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On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators

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ABSTRACT

The intensification of rice production in the Mekong delta (MKD) has helped to address food security in Vietnam and in the region. However, the overuse of inputs coupled with the rising production costs are making it increasingly difficult for smallholder rice farming in the MKD to remain economically and environmentally sustainable. Thus, there is a widely recognized need to improve the sustainability of rice cultivation in the delta. Since 2003, the Vietnam Ministry of Agricultural and Rural Development has led several initiatives to improve rice crop management practices in the MKD, including the 'One Must Do, Five Reductions' (1M5R) integrated technology package and the 'Small Farmer Large Field' (SFLF) model. Under the SFLF model, some contract farming with high-quality rice exporters in MKD are also based on Good Agriculture Practice (GAP) standards, such as GlobalGAP and VietGAP, that farmers must follow for accreditation.

As part of an adaptive research platform, we conducted a household survey of GAP (VietGAP and GlobalGAP), SFLF and conventional (CNV) farmers in Can Tho province in the MKD and established replicated production-scale field trials of 1M5R, with an emphasis on further reducing seed and pesticide inputs by applying limits on their use. We assessed the sustainability performance of 1M5R and the three different management approaches for rice production (i.e. GAP, SFLF and CNV) over two rice cropping seasons using eight farm-level Sustainable Rice Platform (SRP) performance indicators.

We demonstrated that application of 1M5R with clear limits for input use can substantially improve the sustainability of rice production in the MKD through reducing inputs that can have environmentally negative impacts (i.e. fertilizers and pesticides). In the treatment fields, mean total production cost per season fell by 23% (203 USD ha^{-1}) and mean net income increased by 19% (175 USD ha^{-1}), resulting in a 28% increase in the benefit: cost ratio. Five of eight farm-level SRP indicators showed an improvement in sustainability performance, whilst yield, labor productivity and water productivity were maintained. Farmers implementing GAP and SFLF management approaches were slightly more sustainable than CNV farmers, although there is scope for further improvement, especially with regards to reducing rice seed and pesticide application rates. We propose possible strategies to increase adoption of more sustainable crop management practices in the MKD.

1. Introduction

With a growing human population, increasing per-capita food demand and decreasing agricultural land area, there is global pressure to increase food production on the remaining agricultural land (Godfray et al., 2010; GRiSP, 2013; McKenzie and Williams, 2015). Through agricultural intensification, crop productivity has dramatically increased since the 1960s (Hazell, 2009; Pingali, 2012; Petersen and

Abbreviations: AWD, alternate wetting and drying; BPH, brown planthopper; CNV, conventional practice; DS, dry season; FP, farmer's practice; GAP, Good Agricultural Practice; GHG, greenhouse gas; IP, improved practice; MKD, Mekong delta; NUE, nutrient use efficiency; PI, performance indicator; PUE, phosphorous use efficiency; SFLF, Small Farmer Large Field; SRP, Sustainable Rice Platform; WS, wet season; WUE, water use efficiency; 3R3G, Three Reductions Three Gains; 1M5R, One Must Do Five Reductions

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Snapp, 2015). However, the increased use of agricultural inputs associated with agricultural intensification has contributed towards a number of negative human health and environmental consequences, including increased greenhouse gas (GHG) emissions, biodiversity loss and degradation of the agricultural resource base; all imparting threats to the long-term sustainability of food production (Pingali, 2012; Blasi et al., 2016; Berg et al., 2017). There are thus concerns that the productivity of many intensive systems cannot be maintained with current management practices (McKenzie and Williams, 2015). Higher productivity per unit area also does not necessarily equate to better livelihoods for farmers, especially when agrochemicals are overused (McKenzie and Williams, 2015; Tu, 2015). In addition, farmers have a responsibility as natural resource managers to minimize their negative impacts on natural resources and associated ecosystem services that are also valuable to society (Blasi et al., 2016). To ensure the long-term sustainability of agricultural production, there is a need to move towards more eco-efficient management strategies (Tilman et al., 2001; Keating et al., 2010; Shennan et al., 2017) and a balance is required between maximizing profit for economic viability, maintaining productivity to meet global food demands, and minimizing negative effects on the environment and social well-being. Rice is the staple food for more than 4 billion people in Asia (GRiSP, 2013), thus there is an urgent need to analyze rice-based farming systems to identify promising options for economic, environmental and social sustainability.

In Vietnam, much attention has been given to increase rice production in the low-lying delta regions, namely the Red River delta and the Mekong delta (MKD), over the past 30 years. Since 1995, Vietnam's annual rice production has almost doubled, increasing from 25 million t in 1995 to 45 million t in 2014 (GRiSP, 2013), through an expansion of irrigated rice areas accompanied with increases in crop yields (3.7 to 5.8 t ha^{-1}), and in the number of crops grown per year (Kontgis et al., 2015). So much so, that Vietnam is now exporting 16% of its annual rice production and has become one of the world's biggest exporters of rice, thus making an important contribution to global food security (USDA-FAS, 2016; Thang et al., 2017).

The MKD, the world's third largest delta, comprises 45% of Vietnam's rice production area and produces almost 57% of Vietnam's total rice output (Tong, 2017). However, the rapid intensification of rice production in this region from the late 1990s resulted in an overreliance on agrochemicals and farmers adopting attitudes such as 'more is better' to achieve high yields no matter the economic and environmental cost (Huelgas and Templeton, 2010). For example, over the period 1990–2004, seed rates and nitrogenous fertilizer use doubled, from 95 to 144 kg ha^{-1} and 70 to 140 kg ha^{-1}, respectively, far exceeding the locally recommended rates (Huan et al., 2008). Overuse of inputs coupled with the rising production costs, which have outpaced nominal increases in producer paddy prices (Demont and Rutsaert, 2017), are making it increasingly difficult for smallholder rice farming in the MKD to remain economically and environmentally sustainable (Tu, 2015; Tong, 2017). As well as the associated economic and environmental costs, high seed, pesticide and nitrogen fertilizer rates can lead to favorable conditions for pests and diseases, excessive tiller production and lodging (Stuart et al., 2014; Wang et al., 2014; Horgan, 2017).

To address such issues, the Vietnam Ministry of Agricultural and Rural Development in collaboration with the Irrigated Rice Research Consortium, launched the 'Three Reductions, Three Gains' (3R3G) integrated technology package in 2003, aiming to reduce seed rates, nitrogen fertilizer and insecticides, while maintaining yield, improving farmers' health and protecting the environment (Rejesus et al., 2014). This was proclaimed a national priority in Vietnam during 2006 and soon after formed the basis for 'One Must Do, Five Reductions' (1M5R) integrated technology package. 1M5R or 'Mot Phai, Nam Giam' is certified by a Presidential decree (532-QD-TT-CLT) as the national policy to promote best management practices in lowland rice cultivation. The focus of 1M5R is to use good-quality seeds (the one must do) and to reduce seed rates, pesticide use, fertilizer inputs, water use, and postharvest losses.

Building on 1M5R in an attempt to focus on rice quality and adding value rather than quantity of rice, a government model, 'Small Farmers, Large Field' (SFLF), also known as the 'Large Field Model' was introduced in the MKD to increase access by farmers to contract farming and high quality export markets, enabling them to increase their competitiveness, effectiveness and income (Thang et al., 2017). SFLF enables smallholder farmers to benefit from economies of scale by helping them to form farmer organizations that will improve their bargaining power and form contracts with traders and exporters. One of the requirements for SFLF rice farmers in the MKD is that they should follow the 1M5R recommendations.

Complementary to SFLF, some high-quality rice exporters in the MKD also have developed contracts with SFLF farmers who are willing to become certified for Good Agriculture Practice (GAP) standards such as GlobalGAP and VietGAP. These standards can fetch higher prices in certain niche markets where consumers are willing to pay for them (Demont and Rutsaert, 2017). GlobalGAP is a global standard developed by the Food and Agriculture Organization of the United Nations for the certification of production processes of agricultural products and VietGAP is an agricultural production standard issued by the Vietnam Ministry of Agricultural and Rural Development. Both standards have criteria related to the environment, food safety and farm worker health and safety that farmers must follow for accreditation (Demont and Rutsaert, 2017). Furthermore, in 2015, the Vietnam Sustainable Agriculture Transformation Project (VnSAT) was initiated (World Bank, 2015). One of the main project objectives includes improving rice farming practices and value chains in the MKD by scaling out adoption of 1M5R and SFLF. To assess adoption of improved farming practices, the project proposes to set standards for the application of 1M5R and establish key performance indicators.

