.

3.6. Scenario analyses: DSR under future climates

On both the shallow (Table 8) and deep (Table 9) soils, DSR improves yields relative to PTR, under both future climates (i.e. underpinned by either the GFDL or the ECHAM GCMs). On the shallow soil, yield and risk of crop failure under PTR are largely unchanged between present day (1971–2011) and near future (2021–2040) climates, regardless of the GCM used, and regardless of the forecast increases in average cumulative annual rainfall in the future climates (Table 8). This is largely due to early-season drought reducing yields and resulting in crop losses in some years; the relatively high variability of intra-season rainfall continues into the future.

On the deep soil, PTR yields are similar under the present day and more extreme (GFDL) future climate (Table 9). Under the less severe (ECHAM) future climate yields in all but the worst 20% of years are improved over present day. This is most likely attributable to better-timed, more regular rainfall through the growing season under the ECHAM climate which results in lower cumulative average rainfall than that received under GFDL scenarios, but which on the deep soil (where a greater soil water-holding capacity exists than on the shallow soil) leads to higher plant available soil water for longer throughout the growing season.

Under PTR, average yields from all scenarios on the shallow soil vary between 2.00–3.97 t ha^{-1} for the present day climate, 1.96–4.10 t ha^{-1} for the ECHAM climate, and 1.81–3.90 t ha^{-1} for the GFDL climate. Under DSR the range of average yields from all scenarios decreases as lower average yields increase while upper average yields increase by smaller amounts: 2.18–4.02 t ha^{-1} for the present day climate, 2.31–4.23 t ha^{-1} for the ECHAM climate, and 2.41–4.38 t ha^{-1} for the GFDL climate. On the deep soil average yields from PTR scenarios are slightly higher than from DSR scenarios, however the risk of crop failure reduces with DSR.

For any scenario examined, regardless of soil type, the difference in average simulated yield under present day or either future climate (e.g. 0.22–0.38 t ha^{-1} on the shallow soil for Scenario 8) is much smaller than the yield variability within any particular climate scenario (e.g. 3.3 t ha^{-1} under present day, 2.7 t ha^{-1} under ECHAM and 2.4 t ha^{-1} under GFDL on the shallow soil for Scenario 8).

4. Discussion

4.1. Rainfall variability and planting window

The high intra- and inter-seasonal rainfall variability makes rice production uncertain: in focus group discussions farmers reported that in any one season they anticipate rainfall-related crop losses of between 10 and 30 per cent of their potential rice yield due to either drought or flood events. Traditional rice production is finely attuned to the variability in wet season rainfall and effects on soil moisture. Farmers take advantage of the intermittent early-season rains towards the end of the soil wetting Stage 1 and during the soil wetting Stage 2 (Fig. 3) when there is sufficient soil moisture for land preparation activities to occur. Rice seedlings are sown in the nursery, in staggered tranches, in early June, before farmers expect the soil wetting Stage 3 to reliably commence. It is particularly important in a transplanted crop that paddy soils are saturated and some ponded water is present at transplanting, approximately 30 days after sowing, which is most likely to occur in Stage 3. Transplanting occurs after water ponds in fields; staggered nursery plantings optimise the likelihood that a tranche of seedlings will be of transplantable age whenever ponding occurs. However, if transplanting is delayed too long, or early-season rainfall is low, this system bears the considerable risk of terminal drought stress, leading to significant yield penalties and in some instances complete crop failure. In lieu of reliable rainfall forecasts, sowing the nursery at the start of the period of average maximum rainfall reduces the likelihood that the main crop will be water stressed.

The average rainfall in the early May to late June period (Fig. 2) is sufficient to consistently establish a dry seeded rice crop, although rainfall variability is too great for reliable PTR crop establishment. Thus, rice can be established in paddies up to a month earlier under DSR than under PTR. Earlier planting reduces the impact on immature plants of early wet season floods in July in low-lying fields (e.g. in Champhone District) and increases the likelihood of earlier harvesting, thus reducing exposure to terminal drought stress associated with the cessation of the wet season.

4.2. On-farm experiments: inputs applied, yields obtained and labour requirements

The delay in transplanting crops in an optimal window (i.e. after three to four weeks' growth in the nursery) due to insufficient rainfall to form a pond in paddies was considered "normal" by farmers. The contrast between the delayed PTR and the timely-sown and well-growing DSR illustrates the potential to reduce farmers' exposure to climate risk.

Yields achieved in the 2014 on-farm trials in Savannakhet are representative of those across lowland rainfed rice systems in Lao PDR (Linquist et al., 2006) and are similar to those previously observed in very similar environments in northeast Thailand (Fukai et al., 1998) and Cambodia (Dalgliesh et al., 2016), where comparable yields were achieved under direct seeding and transplanting.

