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Economic and environmental indicators of sustainable rice cultivation: A comparison across intensive irrigated rice cropping systems in six Asian countries

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A R T I C L E I N F O

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A B S T R A C T

Quantifying and comparing sustainability indicators are essential to improve the sustainability of smallholder rice cropping systems. The sustainability of rice production systems can be measured based on economic, environmental, social, and institutional indicators. In this paper, we restrict our assessment to economic and environmental indicators. During 2012–2015, farmers were interviewed from 847 households from intensively irrigated rice production regions in Vietnam, Thailand, Indonesia, Myanmar, Sri Lanka, and China. We assessed the sustainability of their farming practices using economic and environmental indicators, i.e., eight of the 12 performance indicators (PIs), as defined by the Sustainable Rice Platform (SRP). Across the six sites, there was a yield gap of 24–42% and a profit gap of 36–82% between the 10% highest-performing farms (mean of top decile) and the mean-performing farms. In addition, there was a labor productivity gap of 12–32%, a nitrogen use efficiency (NUE) gap of 11–20%, a phosphorus use efficiency (PUE) gap of 1–29%, and a water productivity gap of 12–42%. Deliberate modification of conventional practices, including not flooding the field for > 30 days before rice planting, incorporating pre-rice crop residue > 30 days before planting, and adoption of mid-season drainage or alternate wetting and drying irrigation rather than continuous flood irrigation during the rice growing period, could substantially reduce the greenhouse gas (GHG) emission in irrigated rice fields without yield penalty. There is an urgent need to adopt improved management strategies for nitrogen (N), phosphorus (P), potassium (K) fertilizer, irrigation water-use efficiency, as well as for decreasing pesticide use frequency, without sacrificing profitability and yield. We identified the following priority interventions for each site: a) increasing fertilizer use and adopting higher-yielding varieties in Bago, Myanmar; b) reducing pesticide application rates in Can Tho, Vietnam; c) reducing fertilizer use in Guangdong, China; d) reducing nitrogen and labor use in Yogyakarta, Indonesia; e) reducing fertilizer and water use in Polonnaruwa, Sri Lanka and; f) reducing fertilizer use in Nakhon Sawan, Thailand. Additional uses of the PI analysis clearly demonstrated that rice yield and profit gaps can sustainably be closed by increasing efficiencies that will also lead to reduced environmental footprint.

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1. Introduction

Rice is the staple food for almost half the world's population and is the single largest food source for the poor. Nearly 90% of rice is produced in Asia, with > 58% produced in intensive irrigated cropping systems, such as in the "rice bowls" of China, Indonesia, Vietnam, Thailand, Myanmar and Sri Lanka (Maclean et al., 2013). In each of these countries, the area of rice production in 2005–2014 increased by 30% compared with 1961–1970, production increased by 186%, and productivity increased by 124% (FAOSTAT, 2019) with highest increment in Sri Lanka followed by Indonesia and Thailand (Fig. 1).

Increases in rice production have been attributed both to the increase in the rice production area and to increased productivity in favorable environments. Factors improving productivity include improvement of irrigation systems, adoption of high-yielding varieties, and an increase in the use of nitrogen (N), phosphorus (P) and potassium (K) fertilizers, and pesticides (Fig. 1). Averaged across the six countries and comparing 2002–2006 (5 years) with 2010–2014, N fertilizer application increased by 34%, P fertilizer by 29%, and K fertilizer by 51% (FAOSTAT, 2019). Myanmar showed the highest percent increase in fertilizer use, even though the current application is still lower than the other countries.

Despite comparatively high (except Myanmar and Thailand where the national average productivity is $< 4\,t\,ha^{-1}$) rice productivity in these countries (Fig. 1), a significant yield gap still exists (Laborte et al., 2012; Stuart et al., 2016), posing a challenge to feed the growing population by increasing food production with lesser environmental footprint (Lobell et al., 2009). Global food demand will need to be increased significantly by 2035 to keep pace with population growth and the sustainability of agriculture, and ecosystem services are crucial to meet the demands of improving yields without compromising environmental integrity or public health (Maclean et al., 2013; Tilman et al., 2002). Significant production increases (45% to 70% in rice) are predicted from closing yield gaps through optimized use of irrigation, fertilizer, and other agricultural inputs, with careful attention to reducing the environmental impact of agriculture by mitigating nutrient overuse and promoting proper water management (Maclean et al., 2013; Mueller et al., 2012).

Increases in rice production impart various negative impacts on the environment, mostly through increased emission of greenhouse gas (GHG). Currently, rice production alone contributes 16% of the total GHG emission in China, 38% of the GHG in Indonesia, 34% in Myanmar, 39% in Sri Lanka, 58% in Thailand, and 46% in Vietnam (FAOSTAT, 2019). Averaged across all 6 countries, compared to base year (1961–1970) to 2005–2014, the emission from rice cultivation has increased by 31%, which is attributed to an increase in fertilizer inputs

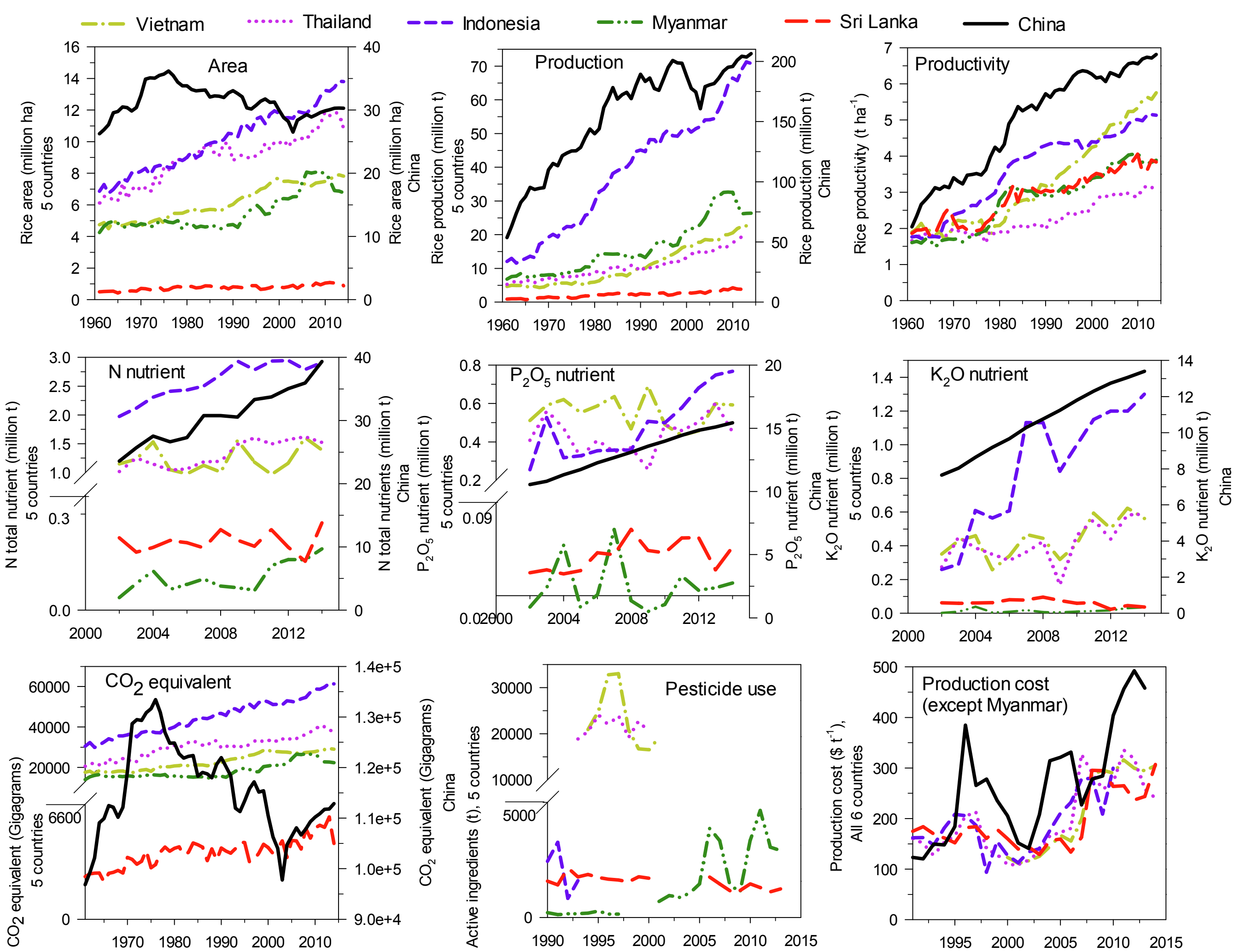

Fig. 1. Trends of rice area, production, and productivity in six rice-producing Asian countries from 1961 to 2015 (top row); trends of total N, P_2O_5 and K_2O nutrient consumption across all crops in each country (middle row); and trends in GHG emission from rice cultivation, total amount of pesticide active ingredient used across all crops, and cost of rice production (bottom row). Data source: (FAOSTAT, 2019). The discontinuity in trend in pesticide use is due to unavailability of the datasets. X axis is year in all graphs.

(FAOSTAT, 2019). Also, compared to 1991–2000, the total cost of production of rice increased by 164% in 2005–2014, the increment can partially be explained by higher labor wage rates and input costs.

Nitrogen and water are major yield-limiting factors for rice (Bouman et al., 2007). However, excessive N fertilization in China (Ju et al., 2009) and pesticide use in Vietnam (Van Hoi et al., 2013) has resulted in economic and environmental problems. Over application of N, and other nutrients like P and K could create problems for the ecosystem and also decrease net profit (Smil, 2004). Quantification of upper and lower threshold and the optimum or desired range for N-, P-, and K- fertilizers, water- and pesticide- use efficiencies can significantly improve the sustainability of rice production system with profitability and environmental sustainability. However, such quantification in such key indicators for decision support for rice production is lacking.

To implement sustainable rice production systems, optimal use of inputs (water, fertilizer, pesticide), labor and costs are crucial. Sustainability can be defined as economic, environmental, social and institutional sustainability (Corsin et al., 2007). In this paper, we restrict our consideration to the economic and environmental pillars of sustainability. The Sustainable Rice Platform (SRP) (http://www.sustainablerice.org), co-founded by United Nations Environment (UNE) and the International Rice Research Institute (IRRI), was established in 2011 for the purpose of promoting widescale adoption of sustainable practices throughout the rice value chains (SRP, 2015a). SRP developed a “Standard for Sustainable Rice Cultivation and 12 Performance Indicators (PI)” for assessment of the economic, social, and environmental sustainability of rice cultivation (SRP, 2015a,b). The PIs data can be used to: a) evaluate farming practices in a particular geographic region to determine the priorities/entry point for an intervention (e.g., nutrient management vs. irrigation technique); b) to evaluate the sustainability results of existing extension efforts in relationship to an internationally-accepted set of indicators; and c) to evaluate the overall sustainability effects of a specific agronomic practice. Furthermore, by computing baseline and target values, e.g., as the percentage (%) improvements from baselines (Blanco Fonseca et al., 2010), system comparisons and assessments of progress in improving the indicators’ for improving sustainability over time can be measured. The overall aim of this study is to compare the economic and environmental sustainability performance indicators of rice production between six intensive rice-producing regions in Asia using SRP PIs. This is the first multi-country comparison of rice production using SRP indicators. Based on the results of this analysis, the specific objectives are to: 1) suggest priorities for research and development; 2) suggest options for setting the target values for each indicator.

