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Co-design and assessment of mitigation practices in rice production systems: A case study in northern Vietnam

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ABSTRACT

Rice production systems are an important source of agricultural greenhouse gas (GHG) emissions. Mitigation techniques, such as alternate wetting and drying, have been developed but have often not taken into consideration the constraints imposed by the practices and preferences of farmers. Since GHG mitigation benefits are not obvious at smallholder farm level, it is essential to design site-specific mitigation technologies with the participation of local stakeholders. The purpose of the present study was to adapt a participatory approach to designing and assessing mitigation practices for the dissemination of climate-friendly rice production systems. To improve the hybridization of scientific and local knowledge, a participatory five-step approach to prototyping was applied: (i) diagnosis based on a literature review and survey of stakeholders, (ii) design of mitigation practices based on laboratory trial and local knowledge (that of farmers, agricultural advisors and regional stakeholders), (iii) testing in growth chambers, (iv) testing in farmers' fields and (v) dissemination and assessment. The study was conducted in An Luong village, Red River Delta, northern Vietnam. In the study area, rice residue burning is restricted and farmers have to incorporate residue into the soil. Current water management practices, *i.e.* conventional continuous flooding and adopted midseason drainage, are not enough to reduce GHG emissions from added residues. Two new water management practices (pre-planting plus midseason drainage and early plus midseason drainage) were designed in participation with local stakeholders, and subsequently tested in the laboratory and in the field with the participation of local farmers. Future mitigation practices were assessed based on the yield, GHG emissions reduction and feedbacks of local stakeholders. Early plus midseason drainage proved to be an effective and feasible mitigation option for rice production in the area. Here we show that participation of local stakeholders in co-designing process help to identify the feasible GHG mitigation options, further it facilitates smallholder rice farmers to implement mitigation practices in their fields.

1. Introduction

Rice farming is one of the most important sources of anthropogenic agricultural methane (CH_4) emissions. It is well known that modified water management practices (early season drainage, midseason drainage, intermittent irrigation, alternate wetting and drying) have considerable CH_4 mitigation potential without the need for any external investment or resulting in a loss of yield for farmers (Pandey et al., 2014; Searchinger et al., 2014). These water management practices have often been tested at research stations and in controlled conditions to accurately determine the greenhouse gas (GHG) mitigation potential of the specific management of added organic amendments (*e.g.* rice residues, compost or manure) (Bhattacharyya et al., 2013; Ly et al., 2015; Tariq et al., 2017a; Zou et al., 2005). The actual implementation of mitigation strategies in farmers' fields is often constrained by local conditions, management practices and preferences. However, the implementation of mitigation strategies into actual field practices is not possible without actively involving farmers and local stakeholders in the planning and testing process. There is an urgent need to combine local field and practice-oriented knowledge with scientific knowledge to design a site-specific low emission rice production system (Stoop et al., 2002; Wassmann et al., 2000). Therefore, an on-farm

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participatory approach, taking advantage of scientific results acquired in the laboratory and applying them to field and on-farm experiments, is required to define optimum mitigating rice production systems.

The co-design of innovative agricultural prototypes for sustainable farming has arisen as a discipline in recognition of the need to combine research and practical knowledge in order to develop complex production systems (Vereijken, 1997). The co-design of mitigation prototypes at field scale is a challenge since climate change mitigation is a global issue rather than a direct concern for farmers. A participatory approach to prototyping in interaction with local stakeholders, preferably including farmers, is beneficial since it allows the interaction of both local and scientific knowledge (Meynard et al., 2012). Rahman and Bulbul (2015) propose the active involvement of local stakeholders to enhance the implementation of mitigation practices in rice production systems.