Where weeds were well managed manually (i.e. with greater attentiveness than traditional farmer practice which relies on standing water to suppress weeds) there was no yield benefit to using chemical herbicides over manual weed control. The use of chemical herbicides is not attractive to farmers who rely on paddy biota (frogs, snails, small fish) for supplementary protein during the wet season. As a consequence this treatment is not being promoted by researchers or extension agents, although it is likely that some farmers will eventually opt for herbicides rather than more labour-intensive manual weeding.

Yields are suppressed by low nitrogen fertiliser applications: despite recommendations for (relatively) higher rates by NAFRI, farmers are reluctant to apply fertiliser as they are vulnerable to poorly timed rainfall events and at high risk of partial or complete crop losses each wet season, particularly under the highly variable rainfall patterns experienced in the region (Fig. 2). Additionally, many farmers are not confident in their ability to correctly identify quality fertilisers at purchase or use them appropriately and so are reluctant to apply recommended rates.

Considerable labour savings are achieved overall when a rice crop is produced under DSR compared to PTR: at establishment DSR requires approximately 25 per cent of the time (8 person days per hectare) taken to sow and transplant a PTR crop (31 person days per hectare). Weed management under PTR requires less time than under DSR, although the differences are not as great as those observed in crop establishment (11 person days for PTR compared to 16 person days for DSR). Timely manual weed management is critical in DSR to maintain yields and minimise the time required in weed control. It is likely that in the on-farm testing additional refinements in weed management (e.g. more thorough land preparation, more timely manual weeding) could further increase yields under DSR, although this would, slightly, increase labour demand.

While farming households perceive little benefit in increasing their rice production above what is required for subsistence (Newby et al., 2013), many farmers seek to maintain current production while reducing input costs (Cramb et al., 2015; Manivong et al., 2014). Household labour which is not required on-farm for rice production can be profitably deployed elsewhere. However, as has been observed (Williams et al., 2015; Manivong et al., 2014; Newby et al., 2013), even when PTR becomes unattractive from a purely economic perspective it will remain attractive for some households who prioritise food security, particularly when rice prices are low and/or volatile, where the return on investment for inputs (e.g. fertiliser) is uncertain and where uncosted (i.e. household) labour is available. Similarly, where members of farming households do not migrate and supply remittances, and therefore labour does not come with a significant opportunity cost, PTR may remain an attractive option.

Higher yields under DSR than PTR have been observed elsewhere in experimental trials in rainfed conditions (Fukai and Ouk, 2012; Fukai et al., 1998) with strong caveats that weeds must be well controlled. Higher or equal yields under DSR when compared to PTR have also been observed in Cambodia under similar rainfed rice production systems (Dalgliesh et al., 2016). Our results and those of Dalgliesh et al. (2016) differ from the earlier work by Fukai in that they were obtained through on-farm, not research station, experiments.

4.3. Cost of production and gross margin analyses

While the labour required, and thus the cost (if it is hired labour), of weed control is higher under DSR than under PTR, we find that overall labour savings are greater under DSR as the labour required for transplanting is considerable. This translates into lower cost of production and higher gross margins under DSR than under PTR when weeds are well controlled (i.e. under GAP conditions) and is similar to results observed by Fukai and Ouk (2012).

Gross margins under PTR are more sensitive to changes in either the rice price or the cost of labour than DSR: this is due to the higher labour demand to produce a rice crop under PTR. For the examined changes of up to 100 per cent increase in labour costs and ± 20% in rice prices, farmers using DSR may experience reduced gross margins relative to those achieved under the current baseline, but they will still be considerably better off (in terms of gross margins) than farmers using PTR under comparable scenarios.

4.4. Farmers' perceptions of DSR

All farmers in the 2013 rice season identified the potential for DSR to enable them to produce comparable yields to PTR while requiring less water and labour. For farmers the attractiveness of DSR is primarily the potential to save on input (particularly labour) costs while maintaining current yields.

Farmers found that, because the timing and method of rice establishment under DSR (including weed management) were so completely different to PTR, testing this new technique was a radical production change: very different from traditional rice cultivation. Farmers were impressed that under DSR they could, in all but the highest (driest) toposequences, satisfactorily establish a crop while the PTR crop was still in the nursery awaiting sufficient rainfall to facilitate transplanting. However, while all farmers identified the potential to save money, labour and time, several also perceived the potential for additional weeds if standing water were not present to suppress growth after crop emergence and the need for alternative weed management practices. Some locations, particularly drier, higher toposequences, were less suitable for DSR as effective manual weed management in very dry conditions is difficult: it is also likely that ponding in these locations will be limited and that weed management in these fields is an ongoing challenge under PTR as well.