2. Material and methods

2.1. Baseline survey

The Closing Rice Yield Gaps in Asia with Reduced Environmental Footprint (CORIGAP) project focused on six intensively cropped rice areas in Asia, in order to improve food security and sustainability in systems that are already highly productive. Each of the study sites represented irrigated lowland rice production, with at least two rice crops grown each year. Farmers were interviewed from 847 households in six CORIGAP countries, namely Vietnam, Thailand, China, Indonesia, Myanmar, and Sri Lanka (Fig. 2; Table 1). For the baseline survey, one site and four villages from each country were purposively selected considering possible intervention sites for CORIGAP. From China, two treatment villages with “Three Controls Technology,” 3CT, implemented (Zhong et al., 2010) and two control (no intervention) villages were selected purposively to evaluate the impact of 3CT treatments on PIs of SRP (Table 2).

Within each country, villages were selected based on similar farm size and demographic characteristics and were located within a 25 km radius in all countries except for China. Respondents were selected randomly from a list of farmers in each village obtained from the local agriculture extension office. In Thailand, the survey involved the complete enumeration of farmers from four community rice centers. Information was collected using a structured pre-tested survey questionnaire, translated into the local language. In the surveyed regions, the respective governments had different programs for increasing rice yield (Table 2).

2.2. Characteristics of the survey sites

2.2.1. Can Tho, Vietnam

The survey site, Can Tho, lies in the Mekong Delta, which ranks 6th among the leading rice-producing provinces of Vietnam (FAOSTAT, 2019). The farmers in Can Tho produce two to three rice crops a year – the dry (winter-spring) season crop (November to March), the early wet (summer-autumn) season crop (April to July), and some produce the late wet (autumn-winter) season crop (July to October). At the completion of the winter-spring season in 2015, 180 farmers (Thanh An town = 50, Thanh Loi = 50, Thanh An = 40, and Thanh Thang = 40) were interviewed in Vinh Thanh district (Table 1).

2.2.2. Nakhon Sawan, Thailand

Nakhon Sawan is located in the central plans of Thailand, and the province produces two rice crops a year – the wet season crop (July to October) and the dry season crop (December to March) (Maclean et al., 2013). At the completion of the wet season in 2013, 84 community rice center member-farmers (Nongjikree = 24, Sapansong = 20, Sakaengo = 21, and Pacluk = 19) were interviewed in Takhli district (Table 1).

2.2.3. Guangdong Province, China

Guangdong Province is one of the major rice producing zones of China with about two million ha of rice. Rice is grown mainly during two seasons; early rice (March to July) and late rice (July to November). In Guandong, the 3CT program was compared with control villages. The 3CT program has three components: (1) reduction of N input especially at basal and tillering stages, (2) reduction of unproductive tillers, and (3) reduction of pesticides for the control of diseases and insects. This program has been promoted by the Department of Science and Technology of Guangdong Province since 2007. In 2013, 248 farmers, (48 farmers from 3CT villages and 200 from control (no intervention) villages were interviewed from Anpu, Dongtang, Liantang, and Yamen cities in Guangdong (Table 1).

2.2.4. Yogyakarta, Indonesia

In Yogyakarta, Java, two-, and occasionally three-, crops of rice are grown each year: the wet season crop (December to March) and the dry season crop (April to July) (Maclean et al., 2013). A total of 180 farmers (Jogotirto = 50, Madurejo = 50, Srimulyo = 40, and Bokoharjo = 40) were interviewed in Sleman district at the end of the wet season in 2014 (Table 1).

2.2.5. Bago, Myanmar

Bago Region is located in the Ayeyarwady Delta (Fig. 2). There are two major rice planting seasons, the wet season (June to January); and dry season (November to May) (Maclean et al., 2013). A total of 100 households, (KyaitSaKaw = 25, KadokePhyaGyi = 25, DoeTan = 25 and MauTan = 25) were randomly selected and interviewed in Daik-U township in 2012 (Table 1).

2.2.6. Polonnaruwa, Sri Lanka

Rice is grown during two seasons; 70% of rice is produced in the wet season (October to March), and 30% in the dry season (April to September) (Maclean et al., 2013). In Polonnaruwa region, a total of 55 households (Kalinga Ela = 30, Kadawalawewa = 25) were randomly selected and interviewed for both wet and dry season in 2014 (Table 1).

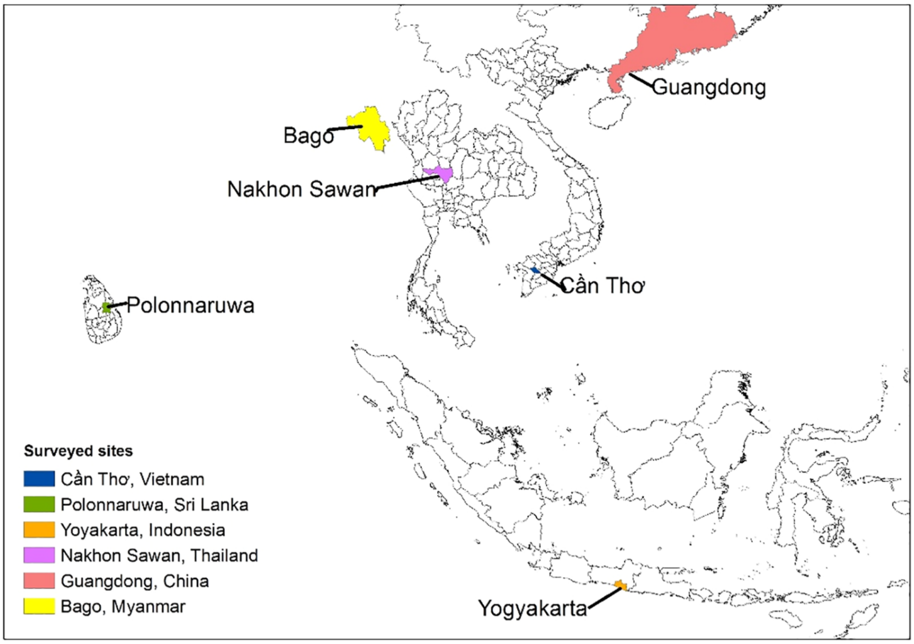

Fig. 2. Map of survey sites within intensive irrigated rice production areas of six Asian countries.

2.3. Data collection, coding and cleaning

The data were collected using computer-assisted personal interviewing software (http://surveybe.com/) in Thailand, Indonesia, and Vietnam, while, paper-based questionnaires were used in Myanmar, China and Sri Lanka. Basic demographic and farm characterization information was collected during the interview. Farmers also were asked to recall all information required for calculation of net profit, labor productivity, and grain yield from both the most recent wet and dry seasons. The approximate depth of irrigation for each application and the number of irrigations applied were requested, from which water use efficiency (in terms of water productivity) was calculated. Farmers were also asked for the amount and timing of all material inputs, (seed, fertilizer, herbicide, insecticide, fungicide, rodenticide, and molluscicides). Missing data relating to the cost of specific field operations were set from the average cost ha^{-1} of co-farmers in their village. Comparing costs of wet-direct seeded rice (wet-DSR; broadcast seeding of pre-germinated seed in puddled soil) with puddled transplanted rice (PTR) was not possible for Sri Lanka and China as there was no PTR in Sri Lanka and no wet-DSR in China (Table 4).

2.4. Calculation of sustainable rice Platform (SRP) performance indicators (PIs)

The PIs were first calculated as defined by SRP (SRP, 2015a), including net profit, labor productivity, grain yield, water use efficiency, nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), pesticide use efficiency, and GHG emission. Net profit was computed by considering all variable inputs, labor, machinery hiring, and land rent (if any) for preparing seed or seedling raising, land preparation, crop establishment, irrigation, fertilizer, pesticide, harvesting, threshing, and cleaning and drying operations, and the gross return considering the fresh grain yield, its market price and the straw income (only if sold). Then, the total variable cost was deducted from the gross income. To compute labor productivity, both hired and own (family) labor of both male and female labors were considered and the number of labor days per season was estimated by dividing the total labor cost per season by the daily wage rate at the time. Grain yield was expressed as kg grain ha^{-1} at 14% moisture content. Water use efficiency was computed based on the total number of irrigations applied and the approximate depth of water application in each irrigation from field preparation to crop harvest, and the total amount of rainfall during the crop growing period, (daily rainfall data from NASA Power Project (NASA POWER, 2018)). Nitrogen-, phosphorus-, and potassium-use efficiencies (NUE, PUE and KUE, respectively) were computed from the elemental form of the total amount of respective fertilizers applied. For the computation of PUE and KUE, the total amount of P_2O_5 and K_2O content of the fertilizers were multiplied by a factor of 0.4364 and 0.8302, respectively to convert them into the elemental form. Then, the total grain yield harvested was divided by the elemental N, P or K and the efficiency expressed in terms of kg grain kg^{-1} elemental N, P or K.

Pesticide use was scored using both the SRP scorecard (2015a) and the Field Calculator method. For the SRP method (2015a), it was assumed that all farmers followed best practice (highest possible score) for three questions, i.e., the use of registered products; followed label instruction; and targeted application of products using the existing knowledge and expert consultation, and total pesticide use efficiency score was computed as defined by SRP (2015a). A modified method, i.e., the Field Calculator (FC) was developed by a group of six pest management scientist at IRRI for scoring survey data (Table 3). In FC method, appropriateness of pesticide use was scored based on the number and timing of application of herbicide, insecticide, fungicide, rodenticide and molluscicide and the overall score was calculated by adding the scores of these sub-pesticide categories. Based on the data availability, pesticide use efficiency was computed using both approaches in three out of the six sites, namely, Can Tho, Nakhon Sawan, and Yogyakarta. We excluded bird control from the computation because there was inadequate information about bird control.

Based on the assumption that methane emission is the most important of the GHG for comparing rice production systems, methane (CH_4) emission was used as a proxy for GHG emission, and was calculated using the formula given by IPCC (Dong et al., 2006; Stuart et al., 2018).

Besides the above indicators, SRP performance indicators includes four other indicators, i.e., food safety, worker health and safety, child labor, and women empowerment. These indicators were not included in the survey instrument, so the present study only analyzes eight of the twelve SRP PIs.

Table 1
Description of survey sites including number of households per village.