The aim of co-designing the low emissions rice cropping system was to mitigate the global warming potential (GWP) of rice production systems without having a negative impact on farmers' yields or livelihoods. Researchers have highlighted the importance of participatory methods in the design and implementation of climate-friendly agricultural production systems (Smith et al., 2007; Vignola et al., 2015). The transition of a prototype from small (field) scale to large (farm or regional) scale is difficult to achieve without the sufficient participation of farmers, local professionals and regional stakeholders (Le Bellec et al., 2012). It is important to understand the process of combining the local agricultural expertise and technical scientific knowledge, and then share it with the participants (Altieri and Koohafkan, 2008). Local stakeholders facilitate communication of the central objective and increase the efficiency of adoption by farmers (Pretty, 1995). Regional stakeholders provide suitable conditions for adopting the innovation techniques, for instance farmers may receive incentives for adopting new technologies. Farmers share their constraints and provide the basis for the possible modification of current practices (Meynard et al., 2012). Krupnik et al. (2012) have demonstrated that mutual learning by researchers and farmers could lead to the development of an innovative irrigated rice system, and could facilitate its adoption under local conditions. Le Bellec et al. (2012) have designed the DISCS method for multi-stakeholders' participatory design and assessment of innovative cropping system. DISCS is a prototyping method which allows multi-stakeholders participatory approach by implementing three progress loops, at experimental field, farm and regional scales. Three categories of professional stakeholders are involved: farmers, researchers, and agricultural advisers, who are collectively in charge of designing and testing the cropping system prototypes. In addition, local public stakeholders including representatives of state institutions are consulted. Progress is assessed using scale-specific sets of indicators. The DISCS method was applied to develop low- pesticide citrus cropping systems in Guadeloupe, French West Indies.

In this study, a participatory approach was used to design and test a mitigation practices for rice production system in the Red River Delta in northern Vietnam. On a national scale, rice straw burning is restricted and the government is encouraging farmers to manage straw sustainably to improve human health and society and to prevent the environmental pollution and global warming (Hai and Tuyet, 2010). Therefore, farmers have to dispose of a large amount of rice straw by incorporating it into the soil. Typically, farmers have no other straw management options available to them, since its use for livestock feed or bedding, composting or bioenergy production is considered unattractive due to absence of livestock facilities, labor shortage or cost issues. Incorporation of rice straw into soil is known to result in increased GWP, particularly due to increased CH_4 emissions under flooded rice conditions (Bossio et al., 1999; Romasanta et al., 2017; Searchinger et al., 2014). Meanwhile, there is growing concern about CH_4 emissions from rice paddies and societal demand for the implementation of agricultural mitigation practices in Vietnam, where rice farming contributes up to 50.5% of national agricultural GHG emissions and 16.3% of all national anthropogenic GHG emissions, of which CH_4 is a major share (MONRE, 2014). It is becoming increasingly important to reduce CH_4 emissions from flooded rice fields to reduce the overall GWP of rice production systems in Vietnam. In that sense, two environmental demands being made on rice farming (reductions in straw burning and in GHG emissions) are potentially in conflict with one another (Romasanta et al., 2017) since farmers' default response to legislation that prohibits burning is to incorporate the straw into the soil. Finally, GHG mitigation does not produce tangible benefits for the farmers, and hence their motivation to adopt such practices will be influenced considerably by external incentives or system constraints.

The objective of this study was to adapt the DISCS participatory approach of prototyping (Le Bellec et al., 2012) to design mitigation practices for rice production systems in a village in northern Vietnam, and to understand the potential benefits and possible constraints in the adoption of mitigation practices in the area in future. The prototyping method was improved by incorporating multi-scale scientific results – from microcosm to field and farm scale – in the participatory process. The main aim was not to design a completely new rice cropping system, but to modify current management practices with the involvement of local stakeholders to minimize GHG emissions without reducing grain yield.

2. Material and methods

2.1. Description of method

The participatory approach of Vereijken (1997) and Le Bellec et al. (2012) was followed, with some modifications, involving local stakeholders in each step of the designing process and incorporating multi-scales experiments (Fig. 1). Four categories of stakeholders were involved in the designing and subsequent assessment process: i) researchers, who provide the scientific knowledge and tools; ii) farmers, as key stakeholders involved in the survey, field experiments and workshops; iii) local agricultural advisors, who provide local technical knowledge and feedback during focus group discussions and workshops; and iv) regional stakeholders, who are engaged in agricultural as well as regional socioeconomic systems. All four categories were involved in all the workshops. The stakeholders' composition at each step is presented in Table 1.

The participatory approach was based on local and scientific-oriented knowledge (Fig. 2). The participatory approach of co-designing included the following five steps: (i) diagnosis, based on a literature review and a stakeholder survey, aimed at identifying possible technical options for GHG mitigation from rice fields and existing smallholders farm practices and constraints, (ii) design of mitigation practices based on initial laboratory tests of possible options and workshops with farmers, local agricultural advisors and regional stakeholders, (iii) testing in growth chambers to explore the technical mitigation potential of designed practices under fully controlled conditions, (iv) testing in farmers' fields to establish the actual mitigation efficiency of designed practices under farmers' variable conditions, and (v) dissemination and assessment, based on laboratory and field trials and the experiences and perceptions of local stakeholders.