While fewer farmers participated in formal experiments in 2014 (n = 9) than in 2013 (n = 51), interest in DSR remained high: over 100 ha were sown in the project regions using mechanised dry seeders by farmers independent of research activities (Khammone Thiravong, pers. comm.). Between 2013 and 2014 farmers' appreciation of the necessity of thorough weed preparation increased and 2014 DSR crops were much more vigorously controlled for weeds than in earlier seasons.

There was a difference in perspective and priorities among researchers and farming households, between managing climate risk and reducing labour costs. For researchers the introduction of the dry seeder is motivated by dealing with climate variability; this link is not immediately seen by many of the farmers who engaged in the participatory research. Instead, most farmers initially see the main attraction as the potential for labour saving if weeds can be well managed. Increasing labour scarcity has been observed in NE Thailand as being a driver of de-intensification (Shirai et al., 2017).

Farmers who participated in the interviews and discussions through 2013 were largely self-selected, generally open to new knowledge and ideas, and eager to improve their production systems. They were well motivated to inform the research team about their production challenges, and their responses to initial DSR testing and suggestions for improvement contributed to the refinement of the seeder and the improvement in on-farm testing in 2014. Of the households who participated in interviews and discussions, some were unable to use the seeder in 2014 due to lack of access to hand tractors. Ongoing access to locally produced (i.e. adapted) and affordable seeders will remain a constraint for the foreseeable future.

As seeders are not commonly used in the region, affordable access will require policy intervention for farmers to overcome this obstacle. A targeted effort by the Lao government's Ministry of Agriculture and Forestry would alleviate access to machinery, either by commissioning a local manufacturer or by buying machines in bulk from a regional manufacturer. This intervention, however, would depend on whether the Lao government deems the suggested intervention as feasible for larger areas.

Given the current strategy of the Lao government to position its rice as a glutinous and pesticide-free boutique export, DSR would lend itself to being included in the current policy. At the same time implementation of DSR increases the available workforce for non-agricultural labour in cities where there is growing demand, which is part of the envelopment approach manifested in the latest five-year National Socio-Economic Development Plan (LPDR, 2015). Thus DSR may be of benefit to meet not only household livelihood but also food security and labour policy goals.

Dry seeding, while a potentially useful management option for many households, is not appropriate for all households. In particular, it is not attractive for highly risk-averse households for whom testing an entirely new establishment practice is too great a risk to food security (Williams et al., 2015). Williams et al. (2015) describe the households most likely to take up DSR as those who have access to irrigation with which to suppress weeds. Farmers who rely heavily on ponded water for weed management, in particular those who have little ability to manually control weeds prior to and during the early stages of the growing season, are unlikely to find DSR well suited to them. Our 2014 field trials, which focussed on improving weed management practices and using machinery adapted to local conditions, suggest that increasing rural labour shortages are driving interest in DSR for many, but by no means all, household types. In particular, households which are labour constrained but which have some capacity for taking risk (i.e. not marginal households) are likely to take up DSR. Those households to which family members regularly send remittances, and which do not rely on the additional cash to cover necessary domestic expenses, will be best placed to take up DSR. The number of households receiving remittances is likely to increase (Manivong et al., 2014), which may increase the capacity to take up DSR. Many farmers stated when asked that access to supplementary irrigation was not a precondition for DSR uptake for them, however did aid weed management.

4.5. APSIM modelling: examining DSR under current climate and management conditions

APSIM simulations suggest that over the longer term (41 year) historical climate record, DSR reduces the risk of crop failure or low yields relative to PTR. The benefit of DSR is comparable to that of applying early-season supplementary irrigation to a transplanted crop. Dry seeding is a more realistic and attractive management option for many farmers than developing the infrastructure necessary for supplementary irrigation. Additionally, DSR increases the likelihood that applied nitrogen fertilisers will not be wasted through crop failure, will increase productivity, and enables earlier, more reliable crop establishment, thus reducing exposure to terminal heat stress and drought.

In general, simulated yields are comparable to those observed in the on-farm trials, as well as those reported by Poulton et al. (2015, 2016) for similar conditions in Cambodia or even other lowland rice areas in the Mekong countries. Provided APSIM is parameterised with location specific climate, soil, crop and management data, it has been shown to perform with a high degree of reliability in rice-based cropping systems (Gaydon et al., 2012a, 2017; Poulton et al., 2016; Hochman et al., 2017).