Country	Surveyed region/site	No. of surveyed villages	Surveyed villages	Year	Season	No. of surveyed household (wet and dry season, respectively)
Vietnam	Can Tho	4	Thanh An town, Thanh Loi, Thanh An, Thanh Thang	2015	Wet, Dry	164,180
Thailand	Nakhon Sawan	4	Nongjikree, Sapansong, Sakaengo, PaKluk	2013	Wet, Dry	84, 80
China	Guangdong	4	Treatment villages: Anpu, Yamen, Dongtang and Liantang	2012	Early (wet) and Late (dry)	188, 248
Indonesia	Yogyakarta	4	Jogotirto, Madurejo, Bokoharjo, Srimulyo	2014	Wet, Dry	180, 176
Myanmar	Bago	4	Kyait Sa Kaw, KadokePhyaGyi, DoeTan, MauTan	2012	Monsoon (wet) Summer (dry)	100, 100
Sri Lanka	Polonnaruwa	2	Kalinga Ela, Kadawalawewa	2013	Wet, Dry	55, 55

Table 2
Country comparison, description of treatments in government programs.

Survey site, country and extension or special program	Year initiated	Components included									
		Certified seed use	Seed rate	Land prep- aration	Water manag- ement	Fertiliz-ers	Pest control	Pesticide use safety	Har-vest	Post- harvest	Mech- anization
1. Can Tho, Vietnam											
1 Must Do 5 Reductions (1M5R)	2009	✓	✓		✓	✓	✓			✓	
Global Good Agricultural Practices (GlobalGAP)	2010					✓	✓	✓			
Small Farm Large Field (SFLF)	2013			✓					✓		✓
Vietnam Good Agricultural Practices (VietGAP)	2014	✓			✓	✓	✓	✓	✓	✓	
2. Nakhon Sawan, Thailand											
Cost Reduction Program (CROP)	2014	✓	✓			✓			✓		
Global GAP	2004				✓		✓	✓	✓	✓	
Large Field Project	2014										✓
Thai Rice GAP (ThaiGAP)	2004				✓	✓	✓	✓	✓	✓	
3. Guangdong, China											
Three Control Technology (3CT)	2007			✓		✓	✓	✓			
4. Yogyakarta, Indonesia											
Integrated Crop Management (ICM)	2015	✓	✓	✓	✓	✓	✓	✓			
5. Polonnaruwa, Sri Lanka											
Best management practices (BMP)	2013	✓			✓	✓	✓	✓	✓		
6. Bago, Myanmar											
Best management practices (BMP)	2014				✓	✓	✓	✓	✓		

Table 3
Computation of pesticide use efficiency using criteria specified by pest management scientists of IRRI (Field Calculator method).

Pesticide category	Gold and acceptable*		Score	Tolerable**		Score	Unsustainable***		Score
	No. of application	Application time (days after crop establishment)		No. of application	Application time (days after crop establishment)		No. of application	Application time (days after crop establishment)	
Herbicide	≤1	< 40	+15	2–3	< 40	0	> 4	≥40	−15
Insecticide	≤1	> 40	+15	2	> 40	0	> 2	< 40	−15
Fungicide	≤ 1	< 70	+15	> 1	< 70	0	> 2	> 70 (< 35 days before maturity	−15
Rodenticide	≤ 1	< 70	+15	> 1	< 70	0	> 1	> 70	−15
Molluscicide	≤1	< 30 (during fallow, or before seeding)	+15	> 1	< 30	0	> 1	> 30	−15

*"Gold" score of 80 out of 80 on SRP scorecard; and score > 60 on Field Calculator method out of total score, i.e., 75 (5 pesticide category × 15, maximum score for each category).
* "Acceptable" score between 65 and 80 on SRP scorecard; and score between 30 and 60 on Field Calculator method.
** "Tolerable" score between 50 and 65 on SRP scorecard; and score between 0 and 30 on Field Calculator method.
*** "Unsustainable" score of < 50 on SRP scorecard; and score < 0 on Field Calculator method.

2.5. Data analysis

Data analyses were conducted using the excel version of the FC (http://webapps.irri.org/beta/vn/fc2/web/#/), and all statistical analysis were conducted using R Version 3.5. To analyze the farmers' input and the management practices which could potentially have affected for the yield gap, the farmers were categorized into the three categories based on grain yield: top decile (top 10th), mid decile (middle 80th) and bottom decile (bottom 10th). As defined by Stuart et al. (2016) the exploitable yield gap computed from the difference between the yield of top decile and the population mean, and the percent yield gap expressed by dividing this difference by the value of the top decile. Using the same percentile categories, values were calculated for gaps in profitability, labor productivity, etc. The FC was used to compute all SRP indicators and to create the radar diagram for trade-offs among the inputs used and SRP PIs for the three categories of farmers based on yield. For the seasonal differences of the PIs, analysis of variance (ANOVA) was computed for each country. Correlations between grain yield, labor productivity, net profit, pesticide use, seed rate, and also the correlation of pesticide use scores using SRP and FC method were computed. As a first approximation of baselines and targets for discussion, we used the population mean as the baseline and the mean of the top decile as the target for each indicator.

2.5.1. Setting priorities for interventions within a region

A normalized bar diagram plotted from the FC was created to show the trade-offs among the seven PIs within each study site. The comparison of these trade-offs was used to make the site and country-specific recommendations for priority interventions for sustainably closing the rice yield gaps with reduced environmental footprints.

3. Results

3.1. Characterization of rice production inputs

The mean farm size varied across the six countries, ranging from 0.1 ha (Guangdong) to 5.6 ha (Myanmar) (Table 4). Among the six countries, rice varietal diversity is highest in Bago (> 20 different varieties) followed by Yogyakarta and Nakhon Sawan, with the lowest in Guangdong, China (< 4 varieties). In all sites, > 80% of farmers used certified seed, but most used more seed than necessary, as shown by the negative correlation between seed rate and grain yield ($r = -0.58$, $p < 0.05$).

Farmers in Bago, Myanmar, applied the highest seed rate, the longest duration rice varieties and the lowest amount of NPK fertilizers (Table 4). In Guangdong, China, the application rates were high for N and K fertilizers and pesticides. In Nakhon Sawan, Thailand, P fertilizer application was high. In all six sites, a majority of the farmers used a combination of two- and four-wheel tractors for land preparation, herbicides for weed management, and combine harvesting. Rice production per hectare was most expensive in Guangdong ($2079 ha^{-1}) and the lowest in Bago ($384 ha^{-1}) (Table 4). The total variable cost of production per hectare was higher (7%) in the dry season than in the wet season. The cost per kg of rice production varied across sites and seasons and was allocated differently across field operations, primarily driven by regional labor cost differences and crop establishment methods (Fig. 3). The average cost of production per kg of rice was $0.22; the highest was in Guangdong ($0.38 kg^{-1} paddy rice) and the lowest in Nakhon Sawan ($0.12 kg^{-1}).

3.2. Sustainable rice production indicators

3.2.1. Profitability

Averaged across the seasons, Can Tho had the highest net profit ($764 ha^{-1} season^{-1}) followed by Nakhon Sawan, Guangdong, Yogyakarta, and Polonnaruwa, and the lowest ($63 ha^{-1}) in Bago (Fig. 4). Net profit was higher in dry-season rice than in wet-season rice. Profit was correlated with grain yield ($r = 0.92$, $p < 0.001$). The averaged profit gap was 47% ranging from 36 to 82%, and the highest profit gap existed in Bago (82%) followed by Guangdong (57%), and the lowest was in Nakhon Sawan (36%).

3.2.1.1. Labor productivity. Labor use in Nakhon Sawan, Can Tho, Guangdong, and Polonnaruwa were lower than in the other two sites (Yogyakarta and Bago) (Table 4). Labor use was affected by the method of rice establishment, where, the average number of labor use days per season was 37 ± 81 ha^{-1} for wet-DSR, while it was 97 ± 57 ha^{-1} for PTR (mean ± SD). Labor productivity was highest (307 kg grain labor day^{-1}) in Nakhon Sawan, followed by Can Tho, while it was lowest in Bago followed by Yogyakarta (Fig. 4). The averaged labor productivity gap was 27% (ranging from 12 to 32%), and the highest gap was in Polonnaruwa. Labor productivity was positively correlated with net profit ($r = 0.57$, $p < 0.05$), but its correlation with grain yield ($r = 0.38$) was not significant.

3.2.1.2. Grain yield and the exploitable yield gaps of rice. The mean rice yield across two seasons was highest in Guangdong (6.0 t ha^{-1}), followed by Can Tho (5.5 t ha^{-1}), Yogyakarta (5.3 t ha^{-1}), Nakhon Sawan (4.8 t ha^{-1}), Polonnaruwa (4.3 t ha^{-1}), and the lowest was in Bago (2.6 t ha^{-1}) (Fig. 4). In all countries, the dry season was more productive than the wet season. Averaged across the sites, the dry season had 16% (0.8 t ha^{-1}) higher yield than the wet season. The variation in grain yield across farmers within site was highest in Yogyakarta followed by Guangdong, and the lowest variation was in

Table 4
Characterization of rice area and production inputs in different sites in six Asian rice producing countries from household survey data of 2012–2015. Values are mean ± standard deviation.

Area, production and production inputs	Can Tho, Vietnam		Nakhon Sawan, Thailand		Guangdong, China	
	Wet	Dry	Wet	Dry	Wet	Dry
Rice area per household (ha)	2.23 ± 1.05	2.16 ± 1.08	2.85 ± 1.55	3.01 ± 1.64	0.09 ± 0.08	0.09 ± 0.08
Sowing/transplanting date	27 April ± 29	29 Nov ± 11	17 July ± 68	13 Dect ± 43	31 Mar ± 8	26 July ± 4
Harvesting date	3 Aug ± 30	14 Mar ± 12	6 Nov ± 65	10 Apr ± 48	8 July ± 2	10 Nov ± 2
Maturity duration (day)	98 ± 10	105 ± 10	120 ± 22	121 ± 22	98 ± 2	107 ± 1
Seed rate (kg ha^{-1})	99 ± 43	101 ± 56	143 ± 28	146 ± 0	70 ± 60	84 ± 124
Elemental N (kg ha^{-1})	100 ± 37	104 ± 35	88 ± 32	114 ± 40	184 ± 82	191 ± 81
Elemental P (kg ha^{-1})	25 ± 12	29 ± 22	37 ± 17	41 ± 21	29 ± 20	28 ± 19
Elemental K (kg ha^{-1})	39 ± 20	40 ± 21	20 ± 15	25 ± 19	101 ± 81	106 ± 72
No. of labor-day ha^{-1}	21 ± 11	23 ± 17	18 ± 9	16 ± 3	55 ± 30	50 ± 27
Irrigation applied (mm)	521 ± 163	982 ± 251	594 ± 272	784 ± 331	600 ± 0	795 ± 120
Rainfall (mm)	868 ± 187	109 ± 59	905 ± 151	146 ± 209	1047 ± 96	519 ± 126
No. of irrigation applicationΠ	5.7 ± 1.7 (99)	6.5 ± 1.7 (1 0 0)	4.0 ± 1.8 (89)	5.3 ± 2.1 (99)	4.0 ± 0 (1 0 0)	5.3 ± 0.8 (1 0 0)
No. of fertilizer application	7.0 ± 2.9	7.3 ± 2.9	6.3 ± 2.8	8.4 ± 2.5	4.0 ± 0	4.0 ± 0
No. of pesticide applicationΠ	9 ± 2.4 (1 0 0)	9 ± 2.6 (97)	4 ± 2.1 (1 0 0)	1 ± 1.5 (43)	3.32 ± 0.8 (1 0 0)	3.14 ± 0.3 (1 0 0)
Rice establishment method (% farmer)	94 = Wet-DSR 6 = PTR	94 = Wet-DSR 6 = PTR	86 = Wet-DSR 14 = DSR	85 = Wet-DSR 12 = DSR 3 = PTR	97 = PTR 3 = MPTR	100 = PTR
Amount of straw incorporated (t ha^{-1})€	2.54 ± 0.97 (51)	2.40 ± 0.61 (35)	3.46 ± 0.94 (67)	2.42 ± 0.53 (46)	3.79 ± 1.04 (61)	3.82 ± 0.99 (56)
Total variable cost of production ($ ha^{-1})	594 ± 171	705 ± 167	606 ± 101	509 ± 107	1944 ± 723	2181 ± 722