2.2. Case study

This section describes the method used in the co-design and assessment of mitigation practices based on residue incorporation for a lowland rice-producing area on the Red River Delta in northern Vietnam. The methods adapted at each step depended on the specific context and need to address the complex issue of GHG mitigation with local stakeholders. The data that resulted from the innovative process of co-design and assessment of mitigation practices is presented in the Results and Discussion sections below.

The study was conducted at a local scale in An Luong Village, An

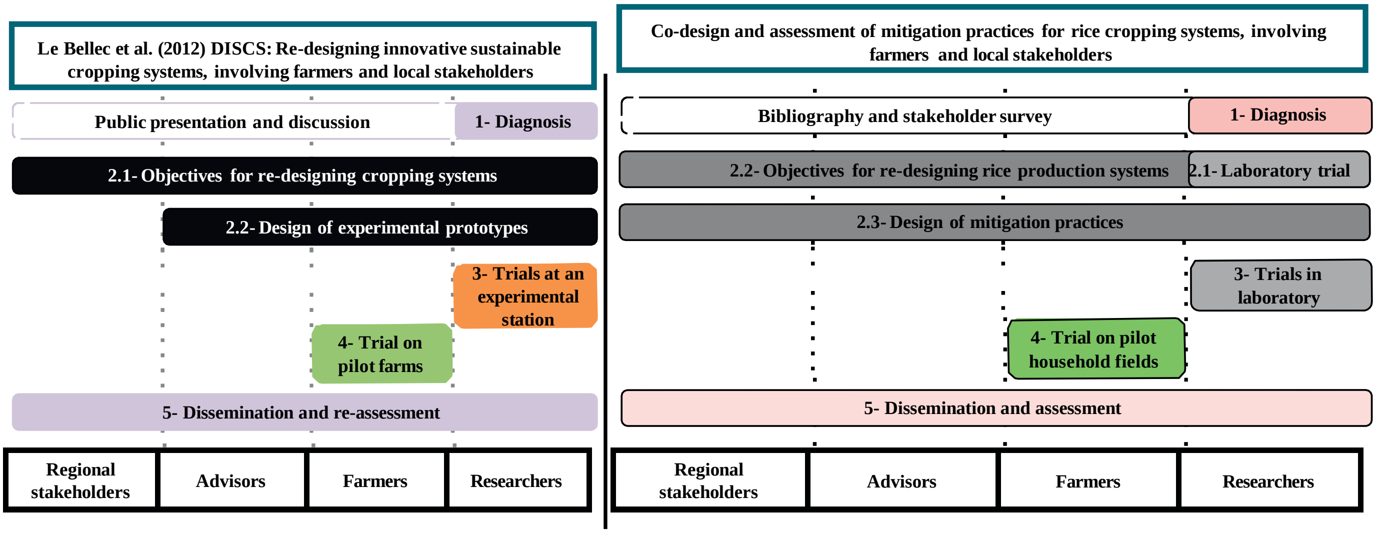

Fig. 1. Co-design and assessment of mitigation practices following the DISCS participatory approach of Le Bellec et al. (2012) with some modifications: i) the inclusion of the literature review in step 1 to diagnose the mitigation options, ii) the inclusion of laboratory trials in steps 2.1 and 3 to understand the fine-tuned processes for the design (2.1), and an assessment (3) of mitigation practices, iii) the inclusion of regional stakeholders in step 2.3 to understand the national policies and programs that support the rice production system.