While there is spatial variability in rainfall across the region of lowland Lao PDR the trends observed in long-term simulation modelling are likely to be applicable through the region: DSR reduces risks associated with variable or untimely rainfall during the rice-growing season, requires little infrastructure to implement, and is likely to sustain or increase productivity. Throughout lowland Lao PDR, in drier, more marginal areas where rice production has higher risks DSR is likely to be less attractive to farmers than in lower-lying areas.

We suggest that further detailed biophysical modelling work (not possible in a multi-disciplinary paper such as this) is indicated to disaggregate the relative influence of individual factors causing performance differences between PTR and DSR (such as timing, soil parameters, exposure to drought, flooding and high/low temperature risks).

4.6. Scenario analyses: DSR under future climates

APSIM simulations suggest that changing from PTR to DSR is an effective management strategy under the 2030 climates simulated: yields are predicted to improve relative to the present day PTR baseline under both the more extreme (GFDL) and less severe (ECHAM) future climates. In the future climates, yields in average and above-average years are higher under the milder, ECHAM, climate. This is a consequence of adequate but not excessive soil moisture available to the crop through the growing season. DSR also reduces risk of crop failure under both present day and future climates relative to PTR. Poulton et al. (2016) observed similar APSIM modelling results under current and 2030 climates in Cambodia.

Climate change is likely to depress overall production, largely through increased extreme events such as higher temperatures and higher frequencies of drought (Hijioka et al., 2014). Other research suggests that, at least in the immediate future, the CO_2 fertilisation effect, and in some instances increases in rainfall, may actually contribute to yield increases under climate change: Mainuddin et al. (2011) observed this in their crop modelling across Mekong countries. A meta-analysis by Challinor et al. (2014) also provides evidence that in many cases predicted yields under climate change might actually be higher than under present day climates.

Increased wet season rainfall in the 2021–2040 period, relative to the present day, is within the range of possible future climates summarised by the IPCC (Hijioka et al., 2014). The results presented by Mainuddin et al. (2011) and Li et al. (2016) point to a likelihood of increased monsoon-driven rainfall. While the future climate data used in this study covered the short-term drought and flood events farmers experience as part of year-to-year climate variability they do not include severe extreme weather events, such as cyclones or widespread flooding, which are predicted to negatively affect agricultural crop production (IPCC, 2012). Also, our data extend only to 2040 which is the temporal limit at which the LMESS model can be rigorously applied. Into the longer term, future climate data may be more significantly different to present day; uncertainty around using these data would also increase.

5. Conclusion

The results of this study show that DSR is technically feasible, attractive to farmers and likely to increase their ability to produce rainfed rice with reduced labour costs and increased resilience to increasing climate variability and change.

DSR achieves comparable yields to traditional PTR in rainfed lowland systems in Lao PDR. These yields can be achieved without the use of chemical herbicides, however weeds must be well controlled in the absence of standing water in paddies. DSR requires considerably less total labour than PTR, notwithstanding the additional labour to manage weeds. These labour savings result in increased gross margins under DSR relative to PTR and are the primary reason farmers are attracted to the adoption of this technology. DSR also reduces farmers' exposure to seasonal climate variability, by utilising early season rainfall that enables farmers to bring forward the timing of the rice crop and reduce the incidence of terminal drought stress with existing varieties.

Beyond benefiting farmers under present climate conditions by helping them manage seasonal climate risk and increasing their opportunities to earn non-farm income, APSIM modelling indicates that DSR is also likely to perform well under future climates, at least until 2040. This is in large part because DSR can better utilise future higher rainfall than TPR. These observations hold for both the milder and more severe future climate scenarios tested. Hence we conclude that DSR is a prospective climate adaptation strategy.

DSR is not appropriate for all farmers. Those who are more risk averse and/or those for whom the challenges of changed agronomic management, in particular weed control, are too great are unlikely to take up DSR at this stage. However, APSIM modelling also suggests that the risk profile of PTR is unlikely to worsen as a result of climate change until 2040. The broader implication of this result is that the gradual changes to climate variables experienced as a result of climate change are unlikely to negatively affect rice food security in Lao PDR in a significant way in the next decades, although it must be noted that the modelling employed does not capture the impact of extreme events such as severe droughts or typhoon-induced flooding.

This paper has not examined potential effects of widespread DSR establishment on the social and cultural practices of Lao PDR. As well as additional research into appropriate weed management strategies, ongoing improvements to machinery design, the social challenges implicit in this new production system (e.g. around timing of sowing and harvest) should be examined, along with the institutional support necessary to facilitate access to machinery across the region.

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