Area, production and production inputs	Yogyakarta, Indonesia		Bago, Myanmar		Polonnaruwa, Sri Lanka	
	Wet	Dry	Wet	Dry	Wet	Dry
Rice area per household (ha)	0.15 ± 0.11	0.14 ± 0.11	5.58 ± 7.44	3.02 ± 4.23	1.34 ± 0.72	0.99 ± 0.54
Sowing/transplanting date	1 Dec ± 34	22 April ± 73	15 July ± 37	8 Jan ± 27	16 Nov ± 6	1 May ± 16
Harvesting date	18 Mar ± 33	28 July ± 71	22 Nov ± 35	1 May ± 24	15 Mar ± 9	19 Aug ± 13
Maturity duration (day)	107 ± 13	98 ± 14	130 ± 23	113 ± 19	110 ± 12	109 ± 11
Seed rate (kg ha^{-1})	40 ± 14	45 ± 17	136 ± 42	150 ± 46	101 ± 24	106 ± 14
Elemental N (kg ha^{-1})	219 ± 103	199 ± 113	37 ± 22	18 ± 19	144 ± 85	96 ± 56
Elemental P (kg ha^{-1})	22 ± 13	23 ± 17	1 ± 3	0 ± 0	22 ± 12	10 ± 10
Elemental K (kg ha^{-1})	43 ± 28	49 ± 51	0 ± 1	0 ± 1	60 ± 46	50 ± 36
No. of labor-day ha^{-1}	210 ± 87	184 ± 79	97 ± 37	80 ± 37	43 ± 18	39 ± 19
Irrigation applied (mm)	529 ± 136	532 ± 166	680 ± 0	1156 ± 0	1294 ± 169	932 ± 206
Rainfall (mm)	654 ± 234	447 ± 172	1159 ± 461	168 ± 197	1358 ± 138	229 ± 32
No. of irrigation applicationΠ	8.4 ± 0.9 (93)	10.4 ± 1.1 (54)	7.0 ± 0 (1 0 0)	12.0 ± 0 (1 0 0)	11.3 ± 1.1 (1 0 0)	10.9 ± 1.1 (1 0 0)
No. of fertilizer application	5.3 ± 3.0	2.8 ± 3.5	1.9 ± 0.6	–	3.7 ± 0.9	3.2 ± 0.7
No. of pesticide applicationΠ	1 ± 0.9 (85)	1 ± 1.5 (26)	0.8 ± 0.9 (55)	0.6 ± 0.6 (52)	NA	NA
Rice establishment method (% farmer)	81 = PTR 18 = Wet-DSR 1 = MPTR	77 = PTR 21 = Wet-DSR 2 = MPTR	90 = PTR 10 = Wet-DSR	53 = PTR 47 = Wet-DSR	100 = Wet-DSR	100 = Wet-DSR
Amount of straw incorporated (t ha^{-1})€	0.69 ± 0.31 (12)	0.74 ± 0.31 (12)	1.11 ± 0.37 (40)	1.16 ± 0.37 (40)	3.20 ± 0.65 (81)	2.30 ± 0.43 (43)
Total variable cost of production ($ ha^{-1})	1071 ± 245	915 ± 224	345 ± 83	423 ± 86	543 ± 83	591 ± 83

ΠFigure in parenthesis indicates percentage farmers apply irrigation or pesticide.
€ Figure in parenthesis indicates percentage of the straw of previous season rice incorporated during this season. Wet-DSR = wet direct seeded rice; DSR = dry direct seeded rice; PTR = puddled transplanted rice; MPTR = machine transplanted rice in puddled soil

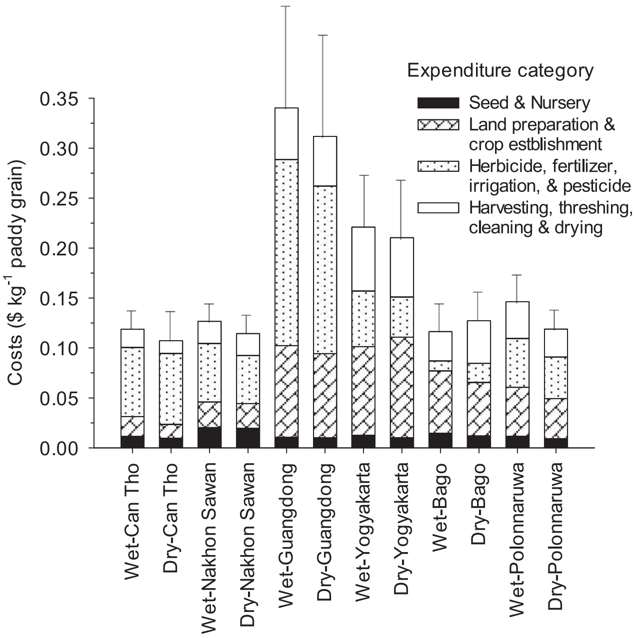

Fig. 3. Cost of different operations (converted to US$ kg^{-1} paddy grain) during rice cultivation in wet- and dry-season in six survey sites. The vertical lines in the figure are standard deviation of the total variable cost.

Bago and Polonnaruwa. For two cropping seasons, Guangdong generated the highest annual yield of 12.0 $t\,ha^{-1}$ followed by Can Tho, Yogyakarta, and Nakhon Sawan, and the lowest was in Bago (5.2 $t\,ha^{-1}$).

The exploitable yield gap for the six survey sites and two seasons ranged from 24 to 42% (1.3 to 3.8 $t\,ha^{-1}$) exploitable yield gap (Fig. 5). Combined over two seasons, the highest yield gap was in Yogyakarta (42%; 3.8 $t\,ha^{-1}$) followed by Bago (36%; 1.5 $t\,ha^{-1}$), Guangdong (28%; 2.3 $t\,ha^{-1}$), Nakhon Sawan, Can Tho (25%; 1.7 $t\,ha^{-1}$) and Polonnaruwa (24%; 1.3 $t\,ha^{-1}$). The exploitable farm yield (mean yield of the top decile farmers) was 9.1 $t\,ha^{-1}$ in Yogyakarta, 8.3 $t\,ha^{-1}$ in Guangdong, 7.4 $t\,ha^{-1}$ in Can Tho, 6.4 $t\,ha^{-1}$ in Nakhon Sawan, 5.7 $t\,ha^{-1}$ in Polonnaruwa and 4.1 $t\,ha^{-1}$ in Bago (Fig. 5). The highest variability in grain yield was in Yogyakarta followed by Guangdong. The lowest yields were in Bago followed by Polonnaruwa and Nakhon Sawan. Yield gaps were similar between seasons for each survey site.

3.2.1.3. Nitrogen use efficiency (NUE). Nitrogen fertilizer application rate was a highest in Guangdong (> 188 $kg\,ha^{-1}$ $season^{-1}$) and lowest in Myanmar (< 28 $kg\,ha^{-1}$ $season^{-1}$) (Table 4). There was high variation in the number of fertilizer applications (from 2 to 7). In Can Tho, Nakhon Sawan, Guangdong, and Polonnaruwa, > 91% farmers applied N, P and K fertilizer during rice cultivation. In Yogyakarta, > 74% farmer applied N, and > 67% farmers applied P and K fertilizer. In contrast, in Bago, only 62% of the total farmers applied N and < 4% farmers applied P and K fertilizers. In Bago, because many farmers did not apply N and P, the NUE and PUE were not calculated. The averaged NUE in the other five sites was 41 kg grain kg^{-1} elemental N application during the wet and 50 kg during the dry season (averaged 45 kg grain kg^{-1}N) (Fig. 6A). The mean NUE gap was 14% (range 11–20%), with the highest gap (20%) in Nakhon Sawan followed by Can Tho, and the lowest NUE gap in Polonnaruwa (11%).