Lam commune, Nam Sach district, Hai Duong province in northern Vietnam. The soil in the area is generally classified as alluvial lowland paddy soil (Acrisols). The climate in the area is humid sub-tropical, with temperatures varying between 20 °C and 30 °C. The maximum rainfall occurs during the summer season (June–August), with the average monthly rainfall between 400 and 700 mm. Rice is traditionally produced in continuously flooded fields, known as rice paddy. Water is generally controlled by regional irrigation companies. Local technical staff are responsible for monitoring water levels in the farmers' fields. A water management project was established in the village in 2013 with the aim of implementing alternate wetting and drying (AWD) practices in the area (Vu and Sander, 2015). AWD is a well-established water management system, where fields are routinely drained and re-flooded during the cropping season. This results in significant lower CH_4 emissions, and reduces water consumption, however it requires careful management to avoid water-stress in the rice, and may lead to increased N_2O (nitrous oxide) emissions (Hou et al., 2012; Itoh et al., 2011; Mazza et al., 2016). The most common crop rotation in the case-study area is an intensive double rice crop rotated with winter fallow or vegetable/onion production. Traditionally, farmers have burnt the rice residues after spring and summer-rice harvesting due to labor shortage and intensive crop rotation. The details of crop residue management and burning intensity are given in Tariq et al. (2017b). Crop residue burning is increasingly being prohibited in Vietnam, and alternative residue management is strongly encouraged to ensure good air quality. Most rice farmers in the area are smallholders who have limited resources for

Table 1
Stakeholders composition and time required at each step of development and assessment of mitigation practices.

		Stakeholders				Time	
		Regional representatives	Agricultural advisors	Farmers	Researchers	Period	Duration (days)
Step 1	Laboratory experiment				UCPH	Jan-Mar, 2015	90
	Survey			35 households	UCPH, IAE, IRRI	Nov, 2015	7
Step 2	Workshop 1	1 head of co-operative 1 head of agriculture department	1 extensionist 1 village leader 1 irrigation officers 1 local irrigation staff 1 agricultural officer	5 households	UCPH, SupAgro, IRRI, IAE	Nov, 2015	1
	Workshop 2	1 head of co-operative 1 head of agriculture department	1 extensionist, 1 village leader, 1 irrigation officers, 1 local irrigation staff 1 agricultural officer	10 households	UCPH, SupAgro, IRRI, IAE	Dec, 2015	1
Step 3	Laboratory experiment				UCPH, IAE	Jan-Feb, 2016	60
Step 4	Field experiments			24 households	UCPH, SupAgro, IRRI, IAE	Feb-Sep, 2016	240
Step 5	Workshop 3	3 head of co-operative 3 head of agriculture department	4 extensionist 1 village leader 4 irrigation officers 1 local irrigation staff 2 agricultural officer	10 households	UCPH, SupAgro, IRRI, IAE	July 2016	1
	Workshop 4	3 head of co-operative 3 head of agriculture department	4 extensionist 1 village leader 4 irrigation officers 1 local irrigation staff 2 agricultural officer	10 households	UCPH, SupAgro, IRRI, IAE	Dec, 2016	1

UCPH = University of Copenhagen, Denmark; IAE = Institute for Agricultural Environment, Vietnam; SupAgro = Montpellier SupAgro, France; IRRI = International Rice Research Institute, Philippines.

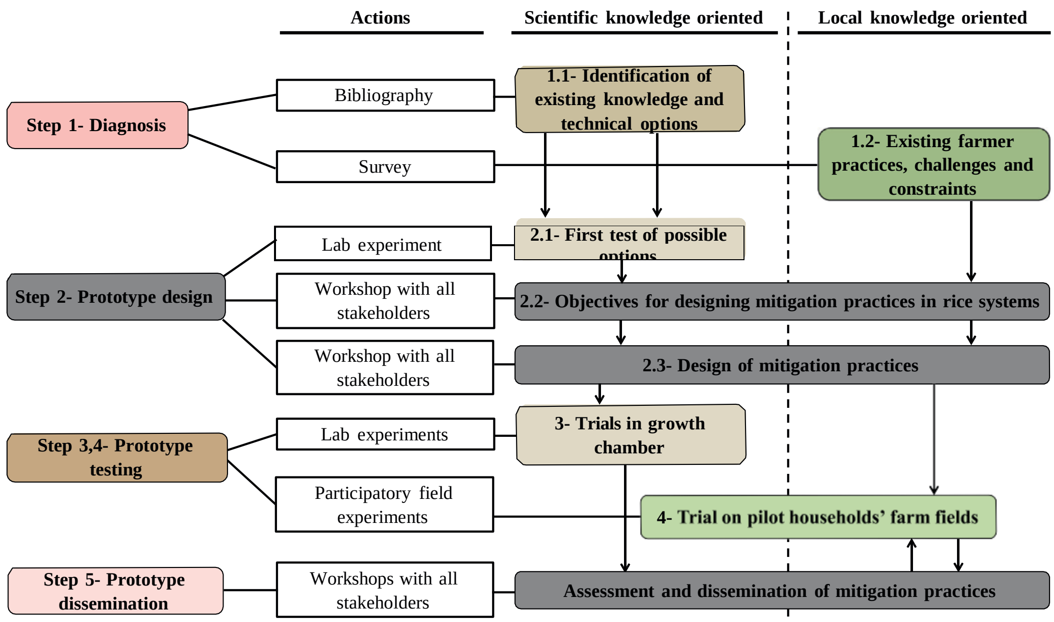

Fig. 2. Methodological framework for the participatory design and assessment of mitigation practices for rice production system.