Farmer participatory experiments on 3R3G and household surveys (conducted between 2003–2007) following the promotion of 3R3G and 1M5R have shown that using higher quality seed and reducing pesticide, seed, fertilizer and water inputs have increased farm yields and profits in the MKD (Huan et al., 2005, 2008; Huelgas and Templeton, 2010; Singleton et al., 2011). However, there remain concerns that inputs, such as pesticides, amongst rice farmers in the MKD are still too high (Berg, 2001; Tong, 2017). Huan et al. (2008) and Huelgas and Templeton (2010) reported that although reduced,the seed, pesticide and N rates were still above the recommended rates a few years after campaigns to promote 3R3G. In addition, Escalada et al. (2009) reported that the frequency of insecticide application increased from 1.2 to 2.5 sprays per season between 2002 and 2007. This is consistent with recent pesticide import trends into Vietnam that indicate an increase in pesticide use between 2003 and 2012 (Schreinemachers et al., 2015). Thus, there is still a need for Vietnamese rice farmers to improve their crop management practices to optimize rice productivity and to reduce the negative environmental impact of rice production.

To promote sustainable rice cultivation, the Sustainable Rice Platform (SRP) recently developed a SRP Standard along with Performance Indicators (PIs) based around a framework for economic, social and environmental sustainability (SRP, 2015a, b; Demont and Rutsaert, 2017). The Standard provides guidance on how to achieve sustainable rice cultivation and the PIs are used to assess improvements in sustainability following adoption of best management practices. The 12 SRP PIs comprise of grain yield, profitability, labor use, food safety, water-use efficiency (WUE), nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), pesticide use, GHG emission, child labor, worker health and safety, and women empowerment (SRP, 2015a).

As part of an adaptive research platform rolled out in six countries in Asia (see Stuart et al., 2016, 2017), we conducted a household survey of GAP, SFLF and conventional (CNV) farmers in Can Tho province in the MKD, followed by replicated production-scale demonstration field trials of 1M5R, with an emphasis on further reducing seed and pesticide

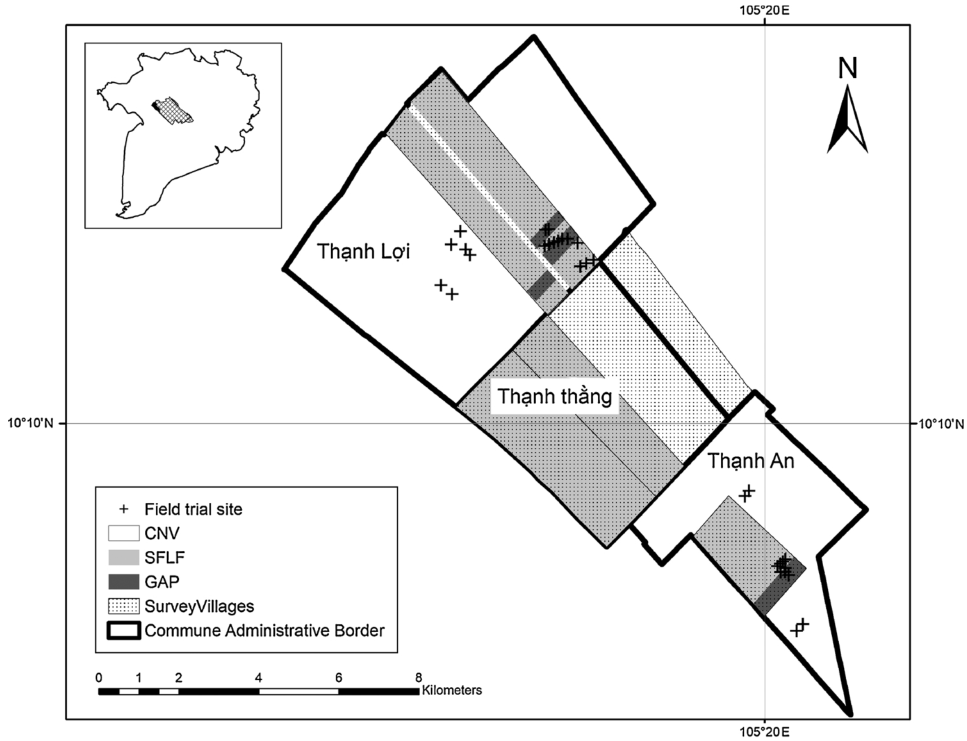

Fig. 1. Location of househould survey villages and GAP (VietGAP/ Global GAP), Small Farmer Large Field (SFLF) and conventional practice (CNV) field trial sites in Vinh Thanh district, Can Tho, South Vietnam. Each cross refers to one field trial site and the polygons refer to a group of fields under the same management approach.

inputs by applying limits on their use. Applying eight of the 12 SRP PIs, the objectives of this study were to 1) assess the sustainability performance of three different management approaches for rice production in the MKD (i.e. GAP, SFLF and CNV) and 2) evaluate whether this can be improved by setting more specific standards for 1M5R. These findings can be used to inform national agricultural development programs, such as the Vietnam Sustainable Agriculture Transformation Project. We hypothesize that GAP and SFLF farmers will have a higher sustainability performance score than CNV farmers, and the sustainability performance of farmers from all three management approaches will be enhanced when following improved 1M5R practices.

2. Methods

2.1. Study sites

A household survey and on-farm field trials were conducted in three communes (Thạnh Lợi, Thanh thắng and Thạnh An) in Vinh Thanh district, Can Tho province in the Mekong river delta (10°12′N 105°17E; See Fig. 1) where rice farming is the primary livelihood. At these sites, rice is mostly grown twice a year, i.e. the Winter-Spring or dry season (DS) crop is from November to March and the Summer-Autumn or wet season (WS) crop is from April to July. Seasonal weather data including rainfall and mean temperature values in Can Tho, Vietnam for the period from January 2014 to December 2015 are presented in Fig. 2. At the start of the WS, irrigation water is required during land preparation before the onset of the monsoon rains, whereas, at the start of the DS, fields have to be drained of floodwaters. The mean farm size is 2.1 ± 0.1 ha, with acid sulphate clay soil type (Stuart et al., 2016). The predominant crop establishment method is wet direct-seeding with broadcasted pre-germinated seed and a majority of farmers use four-wheel tractors for land preparation and combine harvesters for harvesting.

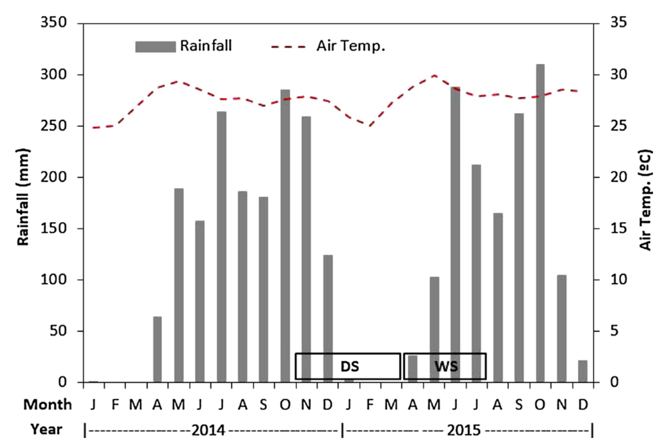

Fig. 2. Monthly rainfall and mean temperature values in Can Tho, Vietnam for the period from January 2014 to December 2015. The dry season (DS) and wet season (WS) cropping periods of the field trials are indicated.

2.2. Household survey

Prior to the implementation of field trials, farmers in three communes (Thạnh Lợi, Thanh thắng and Thạnh An; see Fig. 1) were interviewed in August 2013 (73 farmers), and July 2014 (79 farmers), to collect information about rice production in the previous cropping season. Detailed information were collected on their management practices, production costs and production output. From a total of 155 farming households in the three communes, farmers were randomly selected from three different management approaches: GAP, SFLF and CNV practice. GAP farmers were SFLF farmers who had received either GlobalGAP or VietGAP certification. SFLF farmers participated in SFLF but not GAP. CNV farmers were those not participating in either GAP or SFLF (see Fig. 3). The target sample size was 20 to 40 farmers per management approach (i.e. 20 GAP farmers, 20 SFLF farmers and 40

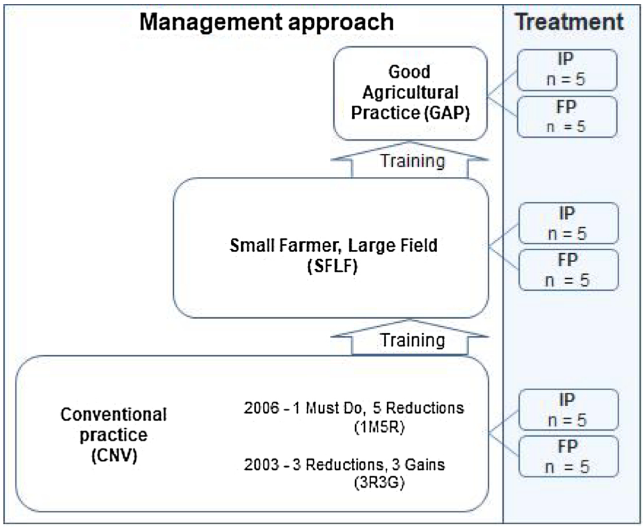

Fig. 3. Schematic diagram to illustrate the progression of farmers from conventional practice (including potential exposure to government campaigns on 'Three Reduction, Three Gains' from 2003 and 'One Must Do, Five Reductions' from 2006) to Small Farmer Large Field and Good Agriculture Practice (VietGAP/ Global GAP), and the assignment of field trial treatments (IP, Improved practice; FP, farmer's practice) to each management approach.