3.2.1.4. Phosphorus use efficiency (PUE). Excluding Bago, the phosphorus use efficiency (PUE) over two seasons was 257 kg grain kg^{-1} elemental P application during wet and 321 kg grain kg^{-1} elemental P application during dry seasons (mean 288 kg grain kg^{-1}P; Fig. 6B). The mean PUE gap was 7% (range 1–29%), and the highest

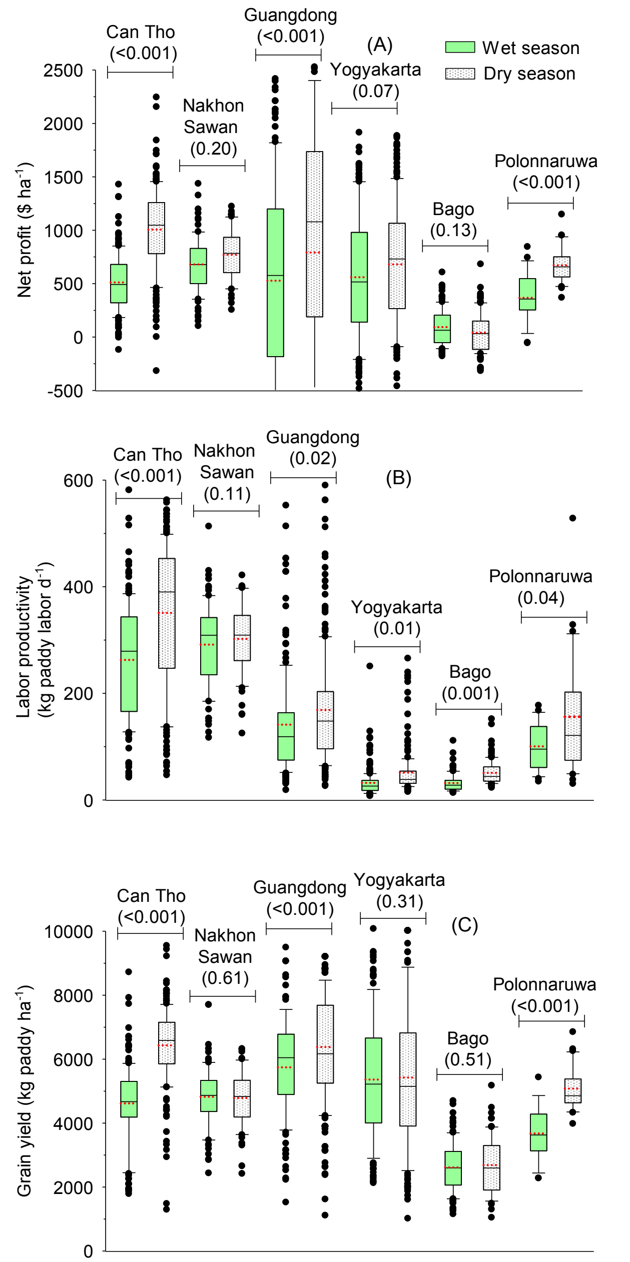

Fig. 4. Net profit (A), labor productivity (B), and grain yield (C) of rice in six sites during a baseline survey carried out in wet- and dry-seasons between 2012 and 2015. Figures in parenthesis are the p value, if the value is < 0.05, the computed value was significantly different between two seasons while the > 0.05 value mean the computed values not different between two seasons. Red dotted lines inside the box are the mean and the black solid lines the median.

PUE of 29% was found in Guangdong followed by in Nakhon Sawan (16%). The lowest PUE gaps were in Polonnaruwa and Can Tho (< 5%).

3.2.1.5. Water productivity. The total number of irrigations per cropping season was lowest in Yogykarta, whereas it was highest in Polonnaruwa, where rainfall was relatively low (Table 4). The amount of irrigation applications during the dry season was 45% (ranging from 1 to 89%) higher than the wet season. The averaged water productivity across all six sites was 3092 L water kg^{-1} grain. One kg of paddy rice production requires 3000–5000 L of water (Cabangon et al., 2014). The water productivity was highest in Yogyakarta and the lowest in Bago (Fig. 7). Fields in Yogyakarta utilized 2100 L water

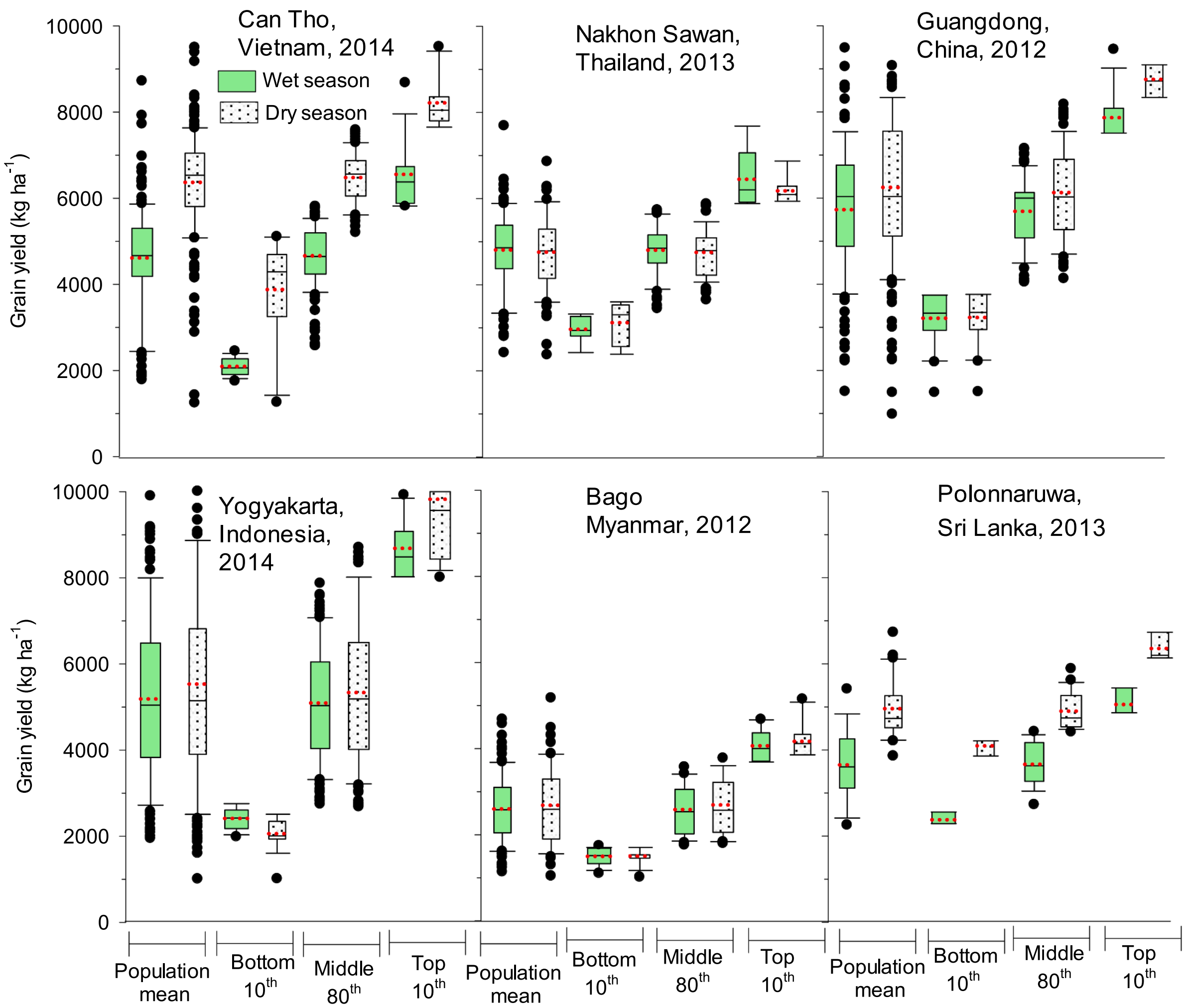

Fig. 5. Rice yield gap range (kg ha^{-1}) between three different percentile category farmers in different years during wet- and dry-seasons in six survey sites. Red dotted lines inside the box are the mean and the black solid lines the median.

(irrigation + rainfall) kg^{-1} of rice grain, while Bago utilized 6700 L water kg^{-1} grain. Besides rainfall, farmers in Yogyakarta utilized the lowest (873 L kg^{-1}) while the farmers in Bago apply the highest (3854 L kg^{-1}) amount of irrigation water. The mean water productivity gap was 26% (range 12–43%), the highest gap was in Bago and the lowest in Nakhon Sawan.

3.2.1.6. Greenhouse gas emissions. Averaged across all countries, there was higher ($p < 0.001$) GHG emissions in the wet than the dry seasons, 5960 and 3660 kg CO_2 equivalent t^{-1}, respectively (Fig. 7B). GHG emissions were higher by 8% for the top grain-yield decile (422 kg CO_2 equivalent ha^{-1}). Flooding the field > 30 days before rice planting, incorporation of pre-crop residue shortly before planting and continuous flood irrigation during the growing period, were the major sources for the higher emission. Deliberate modification of these conventional practices substantially reduced GHG emissions in irrigated rice fields.

3.2.1.7. Pesticide use efficiency. The computed pesticide use efficiency of three countries indicated pesticide use efficiency can be improved by 19% (i.e. the difference between the top decile mean of 65% and the population mean of 46%). Farmers in all three assessed sites applied a greater number of pesticides during the wet- than during the dry-season. In Can Tho, Vietnam, the overall pesticide score using the FC scoring method indicated that 85% of the farmers during the wet- and 81% farmers during the dry-season were in the “unsustainable” category with regard to number and timing of pesticide applications (Table 5). The most common reasons for the unsustainable score were related to insecticide and fungicide application, and the unsustainability was mostly due to more number of application as well as the application within one month of crop maturity, whereas > 86% of farmers fell under the acceptable category for herbicide, rodenticide and molluscicide use. In Nakhon Sawan, during the dry season, 69% of the farmers fell under the gold category, while this decreased to 14% during the wet season with the majority of farmers in the tolerable and acceptable categories. In Yogyakarta, the majority of the farmers were under the category of gold (68% during the dry season and 78% during wet season). In Nakhon Sawan and Yogyakarta, as in Can Tho, insecticides and fungicides mostly attributed to the higher unsustainability of pesticide application.

3.3. *Trade-offs among economic and environmental sustainability indicators in the six countries*

Our analyses highlight the trade-offs among production inputs and SRP indicators and how these varied between countries (Fig. 8). In Can Tho and Nakhon Sawan, the largest difference in input rates between high yielding and low yielding farmers was for P fertilizer use, with a similar difference in PUE in Nakhon Sawan, but no difference in PUE between these groups in Can Tho. Differences in grain yield corresponded to similar differences in water productivity and NUE. In addition, the lowest yielding farmers (bottom decile) emitted at par GHGs

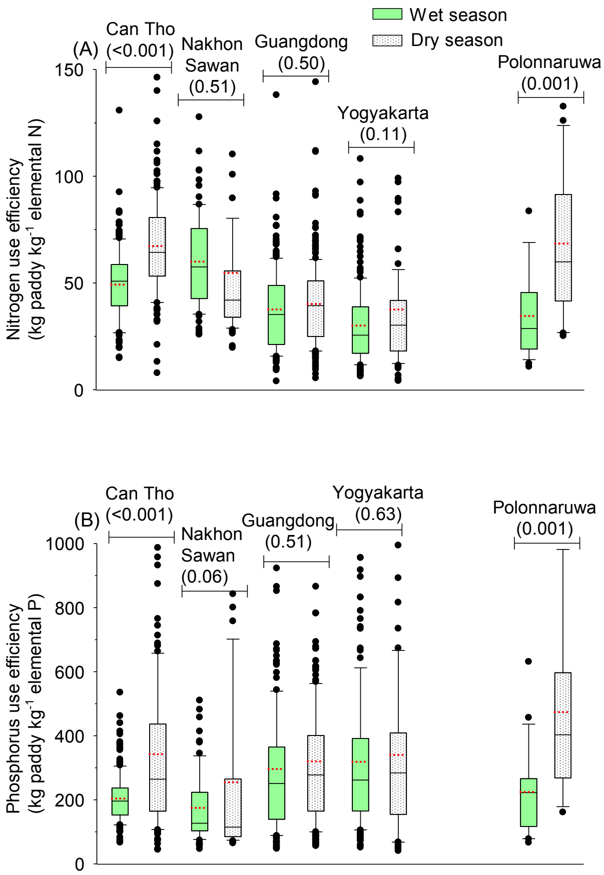

Fig. 6. Nutrient use efficiency, also called partial factor productivity, of N (A) and P (B) in rice in six Asian countries during wet- and dry-season 2012–2014. Figures in parenthesis are p value, if the value is < 0.05, the computed value was significantly different between two seasons while the > 0.05 value mean the computed values not different between two seasons. Values were not computed for Bago, Myanmar due to the prevalence of farmers who added no N or P (resulting in a denominator of 0). Red dotted lines inside the box are the mean and the black solid lines the median.

with the highest yielding farmers, but they applied more pesticides. In Guangdong, the highest yielding farmers used less N, P, and labor and scored better for all the SRP PIs. In Yogyakarta, farmers in the top decile for yield production used more inputs but were more efficient in their input use, as indicated by their higher PI scores, including reduced GHG emissions. Similarly, in Bago, the highest yielding farmers generally used more inputs, especially N, and their grain yield and profit were substantially higher than the lowest yielding farmers. In Polonnaruwa, the highest yielding farmers used less labor and more N but had higher NUE and profit than the lowest yielding farmers. It thus appears that in Bago and Polonnaruwa, N fertilizers were major yield-limiting factors.