alternative residue management. Furthermore, rice farmers have limited control over water management and labor is scarce. These places a tight restriction on smallholder rice farmers to adopt mitigation practices, particularly in the intensive rice cropping systems.

2.2.1. Diagnosis

The diagnosis in this study differed from the original method (Vereijken, 1997) and DISCS approach (Le Bellec et al., 2012) of participatory prototyping since GHG mitigation is not the direct concern of rice farmers. The main objective of the diagnosis was to identify the existing and possible GHG mitigation options, and to explore farmers' existing practices and practical constraints. Researchers used the existing literature to identify the existing GHG mitigation practices from rice production systems. Local agricultural advisors and regional stakeholders were individually interviewed by the research team to understand how the system functioned, as well as current and future policies, national programs and incentives for smallholders. Thirty-five smallholder rice farmers were interviewed in November 2015 to capture the diversity of different land management practices in the area, and to understand their cropping practices and the challenges and constraints faced at field scale. The stratified sampling approach was used to cover the system diversity and geography of the area. The area was divided according the land typology (high, medium and low), water management (efficient and inefficient) and crop rotation (rice-rice-onion, rice-rice-corn/tomato and rice-rice-fallow). Then, farmers were randomly chosen from each group. A comprehensive survey guideline was used to capture the farmers' management operations, constraints, possible options for modifying current practices and future perceptions. Furthermore, farmers' practices were observed during ongoing field visits.

2.2.2. Design of mitigation practices

The development of GHG mitigation practices started with an initial test of possible mitigation options. The mitigation options were tested in a growth chamber experiment at University of Copenhagen from January to March 2015 (Tariq et al., 2017a). The results of the first test of possible mitigation options and diagnosis were discussed in November 2015 with local farmers, agricultural advisors and regional stakeholders in An Luong Village, to create a shared understanding of the performance and potential benefits of improved management options for rice production (Table 1). Finally, a workshop was conducted in December 2015 to design the mitigation practices with all the stakeholders, including local rice farmers in the Village. The mandate for all workshop participants was to emphasize on modifications of residue and water management practices to mitigate GHG emissions without influencing rice yield. The mitigation practices were designed on the basis of three performance indicators: i) avoidance of residue burning and adoption of alternative residue management, ii) cessation of continuous flooding and adoption of improved water management practices as efficiently as possible and iii) increase in rice yield.

2.2.3. Testing of mitigation practices

The design prototypes were initially tested in a growth chamber and then in farmers' actual field conditions with conventional and improved water management. The growth chamber experiments were conducted to develop a detailed understanding of the mitigation process, and to compare the mitigation potential of the designed prototypes and existing local practices in fully controlled conditions. The growth chamber experiment was conducted in pots at University of Copenhagen. Rice plants were grown in the alluvial lowland paddy soil (Acrisols) collected from farmers' fields in the Red River Delta, northern Vietnam. ^{13}C-enriched rice residues were used as a carbon tracer to understand the changes in residue carbon contribution to CH_4 emissions with different water management practices. In the growth chamber experiments the assessment indicators involved a high degree of complexity and precise information. Following the growth chamber experiments, field trials were conducted for two consecutive rice seasons in participation with local farmers, but no adjustment was made in the second season trial. Researchers and local farmers participated in the field trials. The two-rice cropping season field trials were conducted on 24 farmers-fields in two water management systems (efficient water management and inefficient water management). The gas sampling chambers were installed in the farmers' fields for two seasons and moved once at the start of second season. Local technical staff also took part in the field activities (Fig. 3). At field scale, indicators and tools needed to be simple in order to provide the low-level technical, easily understandable information to local farmers. Researchers provided the technical tools and skills to manage the trials, and farmers provided the essential field materials, their lands and their own time in constantly being engaged in field trials.