CNV farmers in the 2013 DS, and 20 GAP farmers, 30 SFLF farmers and 30 CNV farmers in the 2013-14 WS), but some of the selected farmers were unavailable for interview during the survey.

2.3. Field trial design and treatment details

On-farm field trials were conducted for three management approaches for rice production, i.e. GAP (VietGAP or GlobalGAP), SFLF and CNV practice (See Fig. 3). For each management approach, five replicate sites were selected and a block design consisting of an 'improved practice' field (coded as IP) and a 'farmer's practice' field (coded as FP) was established in each site (Table 1). Each field was about one hectare (ha). The FP field was adjacent or nearby the IP field and owned by a different farmer to that of the IP field. Farmers were selected based on the willingness to participate in the field trials. All farmers within the same commune planted the same rice variety and the same fields were used for both seasons.

For all IP fields, land preparation, fertilizer application, and pest management followed improved 1M5R recommendations (see Table S1), while farmers followed their usual practices (related to the management approach, i.e. GAP, SFLF, CNV) in FP fields. The improved 1M5R recommendations included the general recommendations provided for 1M5R (My Phung et al., 2014), as well as the following guidelines, i.e. apply seeds using a manually-pulled drum-seeder at a rate of 80 kg ha^{-1}; pesticide use should only be conducted following consultation with government extension staff, with a proposed limit of two formulated product applications per pesticide group per season; insecticides should not be applied within 40 days of sowing; fungicides should not be applied after the flowering stage; clean the combine harvester regularly to avoid spillage of grain; and the combine operator should thresh rice slowly at the correct drum speed to minimize losses. The pesticide guidelines were developed in line with the SRP Standard (SRP, 2015b). In this study, we were not able to distinguish between fungicides and bactericides because some are sold together as one product. Thus, from here onwards we will refer to both as fungicides. None of the farmers applied organic fertilizers.

Before the start of the field trials, the treatment farmers received on-site briefing and training sessions on the improved 1M5R recommendations. All farmers were asked to record their farming practices, i.e. the amount and timing of inputs applied, and the associated economic costs from land preparation to harvesting in a farmer diary. These data were used to compute inputs and production costs for each plot.

In the treatment fields, seed was directly sown using a manually-

Table 1
Summary of field activities for the improved practice (IP) and farmers' practice (FP) fields in Thanh Lợi and Thanh An communes in Vinh Thanh, Can Tho, Vietnam from November 2014 to August 2015.

Activity/operation	Thanh Lợi - IP	Thanh Lợi - FP	Thanh An - IP	Thanh An - FP
Plot size (ha)	1	1	1	1
No. of replicates	3	3	2	2
Crop establishment	Drum seeding	Broadcast seeding	Drum seeding	Drum seeding
Cultivar				
DS	Jasmine-85	Jasmine-85	Jasmine-85	Jasmine-85
WS	OM5451	OM5451	DS1	DS1
Seed quality	Certified seeds	Certified seeds	Certified seeds	Certified seeds
Date sown				
DS	20 Nov–01 Dec	19 Nov–2 Dec	04–05 Dec	4–6 Dec
WS	29 Mar–11 Apr	21 Mar–11 Apr	23–30 Apr	23–30 Apr
Fertilizer application timing (DAS)				
DS				
1st	10–14	7–12	9–13	8–12
2nd	22–32	16–28	19–25	21–25
3rd	40–46	24–48	42–43	40–43
WS				
1st	1-12	1–25	10–12	0–12
2nd	9-23	8–22	24–29	10–28
3rd	22-42	19–39	47–59	24–53
Date harvested				
DS	3-18 Mar	4–18 Mar	19-22 Mar	19–21 Mar
WS	1-16 Jul	25 Jun–14 Jul	11–18 Aug	11–18 Aug
Speed of combine				
DS	Slow	Conventional	Slow	Conventional
WS	Conventional	Conventional	Slow	Conventional

IP, Improved practice; FP, Farmer's practice; DS, Dry season; WS, Wet season; DAS, Days After Sowing.

pulled drum seeder. All treatment fields were puddled and leveled thoroughly, and excess water was drained before sowing, without allowing the soil surface to become dry. Rice seeds were submerged in 15% NaCl solution for 15 min to remove grain seeds which floated to the surface because they were either empty, partially empty, damaged by pests or infected with bakanae disease. Good seeds were pre-germinated by soaking in water for 24 h and incubated for another 24 h. The sprouted seeds were air-dried in shade for 10–15 minutes before sowing to facilitate the separation of seeds. The drum seeder was calibrated for a seeding rate of 80 kg ha^{-1}. Before sowing, three subsamples of 100 seeds per lot of seeds were evaluated for germination rate.

In the IP fields, PVC field water tubes were installed and used to determine when to irrigate the fields based on 'alternate wetting and drying' (AWD) recommendations (see Stuart et al., 2018). AWD is a water-saving technique that is widely introduced in a number of countries in Asia, wherein the field is allowed to be alternately flooded and non-flooded (Bouman et al., 2007). In the FP fields, irrigation was applied as the farmer's usual practice. SFLF and GAP farmers in both communes were already implementing AWD prior to the start of this study, thus FP farmers following SFLF and GAP management approaches continued to apply this practice. The usual practice for CNV farmers is continuous flooding.

At the end of each season, farmer field days were organized to promote and evaluate the technologies and practices, and to facilitate farmer learning through an adaptive research approach (Flor et al., 2016).

2.4. Measurements and data collection

Most data were collected by farmers and recorded in farmer diaries, which were checked by the government extension staff once a week. The grain yields reported were determined from four 10 m^2 crop cuts manually harvested per plot on the same day as harvest. These were randomly sampled along a cross-diagonal transect. The mean moisture content was calculated from three random samples per crop cut and grain yields are expressed at 14% moisture content (MC).

2.5. Computation of SRP performance indicators

From a total of 12 SRP PIs (SRP, 2015a), we were able to compute five PIs from the household survey data and eight PIs from the field trial data. Net profit, labor productivity, grain yield, WUE, NUE, PUE, pesticide use, and GHG emission were computed using the procedures as defined by SRP (2015a). Questions relating to the remaining SRP PIs, i.e. food safety, child labor, worker health and safety, and women empowerment were not included as part of this study. In the household survey, questions relating to labor, pesticide use or GHG emissions were not included. However, to compare pesticide practice between management approaches, the total frequency of formulated pesticide product applications are reported instead.

To compute net profit, the total production cost was deducted from the gross income. The total production cost included the costs for all inputs, labor, machine hire and land rent required for all farm activities from land preparation to harvesting. These included non-paid out costs that were imputed from family labor and the land rental equivalent for cost of lost opportunity. The gross income was computed based on the fresh grain yield (measured from crop cuts) and the farm-gate price reported by each farmer. The benefit:cost ratio was computed as the gross income divided by the total production cost.

To compute labor productivity, both hired and own (family) labor of male and female laborers were considered and the number of labor days per season (for all activities from land preparation until harvest, including regular field visits by farmers) were estimated by dividing the total labor cost per season by the average daily wage rate at the time taken across all activities (i.e. VND 150,000/ day). WUE, i.e. the total amount of recovered yield per input of water (SRP, 2015a), was measured by either total water productivity or irrigation water productivity. Total water productivity (kg m^{-3}) was computed as the sum of the amount of water applied from irrigation and rainfall. Daily rainfall data were collected at the Can Tho Meteorological Center, located within 50 km of the field trial sites. The amount of irrigation water applied was derived from the total hours of pumping during each irrigation event from land preparation to harvest and the approximate depth of water afterwards, assuming a deficit of 15 cm below the soil surface. Not all farmers reported their irrigation activity during land preparation at the start of the WS. Based on the information from record keeping farmers, an average value of 150 mm of water input during land preparation was estimated for all fields. Irrigation water productivity (kg m^{-3}) was computed from irrigation water alone, without rainfall.

To compute phosphorous (P) and potassium (K) application rates, the amount of P_2O_5 and K_2O for each fertilizer application was determined and multiplied by a factor of 0.4364 and 0.8302, respectively, to convert them into the elemental form. To compute NUE, PUE and KUE, the total grain yield harvested was divided by the elemental nitrogen (N), P or K and the efficiency expressed in terms of kg grain kg^{-1} elemental N, P or K. Even though KUE is not included as an SRP PI, we include KUE due to its importance for rice productivity.

Pesticide use was scored using the SRP scorecard (SRP, 2015a), which is based on the number and timing of application of different categories of pesticide, i.e., herbicide, insecticide, fungicide, rodenticide and molluscicide (see Table S2). The overall score was calculated by adding the scores of each category of pesticide. The maximum score of 10 points per pesticide category was scored when no pesticide was used, with a total attainable score of 50 points. No bird control was applied by farmers in this study, thus the scoring category for bird control was omitted.