4. Discussion

The trade-offs analysis between the six survey sites showed the lowest net profit in Bago, which was mostly attributed by the lowest grain yield due to none/negligible amount of application of N and P fertilizer, which may lead to excessive nutrient mining if nutrients are not sufficiently replaced through monsoon season flood events (Fig. 9; Table 7). Further research is needed to investigate this. Further, as the farmers in Bago applied the highest seed rate and the longest duration and in some cases photo-sensitive rice varieties strongly suggesting that rice yield can be improved significantly with the use of high yielding varieties and quality seed and more fertilizer (Table 4). In contrast, farmers in Yogyakarta, applied high amounts of N fertilizer with low

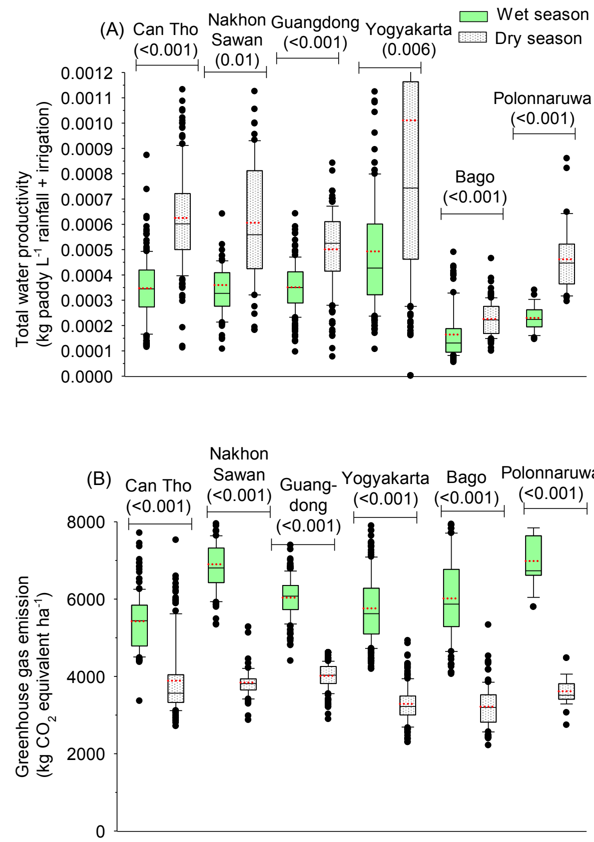

Fig. 7. Total water productivity (A) and greenhouse gas emission (B) in rice cultivation in six Asian countries during wet- and dry-seasons 2012–2015. Figures in parenthesis are p value, if the value is < 0.05, the computed value was significantly different between two seasons while the > 0.05 value mean the computed values not different between two seasons. Red dotted lines inside the box are the mean and the black solid lines the median.

NUE (Table 7), indicating scope to reduce N fertilizer use in this site. Farmers in Nakhon Sawan performed amongst the highest of the survey sites for nearly all the indicators for both seasons, except for grain yield, NUE, and PUE during the dry season. In comparison with Can Tho, N and P use (Table 4) in Nakhon Sawan during the dry season were considerably higher even though lower yields (Table 6) were achieved. This indicates that to optimize nutrient use efficiency in Nakhon Sawan, N and P use can be therefore reduced.

Labor productivity was lowest in Yogyakarta and Bago followed by Polonnaruwa, and Guangdong, whereas it was considerably higher in Can Tho and Nakhon Sawan where wet-DSR was applied, and there was more use of machinery for harvesting and threshing. Similarly, a recent study comparing six countries in Asia concluded that farmers in the Nakhon Sawan, Thailand and the Mekong Delta, Vietnam, were the most labor efficient due to a high level of mechanization (Bordey et al., 2016). These findings highlight the scope to reduce labor use and associated costs through adoption of mechanization in the four countries with low labor productivity.

The high fertilizer and irrigation application rates in Polonnaruwa are most likely a result of government irrigation and fertilizer subsidies of up to 95% (Ekanayak, 2009). The water productivity in both seasons and NUE in the wet season were amongst the lowest of the six countries, indicating scope to reduce these inputs without sacrificing grain yield. Farmers in Can Tho, Vietnam, applied the most pesticide, with no correlation to grain yield, indicating considerable scope for reducing unnecessary pesticide applications. Farmers' in Can Tho has potential to reduce pesticide application (Stuart et al., 2018).

No inherent trade-offs between yield and CO_2 equivalent

Table 5
Overall pesticide use efficiency score based on Field Calculator (FC) and Sustainable Rice Platform (SRP) approaches of computation, and the number (percentage in parenthesis) of farmers using pesticides to control weeds (herbicide), insects (insecticide), diseases (fungicide), rats (rodenticide), and mollusks (Molluscicide) derived using FC approach in Vietnam, Thailand and Indonesia during dry (DS) and wet season (WS), 2012–2015.

Site and seasonΠ	Farmers' sustainability category	Overall score FC method€	Herbicide	Insecticide	Fungicide	Rodenticide	Molluscicide	Overall score SRP method¥
Can Tho, DS (9 ± 2.6)	Gold	2 (1)	–	–	–	–	–	0 (0)
	Acceptable	20 (11)	153 (86)	41 (23)	2 (1)	178 (1 0 0)	173 (97)	8 (4)
	Tolerable	5 (3)	22 (12)	27 (15)	9 (5)	–	2 (1)	102 (57)
	Unsustainable	152 (85)	3 (2)	110 (62)	167 (94)	–	3 (2)	69 (39)
Can Tho, WS (9 ± 2.4)	Gold	1 (1)	–	–	–	–	–	0 (0)
	Acceptable	25 (14)	145 (81)	52 (29)	3 (2)	176 (99)	175 (98)	9 (5)
	Tolerable	8 (4)	29 (16)	29 (16)	5 (3)	–	–	124 (69)
	Unsustainable	145 (81)	2 (1)	95 (53)	171 (96)	–	1 (1)	46 (26)
Nakhon Sawan, DS (1 ± 1.5)	Gold	57 (69)	–	–	–	–	–	0 (0)
	Acceptable	21 (25)	64 (77)	64 (77)	79 (95)	83 (1 0 0)	83 (1 0 0)	74 (89)
	Tolerable	4 (5)	8 (10)	3 (4)	–	–	–	9 (11)
	Unsustainable	1 (1)	11 (13)	16 (19)	4 (5)	–	–	0 (0)
Nakhon Sawan, WS (4 ± 2.1)	Gold	12 (14)	–	–	–	–	–	0 (0)
	Acceptable	38 (46)	22 (27)	26 (31)	62 (75)	83 (1 0 0)	83 (1 0 0)	53 (64)
	Tolerable	21 (25)	26 (31)	1 (1)	8 (10)	–	–	28 (34)
	Unsustainable	12 (14)	35 (42)	56 (67)	13 (16)	–	–	2 (2)
Yogyakarta, DS (1 ± 1.5)	Gold	114 (68)	–	–	–	–	–	119 (71)
	Acceptable	50 (30)	166 (99)	114 (68)	166 (99)	167(1 0 0)	167 (1 0 0)	47 (28)
	Tolerable	1 (1)	–	–	1 (1)	–	–	0 (0)
	Unsustainable	2 (1)	1(1)	53 (32)	–	–	–	1 (1)
Yogyakarta, WS (1 ± 0.9)	Gold	131 (78)	–	–	–	–	–	83 (50)
	Acceptable	34 (20)	164 (98)	132 (79)	167 (1 0 0)	167 (1 0 0)	167 (1 0 0)	84 (50)
	Tolerable	1 (1)	1 (1)	–	–	–	–	0 (0)
	Unsustainable	1 (1)	2 (1)	35 (21)	–	–	–	0 (0)

ΠFigure in parenthesis indicates average number of application ± standard deviation.

($r = -0.23$ ns) suggest it will be possible to reduce GHG emissions without loss of yield or profitability. However, the value of GHG emission varies across locations based on the cropping systems practiced by the farmers, pre-rice irrigation regime, maturity duration of the variety, irrigation during the rice growing period, and the time and amount of pre-season residue incorporation (Wassmann et al., 2000). Our findings computed using the IPCC (Dong et al., 2006) are in line with the researcher managed and measured data on a nearby experimental station reported by Liang et al. (2016) in Guangdong.

There have been too few multi-country comparisons of sustainability indicators and yield gaps. A study of 10 Sub-Sahara African countries reported markedly high yield gaps (against 80% of yield potential) and raised the concern that unless these begin to be closed, then these countries will become strongly reliant on imports of the major cereals (van Ittersum et al., 2016). This study examined the potential of increasing production if more water was available via irrigation but did not examine the relative importance of specific production practices. Similarly, there have been general reviews that promote the need to preserve the quality of cereal production system rather than mine the soil nutrients (Cassman, 1999). Our findings particularly raise concerns that current practices in Myanmar tend to mine soil nutrients. Therefore, our analyses on specific production practices and trade-offs between economic and environmental sustainability indicators provide an important avenue for identifying specific priorities for each country to increase production in intensive lowland rice areas. However, further research is required to understand the trade-offs among all four pillars of sustainability including social and institutional indicators.

4.1. Baselines and targets

The computed baseline (population mean) and target (mean of top decile) values of each indicator quantified the scope to maximize the profit, labor productivity, grain yield, water productivity, NUE, PUE, and pesticide use efficiency (Table 6). For nutrients (N, P, and K) and water, the target should be their optimal rate (Table 7) rather than extreme (wasteful or insufficient) rates. Our findings confirm that the frequency and time of application of N fertilizer affect NUE (Sun et al., 2016).