Based on the assumption that during rice cultivation, methane (CH_4) emission is the largest contributor to global warming potential (SRP, 2015a; Liang et al., 2016; Tariq et al., 2017), the amount of CH_4 emitted per unit of land area was used as a proxy for GHG emission (expressed as CO_2 equivalent emission) and computed using the following formula given by IPCC (2006):

$$CO_2 \text{ equivalent emission } (kg\ ha^{-1}) \text{ from a season} = EF_c\ x\ SF_w\ x\ ESF_p\ x\ SF_o\ x\ T_i\ x\ 25 \quad (1)$$

Where,

EF_c = baseline emission factor for continuously flooded fields without organic amendments, kg CH_4 $ha^{-1}d^{-1}$ = 1.30.

SF_w = scaling factor to account for the differences in water regime during the cultivation period

SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period

SF_o = scaling factor should vary for both type and amount of organic amendment applied

Ti = Cultivation period (growing duration) of a rice variety

For the computation of SF_0, the below equation (II) was used:

$$SF_o = (1 + \Sigma_i ROA_i \times CFOA_i)^{0.59} \quad (2)$$

Where,

ROA_i = application rate of organic amendment i, in dry weight for straw, t ha^{-1}

$CFOA_i$ = conversion factor for organic amendment i (in terms of its relative effect with respect to straw applied shortly before cultivation) as shown in Table 5.14 (IPCC, 2006).

For the computation of GHG emission as required by IPCC (2006), the amount of organic material incorporation in each season, time of pre-rice crop residue incorporation, pre-rice water regime (irrigation status) and irrigation regime during the crop growing period, were requested from the respective farmers. To compute GHG emission from residue burning, a value of 4.51 g CH_4 emission kg^{-1} residue burning was used (Romasanta et al., 2017). Straw yield was computed assuming a 48% harvest index of rice (Dobermann et al., 2004). Calculations related to straw yield and management were based on data from the preceding season. For the computation of GHG for the 2015 DS, we used data from the 2015 WS.

2.6. Arthropod and disease monitoring

During the 2015 DS, arthropods and diseases were monitored by trained government extension staff in each of the IP and FP fields at seedling (4–12 DAS), tillering (30–35 DAS), booting (55–60 DAS) and flowering (65–70 DAS) crop growth stages. Five quadrats (40 x 50 cm) were randomly placed along a cross diagonal transect in each plot. In each quadrat, numbers of brown planthoppers (BPH; *Nilaparvata lugens* Stal) and their natural enemies, such as spiders, ladybird beetles (family *Coccinellidae*), mirid bugs (*Cyrtorhinus lividipennis* Reuter) and rove beetles (*Paederus fuscipes* Curtis), were counted. Other arthropod pests of rice were not recorded due to low occurrences. Disease occurrence was recorded by recording the presence of disease within each quadrat.

2.7. Data analysis

Statistical analyses were carried out using SPSS version 24 (SPSS Inc., Chicago, IL, USA). For the household survey data, univariate GLM was used to compare the three different management approaches for each season separately. For the field trial data, linear mixed models with maximum likelihood estimation were used to analyze differences between treatments and management approaches over the two cropping seasons. The fixed effects entered into the model included season (as a repeated variable with diagonal repeated covariance), treatment and management approach. Site was included as a random effect with no intercept to account for the block design. Dependent variables that produced non-normally distributed residuals were analyzed using log or square-root transformation. Pairwise comparisons of main effects were conducted using the Bonferroni test. Linear regression was used to measure the strength of the linear association between the SRP pesticide PI score and the number of pesticide product applications.

3. Results

3.1. Household survey of farmer groups prior to field trials

During the 2013 WS and 2013–2014 DS, the farmers surveyed in Vinh Thanh district, Can Tho province, had mean grain yields of 4.82 ($\pm$ 0.11 SE) and 7.79 ($\pm$ 0.14 SE) t ha^{-1}, respectively. During the 2013 WS, SFLF farmers had 23–26% higher yields than GAP and CNV farmers, respectively ($p < 0.05$), whilst applying significantly fewer pesticide applications than CNV farmers (by a mean of 28%; Table 2). Both GAP and SFLF farmers were also significantly more efficient in their N, P and irrigation water use than CNV farmers. SFLF farmers were 17% more efficient in K use than GAP farmers, even though they applied 37% more K ha^{-1}. The mean net incomes of GAP and SFLF farmers in the 2013 WS were 21% and 24% higher than CNV farmers, respectively. This is partly because of lower total production costs, higher yields by SFLF farmers and because GAP farmers were able to get a 17% higher farm gate price for their rice (VND 5700 kg^{-1}) during that season.

During the 2013–2014 DS, there was no significant difference in yield between management approaches. Compared with CNV farmers, farmers who adopted GAP and SFLF management approaches applied 17% and 30% fewer pesticide product applications per season respectively. The mean net income of GAP farmers in the 2013-14 DS was 28–30% higher than SFLF and CNV farmers. The increase in income was from lower production cost from fewer inputs (seed, fertilizer, water and pesticides) and 9% higher farm gate rice prices (VND 6000 kg^{-1}). The mean net income of SFLF farmers was only 1.7% higher than CNV farmers and in contrast to the WS, SFLF farmers were significantly less efficient in K use than GAP farmers during the DS, applying 44% more K ha^{-1} than GAP farmers.

3.2. On-farm field trial of integrated best management approaches

3.2.1. Rice production inputs

Across both seasons, seed, N, P, and K application rates were significantly reduced in the IP fields as compared to the FP fields by a mean of 47, 3, 25, and 7%, respectively (Tables 3 and 4). All farmers in the IP fields applied seeds using a manually-pulled drum seeder, following the recommended seed rate of 80 kg ha^{-1}. Meanwhile, farmers in the FP fields used either broadcasting (Than Loi village) or drum seeding (Than An village) methods with seed rates ranging from 120-200 kg ha^{-1} and 102-170 kg ha^{-1}, respectively. N application rate was higher in the DS than in the WS and there was a significant interaction between management approach and season (Table 4). During the WS, CNV farmers applied 16–25% more N than GAP and SFLF farmers, respectively. Amongst the FP farmers only, CNV farmers applied 21–54 % more K than farmers following the other management approaches ($P > 0.05$).

There was a 57% reduction in the number of pesticide applications per season in the IP fields as compared to the FP fields (Fig. 4 and 5; Tables 3 and 4). Both IP and FP farmers applied herbicides, molluscicides, fungicides and insecticides, with the fungicides and insecticides contributing 30% and 53% of the total number of pesticides applied in FP fields. During the DS, IP farmers applied 1–3 insecticide (1.27 $\pm$ 0.15) and 1–5 fungicide (2.80 $\pm$ 0.24) applications, whereas FP farmers applied 3–12 insecticide (5.40 $\pm$ 0.63) and 5–12 fungicide (8.73 $\pm$ 0.50) applications. In the WS, four IP farmers applied one insecticide, with none applied by the other IP farmers, whereas all FP farmers applied at least two insecticides (3.73 $\pm$ 0.36). No IP farmers applied insecticides within the first 40 days after sowing, whereas, 67% and 93% of FP farmers in the DS and WS, respectively, applied insecticides during this early crop stage. Furthermore, 70% and 95% of the total number of insecticide product applications applied by FP farmers in the DS and WS, respectively, were applied within the first 60 days after sowing (before the flowering stage). During both seasons, the majority of farmers only applied one pre-emergence herbicide and one molluscicide.

3.2.2. SRP performance indicators

The mean grain yield was 64% higher in the DS than in the WS (Table 4). Individual field yields ranged from 6.32 to 8.98 t ha^{-1} in the DS, and 3.96 to 6.21 t ha^{-1} in the WS (Table 3). There was no significant difference in grain yield between treatments.

Over both seasons, IP increased the NUE, PUE and KUE of rice production by 12%, 28% and 23% over FP, respectively (Tables 3 and 4; Fig. 5). Due to higher grain yield in the DS, NUE, PUE and KUE were significantly higher this season. When comparing management approaches, PUE was 14% higher in the GAP fields than in the CNV fields ($P > 0.05$).

The mean SRP pesticide PI score was 36% higher in the IP fields than in the FP fields (Tables 3 and 4; Fig. 5). The difference in pesticide score between treatments was more pronounced in the WS, with mean scores of 30 and 21 (out of 50) for IP and FP fields, respectively. During the DS, the mean scores were 25 and 19, respectively. There was no difference in pesticide score between management approaches. When measuring the strength of linear association between the SRP pesticide PI score and the number of pesticide product applications, there was a significant negative linear association for fields that had < 13 applications per season ($R^2 = 0.635$, d.f. = 35, $P < 0.001$), but there was no association for fields that had > 12 products applied ($R^2 = 0.279$, d.f. = 21, P = 0.197; Fig. S1).

Fields in the DS had significantly higher total water productivity

Table 2
Key performance indicator values (mean followed by SE in parenthesis) of different management approaches of farmers surveyed in Can Tho province, Vietnam. Management approaches are categorized as: GAP, VietGAP/ Global GAP; SFLF, Small Farmer Large Field; CNV, conventional practice.