The baseline and the target value computations of indicators could assist to develop best management practices and design and scaling out of systematic innovations that can drive rice production system towards economically, ecologically, and socially viable, plus acceptable and ultimately sustainable. One of the major indirect impacts of the computation of indicators from the survey data was the development of the decision support tool, i.e., Field Calculator, which computes all 12 indicators of sustainability for rice production and provides decision support (recommendation) to the farmers for improving all indicators and closing yield and profit gap with reduced environmental footprint. It demonstrates possible trade-offs among various indicators and the inputs. The baseline computation of GHG could assist to develop and test the mitigation strategies through the deliberate modifications of agronomic practices. Further, it could provide the basis for socio-economic feasibility of mitigation technologies for specific sites and seasons (Wassmann et al., 2000).

Our approach to set the target value of each indicator from the baseline data provides a pathway of action to meet the target value of the respective indicator as defined by a national government. For example in Vietnam, the government has set a target to increase rice farmers' profit by ≥30%, decrease seed sown to 80 kg per ha^{-1}, apply integrated pest management in > 75% of rice areas, apply sustainable farming practices (1 Must Do, 5 Reductions, Viet GAP; Table 2) in > 50% of areas, lower fertilizer and pesticides use by 30%, and lower GHG emissions by 10% by 2020 (ASEF, 2015). Another approach for setting targets based on survey data could be using certain numeric algorithms (Rossberg et al., 2017), and time series analyses of the respective indicators in the respective countries (Probst and Stelzenmüller, 2015). The approach we favor to set target for each indicator is based on the gap for each indicator (the difference between top 10th decile and population mean) from baseline survey data (Lobell et al., 2009; Stuart et al., 2016). Our assumption that these targets can be attained is based on the top decile (top 10th) farmers, who are already obtaining the prescribed level of the indicator (target) under the

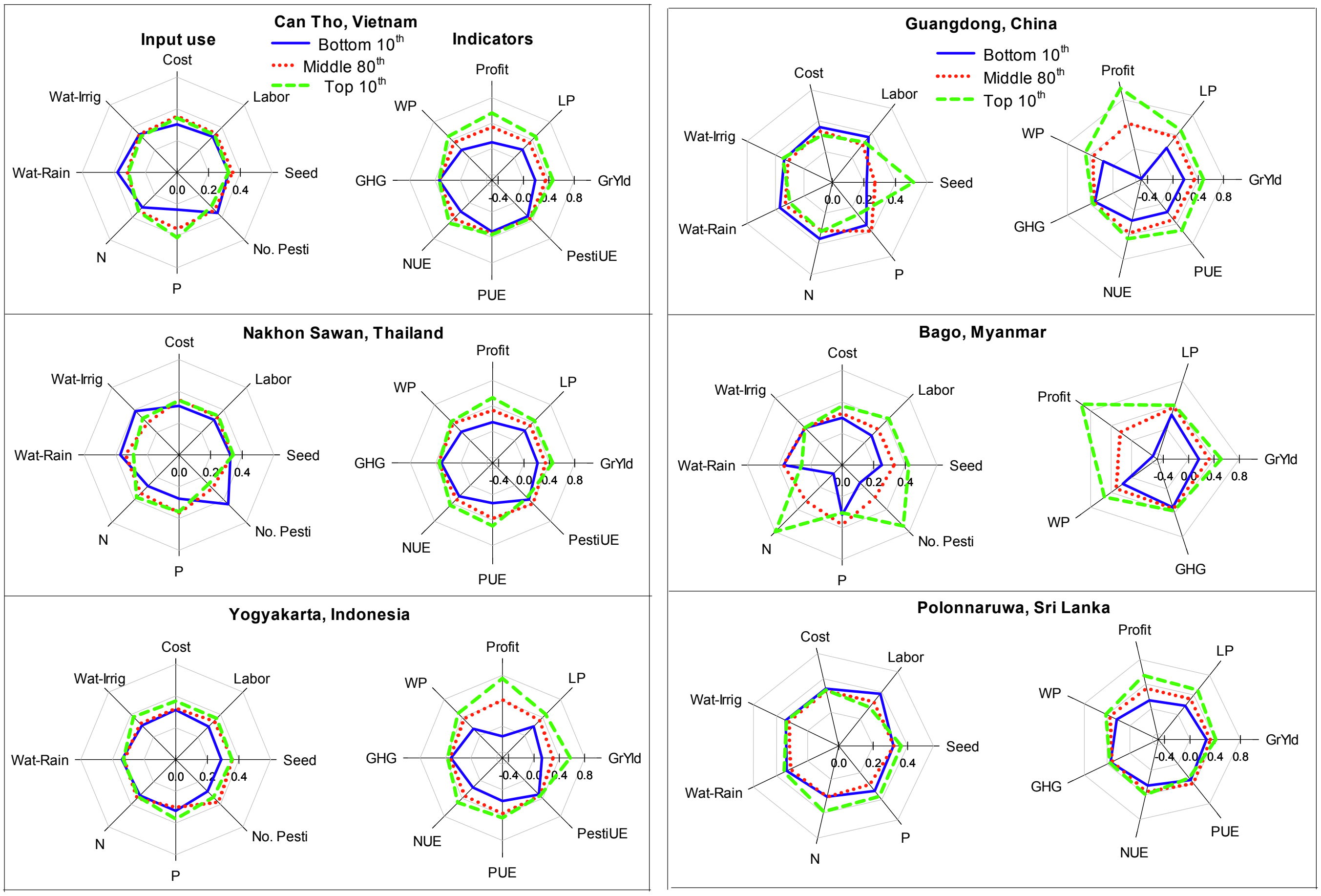

Fig. 8. Trade-off comparison among different production inputs and performance indicators among three categories of farmers (delineated by grain yield performance percentile category) in each survey site (combined over two season). Figure in the left side in each panel are input use and the right side are the performance indicators. Note that for all indicators except greenhouse gas emission, higher values (moving outward from center) indicate better performance, while the reverse is true for GHG emissions. Symbols and units for inputs used: Seed = seed input (kg ha^{-1}), Labor = labor input (person-days ha^{-1}), Cost = cost (currency $ ha^{-1}), Wat-Irrig = irrigation water input (amount of irrigation, mm season^{-1}); Wat-Rain = rainfall (mm season^{-1}); N = nitrogen fertilizer input (elemental N, kg ha^{-1}), P = phosphorus fertilizer input (elemental P, kg ha^{-1}), No. Pesti. = (number of cumulative crop protection product input applications season^{-1}). Symbols and units for indicators: GrYld = grain yield (kg ha^{-1}), LP = labor productivity (GY Labor^{-1}); Profit = profit from rice (currency $ ha^{-1}), WP = water productivity (kg grain L^{-1} water (irrigation + rainfall), GHG = greenhouse gas emission (CO_2-equivalent kg ha^{-1}), NUE = nitrogen use efficiency (kg grain kg^{-1} fertilizer N), PUE = phosphorus use efficiency (kg grain kg^{-1} fertilizer P), PestiUSE = Pesticide use efficiency score (using Field Calculator approach).

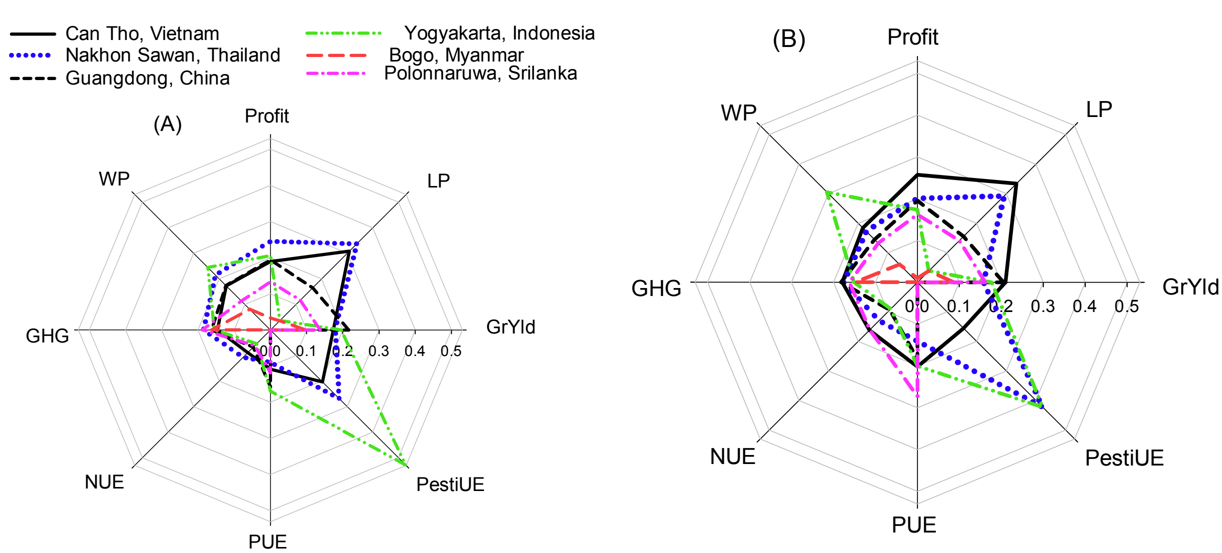

Fig. 9. Trade-off among Sustainable Rice Platform (SRP) defined performance indicators (PIs) in 6 different survey sites during wet (A) and dry (B) seasons. In both (Figs. A and B), nitrogen and phosphorus use efficiencies were not computed for Bago, Myanmar. Description of the figure labels in Fig. 8.

Table 6
Baseline (population mean) and the target (mean of the top decile; top 10th) values for each performance indicators in each survey sites in six Asian countries. Values are mean ± standard deviation and dash (-) in the table are either the values are not available or not applicable.