	Management Approach									
	GAP			SFLF			CNV			*P*
2013 WS	(n = 20)			(n = 15)			(n = 38)			
Grain yield (t ha^{-1})	4.66	(0.17)	a	5.72	(0.17)	b	4.55	(0.16)	a	***
Nitrogen-use efficiency (grain kg N kg^{-1})	57.88	(2.48)	a	63.62	(3.77)	a	48.00	(2.15)	b	**
Phosphorus-use efficiency (grain kg P kg^{-1}) [a]	101.3	(7.77)	a	103.0	(6.58)	a	77.30	(4.80)	b	**
Potassium-use efficiency (grain kg K kg^{-1}) [b]	105.2	(5.13)	a	123.2	(7.14)	b	103.2	(9.68)	ab	*
Irrigation water use productivity (grain kg m^{-3})	1.61	(0.11)	a	1.62	(0.16)	a	0.96	(0.05)	b	***
No. of pesticide applications	11.25	(0.95)	ab	9.40	(0.75)	bc	13.08	(0.64)	a	**
Total production cost (USD ha^{-1})	704.7	(30.31)	a	632.9	(39.17)	a	740.4	(25.74)	a	ns
Net income (USD ha^{-1}) [a]	623.0	(58.22)	a	632.0	(46.31)	a	328.2	(51.10)	b	**
2013-2014 DS	(n = 19)			(n = 30)			(n = 30)			
Grain yield (t ha^{-1})	7.38	(0.16)	a	7.81	(0.25)	a	8.03	(0.24)	a	ns
Nitrogen-use efficiency (grain kg N kg^{-1}) [a]	77.68	(2.65)	a	72.65	(2.81)	a	78.54	(2.18)	a	ns
Phosphorus-use efficiency (grain kg P kg^{-1}) [b]	177.5	(33.97)	a	129.0	(9.64)	a	123.0	(6.23)	a	ns
Potassium-use efficiency (grain kg K kg^{-1}) [b]	205.30	(13.72)	a	123.2	(7.15)	b	172.8	(19.87)	ab	**
Irrigation water use productivity (grain kg m^{-3}) [a]	2.59	(0.18)	a	2.32	(0.18)	a	2.21	(0.17)	a	ns
No. of pesticide applications [a]	12.61	(0.82)	a	14.80	(0.77)	a	17.90	(0.64)	b	***
Total production cost (USD ha^{-1})	654.3	(28.40)	a	805.7	(36.35)	b	847.3	(28.16)	b	**
Net income (USD ha^{-1})	1401	(69.39)	a	1,097	(70.42)	b	1,079	(60.31)	b	**

ns = $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
Means within a row followed by the same letter are not different at 0.05 probability level following pairwise comparisons.
[a] Analyzed using square-root transformed data.
[b] Analyzed using log-transformed data.

(1.88 kg m^{-3}) and irrigation water productivity (2.80 kg m^{-3}) than fields in the WS (0.50 kg m^{-3}; 1.17 kg m^{-3}, respectively; Tables 3 and 4). Total water input per field ranged from 292 to 738 mm in the DS, with 70% coming from irrigation, while in the WS it ranged from 746 to 1357 mm, with 56% coming from rainfall.

Labor productivity was 50% higher in the DS than in the WS (Tables 3 and 4). This is mainly a result of higher grain yield during this season as labor use was slightly lower in the DS (58.6 ± 0.6 days) than in the WS (64.9 ± 2.1 days). There were no significant differences in labor productivity between treatments and management approaches.

The mean CO_2 equivalent emission per field was 18% higher during the WS than during the DS (Tables 3 and 4). During both seasons, CNV fields had the highest mean CO_2 equivalent emissions, with higher emissions in the FP fields than in the IP fields (Table 3). The differences between CNV fields and SFLF and GAP fields were more pronounced during the DS (Table 4).

The mean total production cost per season in the IP fields was reduced by 23% (202 USD ha^{-1}) compared to the FP fields (Fig. 6, Tables 3 and 4). The mean net income and benefit:cost ratio were significantly higher for IP fields over FP fields (mean difference of 19% and 28%, respectively; see Fig. 5), although the difference in benefit:cost ratio between treatments was less pronounced for the WS. Overall, the mean production cost was 6% higher for the WS crop than for the DS crop (which is mainly attributed to higher harvesting costs), whereas the mean net income and benefit:cost ratio were 59% and 56% lower, respectively.

3.2.3. Arthropod and disease assessment

During the DS, significantly more BPH ($F_{1,14} = 33.810$, $P < 0.001$) and significantly fewer natural enemies ($F_{1,14} = 30.503$, $P < 0.001$) were recorded in the FP fields than in the IP fields, with the largest differences during the booting and flowering crop stages (crop stage*-treatment interaction for BPH and natural enemies: $F_{3,42} = 8.637$, $P < 0.001$; $F_{3,\ 42} = 11.492$, $P < 0.001$, respectively; Fig. 7). This timing corresponded to when insecticides and fungicides had been applied. For the disease assessment during the DS, rice blast fungus, *Magnaporthe grisea* (Hebert) Barr, was present in all fields from the tillering stage until the flowering stage. No other fungal, bacterial or viral diseases were detected.

4. Discussion

The intensification of rice production in the MKD has helped to address food security in Vietnam and in the region (GRISP, 2013). However, there is a widely recognized need to improve the sustainability of rice cultivation in the delta (Tu, 2015; Demont and Rutsaert, 2017; Tong, 2017). We demonstrated that application of IP in Can Tho province enabled smallholder farmers to improve the sustainability of their rice production through reducing inputs that could have considerable negative environmental consequences when overused (i.e. fertilizers and pesticides; Tilman et al., 2001) without compromising land productivity.

4.1. Comparison of management approaches for rice production

The results from the household survey indicate that the introduction of SFLF and GAP (GlobalGAP and VietGAP) contributed to significant reductions in inputs (i.e. N, P, water and pesticides) and increases in input use efficiency and profitability, especially during the WS. This may be attributed due to the increased training activities on 1M5R technology (Sato et al., 2014), higher yields for SFLF farmers in the WS and higher farm-gate rice prices for GAP farmers. The reason for the higher yields by SFLF farmers in WS is not clearly identifiable, but it is likely due to a combination of better management, e.g. nutrient management, and the use of a lower yielding premium rice variety by VietGAP farmers (n = 10). In the WS, KUE was significantly higher for SFLF farmers than for GAP farmers, suggesting that the KUE for GAP farmers can be improved. However, the increase in crop yield by SFLF farmers was disproportionate to the increase in K, suggesting that the KUE of SFLF farmers could be further optimized by slightly reducing K application rates. In support, KUE was significantly lower for SFLF farmers than for GAP farmers during the DS even though higher rates of K were applied.

When comparing the three management approaches across untreated FP fields during the field trials, GAP and SFLF farmers had reduced N fertilizer inputs in the WS, K fertilizer inputs and GHG

Table 3
Key inputs and outputs (mean values followed by standard error in parenthesis) of crop production across six field trial treatments during the 2015 dry and wet seasons in Can Tho Province. Management approaches are categorized as: GAP, VietGAP/ Global GAP; SFLF, Small Farmer Large Field; CNV, conventional practice. Statistical analysis can be found in Table 4.

	Improved Practice (IP)						Farmer's Practice (FP)					
	GAP		SFLF		CNV		GAP		SFLF		CNV	
2015 DS:												
Grain yield (t ha^{-1})[a]	7.42	(0.22)	8.22	(0.22)	7.68	(0.22)	7.92	(0.29)	7.72	(0.31)	7.73	(0.37)
Seed rate (kg ha^{-1})	80.0	(0.00)	80.0	(0.00)	80.0	(0.00)	148.0	(13.19)	148.8	(9.24)	154.6	(6.87)
Fertilizer rate (kg ha^{-1})												
Nitrogen (kg ha^{-1})	87.11	(2.18)	85.64	(4.17)	86.65	(2.71)	92.60	(6.10)	97.11	(7.51)	101.1	(5.79)
Phosphorus (kg ha^{-1})	17.34	(0.05)	20.09	(1.78)	18.35	(1.04)	22.64	(1.56)	24.87	(3.05)	27.91	(3.61)
Potassium (kg ha^{-1})	27.28	(0.97)	29.49	(2.27)	25.13	(0.11)	32.40	(3.42)	41.51	(4.27)	50.03	(12.04)
Nitrogen-use efficiency (grain kg N kg^{-1})	85.71	(4.85)	97.39	(7.38)	88.90	(3.29)	86.86	(5.58)	81.10	(6.00)	76.75	(2.25)
Phosphorus-use efficiency (grain kg P kg^{-1})	428.2	(12.60)	419.7	(31.36)	421.4	(15.65)	355.5	(23.01)	327.6	(39.31)	295.5	(35.65)
Potassium-use efficiency (grain kg K kg^{-1})	273.9	(14.66)	287.2	(28.09)	305.6	(9.75)	265.6	(50.84)	192.3	(17.43)	204.3	(62.10)
No. of pesticide applications	6.80	(1.11)	6.20	(0.73)	6.60	(0.60)	16.20	(2.22)	16.00	(1.05)	17.80	(1.36)
Pesticide score	24.20	(1.71)	24.20	(1.85)	24.40	(0.60)	19.40	(0.60)	18.80	(0.73)	18.80	(0.73)
Irrigation water productivity (kg m^{-3})	2.70	(0.34)	2.98	(0.42)	3.17	(0.23)	2.52	(0.38)	2.66	(0.36)	2.77	(0.54)
Total water productivity (kg m^{-3})	1.85	(0.20)	2.01	(0.22)	2.02	(0.12)	1.75	(0.18)	1.82	(0.18)	1.80	(0.25)
Labor productivity (kg days^{-1})	135.7	(3.88)	142.9	(4.67)	128.7	(6.52)	132.0	(2.09)	132.4	(7.66)	126.8	(5.02)
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	5789	(524.2)	5330	(319.7)	5610	(365.6)	5135	(329.8)	5209	(237.6)	9159	(667.3)
Total production cost (USD ha^{-1})	625.7	(10.25)	663.1	(16.39)	682.4	(18.61)	872.7	(18.77)	859.3	(34.40)	870.5	(31.59)
Cost per kg paddy (USD kg^{-1})	0.08	(0.00)	0.08	(0.00)	0.09	(0.00)	0.11	(0.00)	0.11	(0.01)	0.11	(0.00)
Net income (USD ha^{-1})	1343	(35.10)	1444	(43.14)	1261	(53.06)	1222	(70.86)	1189	(105.3)	1136	(71.15)
Benefit: Cost ratio	3.15	(0.05)	3.18	(0.06)	2.86	(0.11)	2.41	(0.10)	2.41	(0.17)	2.31	(0.07)
2015 WS:												
Grain yield (t ha^{-1})[a]	4.90	(0.41)	4.51	(0.24)	4.77	(0.34)	4.56	(0.34)	4.53	(0.22)	5.20	(0.38)
Seed rate (kg ha^{-1})	80.00	(0.00)	80.00	(0.00)	80.00	(0.00)	160.6	(20.58)	148.4	(20.56)	148.6	(20.42)
Fertilizer rate (kg ha^{-1})												
Nitrogen (kg ha^{-1})	75.57	(1.37)	71.09	(1.89)	88.76	(4.16)	89.33	(3.92)	82.12	(3.37)	102.8	(0.48)
Phosphorus (kg ha^{-1})	17.53	(1.25)	18.01	(1.55)	21.42	(1.80)	22.69	(3.14)	23.85	(1.71)	28.65	(1.41)
Potassium (kg ha^{-1})	27.43	(0.92)	31.55	(2.50)	26.43	(2.06)	29.12	(3.67)	32.20	(3.50)	37.26	(2.66)
Nitrogen-use efficiency (grain kg N kg^{-1})	64.49	(4.41)	63.41	(2.90)	54.47	(5.16)	50.78	(2.13)	55.31	(2.49)	50.65	(3.73)
Phosphorus-use efficiency (grain kg P kg^{-1})	283.8	(26.79)	258.0	(24.79)	230.9	(27.58)	221.1	(45.23)	192.4	(12.03)	185.8	(21.54)
Potassium-use efficiency (grain kg K kg^{-1})	181.0	(20.22)	146.3	(12.81)	187.0	(23.64)	170.9	(32.04)	145.3	(12.17)	140.5	(7.92)
No. of pesticide applications	5.60	(0.68)	6.60	(0.68)	7.60	(0.75)	12.60	(1.03)	14.20	(1.69)	14.20	(1.43)
Pesticide score	31.00	(1.87)	29.40	(1.69)	28.00	(2.21)	19.40	(0.60)	22.40	(1.66)	19.60	(2.18)
Irrigation water productivity (kg m^{-3})	1.18	(0.16)	1.06	(0.12)	1.15	(0.23)	1.20	(0.09)	1.26	(0.10)	1.14	(0.19)
Total water productivity (kg m^{-3})	0.51	(0.07)	0.46	(0.05)	0.50	(0.08)	0.48	(0.04)	0.50	(0.04)	0.52	(0.08)
Labor productivity (kg days^{-1})	81.58	(13.80)	73.61	(6.80)	76.54	(11.64)	71.55	(9.08)	71.81	(7.07)	83.93	(12.58)
Greenhouse gas emission (kg CO_2 equivalent ha^{-1})	4616	(279.9)	5066	(318.3)	4711	(240.6)	4862	(161.4)	4690	(184.5)	6858	(206.6)
Total production cost (USD ha^{-1})	698.2	(74.05)	696.1	(37.51)	736.1	(50.24)	922.1	(39.00)	852.9	(23.64)	936.7	(78.79)
Cost per kg paddy (USD kg^{-1})	0.15	(0.03)	0.16	(0.02)	0.16	(0.02)	0.21	(0.02)	0.19	(0.01)	0.19	(0.03)
Net income (USD ha^{-1})	669.7	(117.9)	636.3	(20.59)	593.3	(53.98)	377.9	65.13	482.2	(39.27)	515.0	(103.3)
Benefit: Cost ratio	2.07	(0.26)	1.93	(0.06)	1.84	(0.12)	1.42	(0.09)	1.56	(0.04)	1.60	(0.15)

[a] Adjusted to 14% MC.

emissions as compared to the CNV fields, whilst maintaining similar yields (see Tables 3 and 4). During the DS, however, there was no difference in N application rates or NUE between the three management approaches, with all applying higher than recommended N rates when comparing with the IP treatment application rates. Even though there was no significant difference in P use between management approaches during the field trials, the higher PUE for GAP fields in comparison with CNV fields for both treated and untreated fields suggests that further improvements in P use by CNV farmers can be achieved, as supported by the results of the IP treatment. The reduction in GHG emissions (as measured using CH_4 emissions) in GAP and SFLF fields was mainly attributed to the adoption of AWD, which has previously been demonstrated to significantly reduce CH_4 emissions with minimal effect on N_2O (Linquist et al., 2015; Liang et al., 2016; Tariq et al., 2017; Tirol-Padre et al., 2017). If well implemented, AWD can also reduce water use and pumping costs as has been reported elsewhere in southern Vietnam, Bangladesh and the Philippines (Lampayan et al., 2015). During the WS, WUE was slightly higher for GAP and SFLF fields as compared to untreated CNV farmers, although the difference was not significant.

When making comparisons using the SRP indicators, the GAP and SFLF farmers did not always outperform the CNV farmers. For example, during the field trials, there was no difference in pesticide use between management approaches, even though a reduction in pesticide application rates by SFLF and GAP farmers was indicated in the household survey. This may be due to the smaller sample size of the field trials or from changing practice over time. Production cost and net income during the field trials also did not differ between the three management approaches during the field trials. One explanation could be the minimal difference in pesticide use, which contributed to 21% of the total production cost of FP farmers. Another is that unlike in the household survey, the GAP farmers in the field trials did not receive a premium for their rice sold. This may perhaps be due to limited consumer demand for GAP certified rice, (Demont and Rutsaert, 2017), which poses a potential challenge to adoption and scaling out of GAP. Other weaknesses in the Vietnamese rice export sector that were identified by Demont and Rutsaert (2017) are poor linkages in the value chain and the lack of a national brand/ international reputation in international markets. These issues will need to be addressed to increase the success of certification schemes for the sector.

When assessing whether the differences in management approaches are consistent between seasons, only GHG and N application rates were significant for this interaction. GHG emissions were higher in the DS for the CNV fields, but this was mainly due to the local practice of straw

Table 4
Linear mixed model results of the effects of field trial treatment, management approach and season on input, output and economic variables during the 2015 dry and wet seasons in Can Tho Province.