IndicatorsΠ	Items	Can Tho, Vietnam		Nakhon Sawan, Thailand		Guangdong, China
		Wet	Dry	Wet	Dry	Wet
Profit	Baseline	511 + 267	1002 + 408	664 + 272	783 + 252	524 + 1047
	Target	957 + 224	1531 + 305	1130 + 171	1144 + 143	1431 + 974
LP	Baseline	263 ± 109	350 ± 138	287 ± 82	306 ± 70	141 ± 101
	Target	403 ± 114	455 ± 162	387 ± 93	385 ± 72	192 ± 144
Grain yield	Baseline	4615 ± 1253	6417 ± 1207	4745 ± 1003	4826 ± 936	5733 ± 1450
	Target	6596 ± 799	8185 ± 563	6453 ± 727	6276 ± 378	7902 ± 598
WP	Baseline	0.000347 ± 0.0-00125	0.000623 ± 0.0-00198	0.000433 ± 0.0-00850	0.000585 ± 0.0-00240	0.000350 ± 0.0-00095
	Target	0.000493 ± 0.0-00091	0.000859 ± 0.0-00220	0.000448 ± 0.0-00097	0.000704 ± 0.0-00247	0.000488 ± 0.0-00052
NUE	Baseline	49 ± 17	67 ± 23	59 ± 21	56 ± 51	37 ± 19
	Target	65 ± 12	85 ± 21	70 ± 24	85 ± 91	50 ± 11
PUE	Baseline	204 ± 78	341 ± 267	168 ± 105	238 ± 315	295 ± 242
	Target	237 ± 73	313 ± 166	202 ± 87	283 ± 279	384 ± 213
PestiUseEffi.	Baseline	25 ± 13	22 ± 12	33 ± 15	65 ± 14	–
	Target€	46 ± 4	49 ± 8	69 ± 8	75 ± 0	–
CO_2 equiv.€	Baseline	5428 ± 719	3875 ± 935	6874 ± 786	3808 ± 404	6030 ± 514
	Target	5418 ± 827	3936 ± 850	7255 ± 562	3769 ± 427	6524 ± 356

IndicatorsΠ	Guangdong, China	Yogyakarta, Indonesia		Bago, Myanmar		Polonnaruwa, Sri Lanka	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Profit	970 + 1145	556 + 591	677 + 581	88 + 172	37 + 189	360 + 230	633 + 163
	2035 + 666	1476 + 260	882 + 301	361 + 156	315 + 163	725 + 119	935 + 166
LP	163 ± 105	31 ± 26	40 ± 42	31 ± 17	40 ± 23	99 ± 44	132 ± 78
	233 ± 141	45 ± 22	57 ± 34	41 ± 15	40 ± 13	157 ± 21	184 ± 161
Grain yield	6280 ± 1678	5186 ± 1897	5410 ± 2265	2599 ± 803	2675 ± 857	3654 ± 807	4951 ± 655
	8764 ± 482	8661 ± 739	9675 ± 449	4067 ± 356	4183 ± 402	5031 ± 330	6345 ± 328
WP	0.000489 ± -0.000146	0.000492 ± -0.000262	0.001009 ± -0.000995	0.000163 ± -0.000100	0.000204 ± -0.000068	0.000227 ± -0.000050	0.00044-6 ± 0.0001-34
	0.000671 ± -0.000051	0.000793 ± -0.000292	0.001331 ± -0.000658	0.000328 ± -0.000113	0.000312 ± -0.000064	0.000298 ± -0.000036	0.00054-8 ± 0.0000-99
NUE	39 ± 19	30 ± 20	37 ± 49	339 ± 291	135 ± 99	34 ± 20	67 ± 34
	50 ± 18	43 ± 18	48 ± 19	381 ± 350	146 ± 63	37 ± 21	86 ± 68
PUE	310 ± 229	317 ± 223	332 ± 245	759 ± 447	–	222 ± 132	461 ± 281
	465 ± 161	376 ± 186	345 ± 293	–	–	221 ± 60	287 ± 169
PestiUseEffi.	–	68 ± 12	65 ± 14	–	–	–	–
	–	75 ± 0	75 ± 0	–	–	–	–
CO_2 equiv.€	3937 ± 329	5751 ± 921	3276 ± 481	6005 ± 1055	3207 ± 541	6969 ± 697	3511 ± 365
	4128 ± 289	6586 ± 763	3327 ± 350	6505 ± 1393	3697 ± 838	7690 ± 472	3581 ± 723

ΠProfit = net profit (\$ ha^{-1}), LP = Labor productivity (kg grain $labor^{-1}$ day), grain yield (kg ha^{-1}), WP = water productivity (kg grain L^{-1} water), NUE = kg grain kg^{-1} elemental N, PUE = kg grain kg^{-1} elemental P, PestiUseEffi = pesticide use efficiency (calculated based on the FC method,), CO_2 equiv. = CO_2 equivalent emission (kg ha^{-1}).
€The indicator whose lower value is preferred for the target.

Table 7
Percentage farmers in higher or upper, desired or optimum, and the lower or bottom threshold levels for the water-, nitrogen (N)-, phosphorus (P)-, and potassium (K)- use efficiencies in irrigated rice in different survey sites.

Upper, optimum and the lower threshold levels	Can Tho, Vietnam	Nakhon Sawan, Thailand	Guangdong, China	Yogyakarta, Indonesia	Bago, Myanmar	Polonnaruwa, Sri Lanka
Water productivity (L water kg^{-1} grain)						
High (wasteful water, > 5000)	2	4	4	3	73	13
Desirable range (2500–5000)	37	46	33	24	27	55
Low (insufficient water, < 2500))	62	50	63	72	0	33
Nitrogen use efficiency (NUE, kg grain kg^{-1} elemental N)						
Too high (soil mining, > 80)	6	11	1	3	92	20
Desirable range (40–80)	85	66	44	20	8	36
Too low (wasteful application, < 40)	10	23	56	76	0	44
Phosphorus use efficiency (PUE, kg grain kg^{-1} elemental P)						
Too high (soil mining, > 350)	21	12	31	31	60	30
Desirable range (150–350)	64	32	51	48	40	47
Too low (wasteful application, 〈1 5 0)	15	55	17	20	0	23
Potassium use efficiency (KUE, kg grain kg^{-1} elemental K)						
Too high (soil mining, > 200)	28	71	3	27	75	16
Desirable range (70–200)	70	26	55	58	25	55
Too low (wasteful application, < 70)	2	2	42	14	0	29

given socio-economic and biophysical conditions of a location. However, to set top decile farmers mean value of the PIs as the target is challenging because the top decile farmers are likely to have progressed faster than other farmers. Further, this exploitable yield value does not always account for difference between the theoretical yield potential of fields, which is dependent on specific soil and micro-climatic conditions (Buresh and Witt, 2007; Peng et al., 2010) and water availability (Bouman et al., 2007; Lampayan et al., 2015). Under such conditions, a combination of top decile (as the target) and population mean (as the baseline) with the percent increment/improvement in the PIs after certain years of the intervention compared to the average value in the baseline, could better reflect the impact of farmers adopting improved management practices for rice production.

4.2. Using indicators to prioritize the interventions for improving sustainability

In the future, the area of rice production in most countries, particularly in Asia, is likely to reduce (Suroso et al., 2013), therefore careful utilization of rice land, and sustainable intensification by narrowing the yield gaps is essential to feed the growing global population (van Ittersum et al., 2016). Our study (Fig. 5), as well as a previous study by Stuart et al. (2016) showed that an important rice yield gap exists in all the sites surveyed. The target values for all the SRP indicators (Table 6) suggests that a further increase in rice yield with improved economic and environmental sustainability is possible in all six country sites. In addition, 80% of the simulated climatic potential yield of rice in Bago, Myanmar during the same wet season covered by the survey was 6.4 t ha^{-1} (Stuart et al., 2016), whereas, the top decile farmers' yield was < 5 t ha^{-1} indicates that exploitable yield gaps may even be underestimated when using survey data from low production environments. However, as the latter method of computation incorporates both socio-economic and bio-physical factors which affect rice production, the survey results may represent a more realistic estimate of the exploitable yield gaps that can be closed given the local socio-economic conditions (Stuart et al., 2016).

Considerable scope exists for farmers from Bago and Polonnaruwa (low production sites) to improve and increase productivity; and Can Tho, Guangdong and Yogyakarta (high production sites) to decrease pesticide and other input use to improve environmental sustainability and maintain or increase competitiveness in both national and international markets. The need to optimize nutrient and irrigation water use efficiency exists at most sites (Table 7). Farmers in low production system sites like Bago could benefit from the implementation of a "best practice" programme on seed and fertilizer use (Owen, 2014). In Yogyakarta and Polonnaruwa, reduction of fertilizer subsidies and irrigation subsidies for the latter could be a priority to help minimize over-application. The current policy of the Government of Sri Lanka is to maintain self-sufficiency in rice production and consumption through market support, and subsidy in irrigation and fertilizer up to 95% (Ekanayak, 2009). Similarly, programmes for pesticide and P fertilizer reduction are needed in Vietnam (Heong et al., 2010; Van Hoi et al., 2013) and for NPK fertilizer reduction in China (Ju et al., 2009; Zhong et al., 2010), and narrowing yield gap with lower/acceptable environmental footprint in Yogyakarta, Indonesia and Nakhon Sawan, Thailand (Stuart et al., 2017), are crucial for the intensively managed lowland rice production in these Asian countries.

Rice production has been criticized for its high levels of methane emission. Modification of the water regime before rice planting (short period pre-rice flooding), adoption of one or multiple mid-season drainage or alternate wet-and-dry method of irrigation during the crop growing period, timely and optimum amount of incorporation of organic amendments, crop establishment method, and crop growing duration are the major factors that lead singly or in combination for the reduced GHG emission during dry season in all countries. Straw burning emits a significantly lower amount of GHG but emits particulate matter (Gadde et al., 2009) and other gases which are harmful for the human health, for example, carbon monoxide (CO) and nitrous oxide (N_2O) (Miura and Kanno, 1997), while residue incorporation builds soil organic carbon stock and improves soil health. The higher amount of CH_4 (CO_2 equivalent) emission during the wet season (almost double) is mostly influenced by the continuous flood irrigation. The calculated amount of methane emission (Fig. 7) is in agreement with the methane emission as reported by Wassmann et al. (2000) and Liang et al. (2016). Based on the FAOSTAT (2018) dataset (Fig. 1) in 2014 from these six countries, 1,075,304 Gigagram of CO_2 equivalent was emitted from agriculture, and 282,242 Gigagram was from rice field (26%). The SRP PI for GHG does not include nitrous oxide emissions. A recent paper highlights that more research is required on the trade-off between CH_4 and N_2O emissions and yield under irrigated rice production systems (Kritee et al., 2018).

5. Conclusions

Assessment of the SRP PIs provide knowledge-based decision support for input optimization and crop management to narrow the rice yield gap, increase economic returns and decrease environmental problems in major rice producing six East Asian countries. Proper characterization of the rice production inputs would assist in setting research prioritization, development of efficient and improved rice production technologies, and efficient delivery mechanism considering sustainability, costs, scales of adoption, and socio-economic and environmental impact. Indicators can be used to assess the sustainability of rice production. The baseline and target values sets a roadmap for systematic innovation and sustainable intensification. The indicators highlight the gaps (yield, profit, labor productivity, and water productivity) and the potential to decrease the pesticide use especially in Vietnam, which in turn underlines the enormous potentiality of SRP PIs for measuring and progressing towards the economic and environmental sustainability of intensive lowland rice production with a low environmental footprint.

Eight PIs are adequate to assess the economic and environmental sustainability of rice production and the Field Calculator can be used as a decision support tool to optimize crop management practices with a low environmental footprint. Analysis of trade-offs between different production inputs can be useful for identifying sustainable rice intensification strategies, as well as for impact assessment, technology comparison, and country comparison. We show that a mix of agronomic and economic data can be integrated using appropriate indicators, which in turn demonstrate that closing yield and profit gaps with reduced environmental footprint and sustainability is not fiction, but a reality.

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