Dependent variable	Treatment		Management		Season		Treatment* Management		Management* Season		Treatment* Season		Treatment* Management* Season	
	F	P	F	P	F	P	F	P	F	P	F	P	F	P
Seed rate (kg ha^{-1})	169.2	***	0.06	ns	0.04	ns	0.09	ns	0.25	ns	0.04	ns	0.25	ns
Nitrogen (kg ha^{-1}) [a]	42.11	***	5.85	*	15.32	***	0.36	ns	7.80	**	1.28	ns	0.69	ns
Phosphorus (kg ha^{-1})	39.35	***	3.63	ns	0.03	ns	1.07	ns	0.98	ns	0.06	ns	0.24	ns
Potassium (kg ha^{-1}) [a]	16.22	***	2.25	ns	1.49	ns	3.48	*	0.05	ns	3.42	ns	0.26	ns
Nitrogen-use efficiency (grain kg N kg^{-1})	12.08	**	2.69	ns	164.8	***	0.64	ns	0.66	ns	0.23	ns	2.40	ns
Phosphorus-use efficiency (grain kg P kg^{-1})	25.34	***	3.38	*	99.02	***	0.23	ns	0.36	ns	2.58	ns	0.38	ns
Potassium-use efficiency (grain kg K kg^{-1})	8.41	**	1.33	ns	38.10	***	1.56	ns	0.00	ns	2.65	ns	0.85	ns
No. of pesticide applications [a]	226.3	***	1.80	ns	2.85	ns	0.09	ns	0.89	ns	3.53	ns	0.67	ns
Pesticide score	83.81	***	0.62	ns	18.30	***	0.56	ns	0.67	ns	5.74	*	1.02	ns
Irrigation water use productivity (grain kg m^{-3})	0.41	ns	0.22	ns	113.0	***	0.11	ns	0.85	ns	1.77	ns	0.06	ns
Total water use productivity (grain kg m^{-3})	0.03	ns	0.07	ns	505.1	***	0.10	ns	0.65	ns	2.22	ns	0.13	ns
Labor productivity (kg days^{-1})	0.65	ns	0.03	ns	179.7	***	0.54	ns	1.43	ns	0.21	ns	0.37	ns
Greenhouse gas emission (kg CO_2 equivalent ha^{-1}) [a]	12.97	**	32.20	***	28.50	***	17.30	***	8.35	**	0.04	ns	0.21	ns
Grain yield (t ha^{-1})	0.04	ns	0.08	ns	588.0	***	1.31	ns	3.00	ns	0.01	ns	2.96	ns
Total production cost (USD ha^{-1})	91.73	***	0.73	ns	4.49	*	0.68	ns	0.55	ns	0.16	ns	0.13	ns
Net income (USD ha^{-1})	24.61	***	0.69	ns	437.8	***	1.01	ns	1.21	ns	0.01	ns	1.46	ns
Benefit:Cost ratio	82.85	***	1.21	ns	262.5	***	1.98	ns	0.96	ns	5.14	*	0.59	ns

ns = $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
[a] Analyzed using log-transformed data.

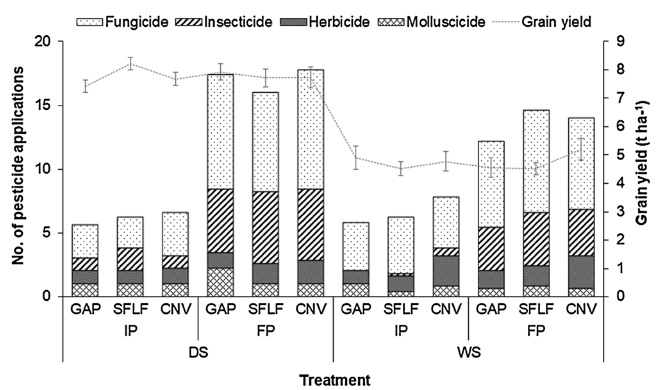

Fig. 4. Mean number of pesticide applications by pesticide group and mean grain yield in the improved practice (IP) and farmers' practice (FP) fields during the 2015 DS and WS rice crops. Management approaches are categorized as: GAP, VietGAP/ Global GAP; SFLF, Small Farmer Large Field; CNV, conventional practice. Standard errors are indicated for grain yield (n = 5).

residue incorporation at the start of the DS, whereas at the start of the WS, about 50% of the straw was burned. The calculations are based on a previous study that indicated burning straw emits a lower amount of GHGs as compared to straw residue decomposition under flooded conditions (Romasanta et al., 2017). However, this needs to be balanced against the atmospheric pollution caused by straw burning that is hazardous to human health as well as the environment (Miura and Kanno, 1997). Thus, alternative methods of straw management are needed to further mitigate GHG emissions in the MKD (Nguyen et al., 2017).

4.2. Improved management practices based on 1M5R

Following the application of improved management practices that were based on 1M5R recommendations along with clear thresholds for input use, the findings from our field trials highlight that seed, fertilizer (including N, P and K), pesticide and water inputs can be reduced by rice farmers in the MKD across all the management approaches assessed, without compromising yield. Similar results have been obtained in the MKD and in other intensive irrigated rice-producing regions in Asia following the application of improved management practices (Huan et al., 2005; Tin et al., 2008; Alam et al., 2013; Chen et al., 2014; Stuart et al., 2018). Compared to these previous studies, our study appears to be the first to impose clear limits for pesticide use, i.e. no more than two formulated product applications per pesticide group per season. Analysis using the SRP farm-level indicators shows an improvement in the sustainability performance for IP in relation to FP (Fig. 5). Overall, IP treatment had a positive net effect on net income, NUE, PUE and pesticide use during both seasons and on water productivity in the DS. The largest improvements were a 29–51% increase in the SRP pesticide score, a 30–35% increase in PUE, and a 17–31% increase in net income per season. Net income increased by an average of USD 167–183 per season, mainly through a reduction in pesticide, fertilizer and seed inputs. These increases in income are similar to findings by Singleton et al. (2011) and Tin et al. (2008) following the introduction of 1M5R and improved practices for seed production, respectively, in the MKD. For the CNV farmers, there also was a reduction in the GHG emissions following application of IP, which was mainly attributed to implementation of AWD (as described above).

Pesticide use across the household survey and field trial sites was extremely high, with a mean of 11–13 product applications, or mean cost of USD 190 ha^{-1}, per season. This is a substantial increase in pesticide application number and cost as compared to previous studies conducted in the MKD between 2003 and 2007 (Huan et al., 2008; Tin et al., 2008; Escalada et al., 2009; Huelgas and Templeton, 2010; Berg and Tam, 2012). Fungicides were the most frequently applied group of pesticides, followed by insecticides, both of which appear to be showing an increasing trend in their use irrespective of their negative impacts towards human and environmental health (Van Hoi et al., 2013). An argument for this trend may be that pests and diseases are more prevalent than they were 10 years ago due to intensified rice production practices, including higher cropping intensities, mono-cropping and planting large areas with similar varieties (Kontgis et al., 2015; Horgan, 2017; Tong, 2017), and the fear of repeated BPH outbreaks (Heong et al., 2013). However, even if this were true, fungicide use appears to be far in excess of what is best practice and frequent insecticide use in rice is more likely to exacerbate insect pest problems rather than reduce them (Bottrell and Schoenly, 2012; Heong et al., 2013; Horgan, 2017). In response to the presence of rice blast fungus, fungicide (and bactericide/anti-microbial agents) use by the IP farmers in this study was

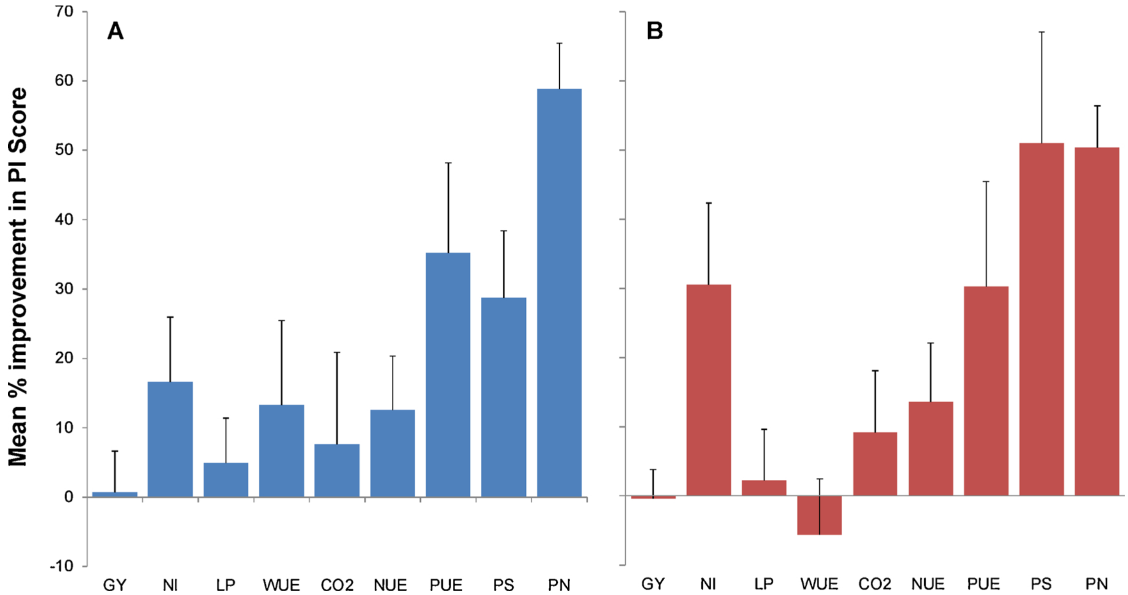

Fig. 5. The net effect of improved practice (relative to farmers' practice) on Sustainable Rice Platform (SRP) performance indicator (PI) scores during the dry season (A) and wet season (B) rice production in Can Tho province. Standard errors are indicated (n = 5). Positive change implies improvement in the score. Note that values for CO_2 equivalent emission and pesticide application number were reversed to show improved changes. SRP PIs are abbreviated as follows: GY, grain yield; NI, net income; LP, labor productivity; WUE, water use efficiency; CO2, CO_2 equivalent emission; NUE, nitrogen use efficiency; PUE, phosphorous use efficiency; PS, pesticide PI score; PN, pesticide product application number.

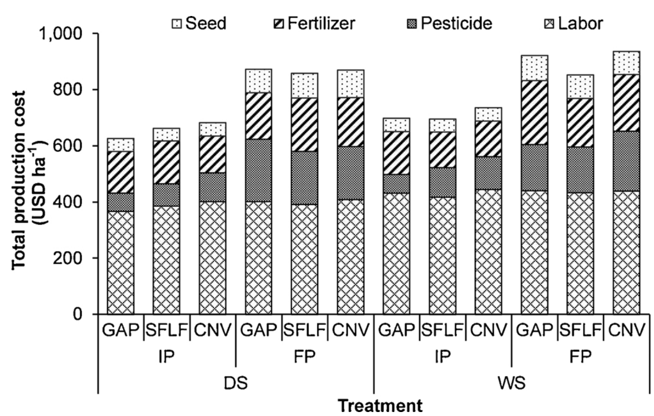

Fig. 6. Mean production cost for the improved practice (IP) and farmer practice (FP) fields during the 2015 dry season (DS) and wet season (WS) rice crops in Can Tho province. Management approaches are categorized as: GAP, VietGAP/ Global GAP; SFLF, Small Farmer Large Field; CNV, conventional practice.

still high (1–5 product applications), and both FP and IP farmers were regularly applying fungicides to target bacterial diseases. There is thus a need to identify the reasons for such misuse, despite substantial government efforts to reduce pesticide use, as well as educate and enhance the capacity of farmers and extension staff in sustainable pest management strategies for insect pests and plant diseases in particular. Rice export companies should also be made aware of the high level of pesticide misuse that can have potential risks to the consumer. It is indeed surprising that even GAP farmers were applying pesticides at such high frequency when GlobalGAP products require pesticide residue testing (Liu, 2007).

Rice yield was maintained in our IP sites with a 51–59% decrease in pesticide application rates during the DS, including a 45–68% decrease in fungicides and 77–93% decrease in insecticides. In addition, in the WS 2016, there was no yield gain, and thus no net economic benefit, through the application of insecticides. This supports previous

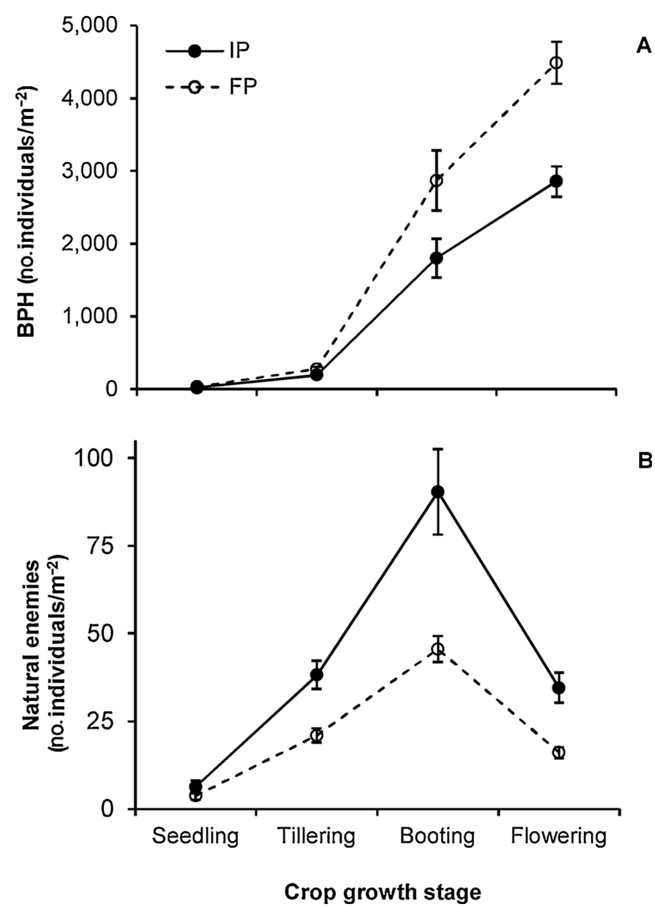

Fig. 7. Mean abundance of brown planthoppers (BPH; A) and arthropod natural enemies (B), in the improved practice (IP) and farmers' practice (FP) fields during the 2015 dry season rice crop. Standard errors are indicated (n = 5).

literature indicating that insecticide use rarely increases the profitability of rice production (Bottrell and Schoenly, 2012; Heong et al., 2013; Ali et al., 2017), especially when taking into consideration the cost of treating pesticide-related illness (Pingali and Roger, 1995). Insecticides should also be regarded as a last resort (Heinrichs et al., 2017) due to the risk of insecticide resistance development and the need to maintain natural enemies of insect pests, especially in the first 40 days after sowing, to avoid pest resurgence (Hardin et al., 1995). Consistent with previous findings on insecticide-induced resurgence (Hardin et al., 1995; Horgan, 2017), the FP fields in this study had fewer natural enemies and subsequently more insect pests, i.e. BPH, following earlier and more frequent insecticide application.

4.3. Value of using SRP indicators

The SRP PIs were developed to assess improvements in sustainability following adoption of best management practices (SRP, 2015a). The findings from our study showed improvements in the sustainability score for five of the eight farm-level PIs following application of improved practice (Fig. 4). The improved practices did not lead to improvements in WUE, labor productivity or grain yield. Stuart et al. (2016) identified a 26% exploitable yield gap in Can Tho province, suggesting that yields can be increased in the region through improvements in crop management practices. In this study, no yield increase was observed for farmers following implementation of IP, suggesting that yields attained by both the farmers involved in this study may already be close to the attainable yield given the local socio-economic and biophysical conditions (including the rice varieties grown). Our results indicate that IP farmers had a higher allocative efficiency than FP farmers (i.e. similar yield with less input), but further research is needed to determine how close IP farmers were to the production frontier (Silva et al., 2017) and whether there is scope to further improve yields whilst reducing environmental impacts through the introduction of other technologies, such as higher yielding varieties, laser land-levelling and precision agriculture techniques. With regards to labor productivity, a recent study comparing countries in SE Asia concluded that farmers in the MKD were amongst the most labor efficient due to a high level of mechanization (Bordey et al., 2016). Mechanization of seed, fertilizer and pesticide application will likely lead to further reductions in labor in the near future.

For the GAP and SFLF farmers, those who followed IP did not show any improvement in GHG emissions due to both IP and FP farmers already implementing AWD. However, the GHG calculation does not incorporate the energy requirements to produce and transport chemical inputs (Pampolino et al., 2007; Chen et al., 2014), all of which were reduced in the IP fields. When fewer than 13 formulated pesticide products are applied per season, the SRP pesticide PI score has a relatively strong association with the level of pesticides applied. However, a farmer who applied 23 pesticide product applications achieved the same score as another who applied 8. Thus, there appears to be a need to improve this PI to capture when particularly high numbers of pesticides are applied. We recommend introducing a negative scoring system when greater than 12 pesticide products are applied.

5. Conclusions

Using the SRP PIs, our results show that implementing 1M5R with clear limits for input use can substantially improve the sustainability of rice production in the MKD through reduced inputs, that can have negative environment impacts, and increased profitability. Farmers implementing GAP and SFLF management approaches that were developed to improve rice farming practices in the MKD, were more sustainable than CNV farmers. Such approaches may also serve as a model for the sustainable intensification of rice production in other rice bowls in SE Asia. Although there is evidently scope for further improvement, especially with regards to reducing rice seed and pesticide application rates. Promotion of 1M5R strongly emphasizes a reduction in inputs as well as the use of certified seed and the results are compelling. A word of caution is that 1M5R along with 3R3G technologies have been promoted in the region for over a decade, but a number of inputs continue to be overused, with some even showing increasing trends. One strategy to address this issue is to provide clearer guidelines and incentives to further reduce inputs to within "acceptable" limits that do not increase vulnerability to risk. However, there is a need to comprehensively understand farmers' perceptions of risk (e.g. have farmers' perceived risks of biotic stresses increased in recent years?) to understand how these change over time following training and knowledge dissemination events, and to identify the main influential factors that promote or limit uptake of improved management practice (Heong et al., 2013; Flor et al., 2017).

The SRP Standard provides guidelines on limits to pesticide application frequency and conditions for use to achieve sustainable accreditation, including taking into account food safety standards. Our study provides evidence to support such an approach, which could complement promotion of key messages such as 'spraying in the first 40 days is not necessary' (Huan et al., 2008), with the aid of on-farm training and demonstrations on IP for sustainable rice production. Previously, training on 1M5R in the MKD was targeted at the individual farmer level and there is a need for future training to target farmers at a farmer group level to facilitate implementation of IP at a community and landscape scale. Along with on-farm demonstrations, regular visits by government extension staff are needed to reinforce these messages, to provide reassurance and to help farmers understand the social, economic and environmental benefits of improved practices.

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