Fig. 3. Presentation of field trail and participatory activities: a) chambers placement in farmers' fields, b) gas sampling by local technical staff, c) crop harvesting by researchers and farmers from pilot field plots, d) farmers interview, e) group discussion during workshop, f) individual feedback by participants during workshop.

Different stakeholders needed different assessment tools (Stein et al., 2001) to assess the mitigation practices. Researchers used more technical tools in the growth chamber experiments and concentrated on the processes and mechanisms involved in GHG mitigation from paddy rice soils. For the growth chamber experiments, assessment indicators focused on mitigation alone. The assessment indicators for growth chamber experiment included CH_4 emissions, N_2O emissions and the combined GWP, calculated following the IPCC factors over the 100-year time scale, according to Myhre et al. (2013). For the field trials, assessment indicators focused on both mitigation and local farmers' interests *i.e.* rice yield and ease of implementation. The assessment indicators used in the field trials included CH_4 emissions, N_2O emissions, GWP, grain yield and greenhouse gas intensity (GHGI), in addition to feedback from farmers on workload and feasibility.

2.2.4. Dissemination and test-year evaluation

The researchers directed the dissemination process based on a multi-criteria participatory assessment at a scientific level and with local and regional stakeholders. The dissemination was based on the implementation of mitigation practices by local farmers and their possible adoption in other places with similar constraints. The follow-up workshops were conducted after each trial with local farmers, agricultural advisors and regional stakeholders. The multi-stakeholder workshops provide a platform for stakeholder groups to raise and discuss their views (Hulsebosch, 2001). First the researcher delivered the scientific findings to the local stakeholders based on testing of mitigation practices in growth chambers and farmers' fields. The follow-up focus group sessions discussed the mitigation potential, yield benefits, challenges, drawbacks and possible adoption strategies for each mitigation practice tested under farmers' field conditions (Fig. 3). In the first session, all participants (Table 1) were divided into three groups with presentation of each category of stakeholder in each group. Nevertheless, differences in ability to negotiate and power hierarchy between stakeholder categories may have played a role. In line with our expectations, stakeholders were grouped according to their categories in the second session, such as; farmers, agricultural advisors and regional stakeholders. The general perceptions were developed by presentations of each group and follow-up discussion. The specific experiences and perception of all participating stakeholders were also obtained individually by completing the feedback form. The performance assessment indicators for each management category (water and residue) were mentioned and ranked from 0 (low) to 4 (high) in the individual feedback form. The mean values of all performance indicators for each stakeholder categories were calculated.

3. Results and discussion

3.1. Diagnosis

3.1.1. Descriptive characteristics of rice farmers

The survey of local stakeholders showed that most rice farmers in the area have small landholdings varying between 0.1 and 0.2 ha. The households have scattered plots which are separated from each other. The dominant crop rotations are a double rice crop (spring and summer rice) with either winter vegetable/corn or fallow in the third part (October to January) of the year (Fig. 4). The majority of farmers, *i.e.* more than 70%, follow the winter fallow rotation. The residue management depends on the crop rotation followed by the farmers. Generally, farmers have no alternate residue management options *e.g.* for animal feed/bedding, composting, biogas, due to limited livestock numbers, limited and aged family labor and the intensive crop rotation. In general, households have no livestock: fewer than 10% own 1 to 2 cattle per households. The average family size is 5 to 6 individuals per household, of whom 1 or 2 individuals are involved in agricultural activities. More than 75% of all rice farmers are female, with the men mainly involved in off-farm activities. The average age of farmers is 56 years, with the majority (59%) aged between 55 and 65 years.

3.1.2. Management practices of rice farmers

The local water management system is traditionally based on conventional continuous flooding of rice fields. The regional irrigation department controls water management in the area with the help of local irrigation staff. Local technicians are appointed by the irrigation department to control the water on farmers' fields. The provincial agricultural department has initiated a controlled water management project, known locally as the AWD project. The AWD project was established on a small scale (on 15 ha of the 90 ha of cultivated land) in 2013 with the aim of upscaling the improved water management technique (*i.e.* midseason drainage at the end of the tillering stage). The water in the AWD project area is controlled by local irrigation staff according to a fixed schedule, with an improved infrastructure for water inlets and outlets. Water management in the rest of the village farm area is also controlled by the same irrigation staff, but in accordance with farmers' demand. The farm area outside the AWD project

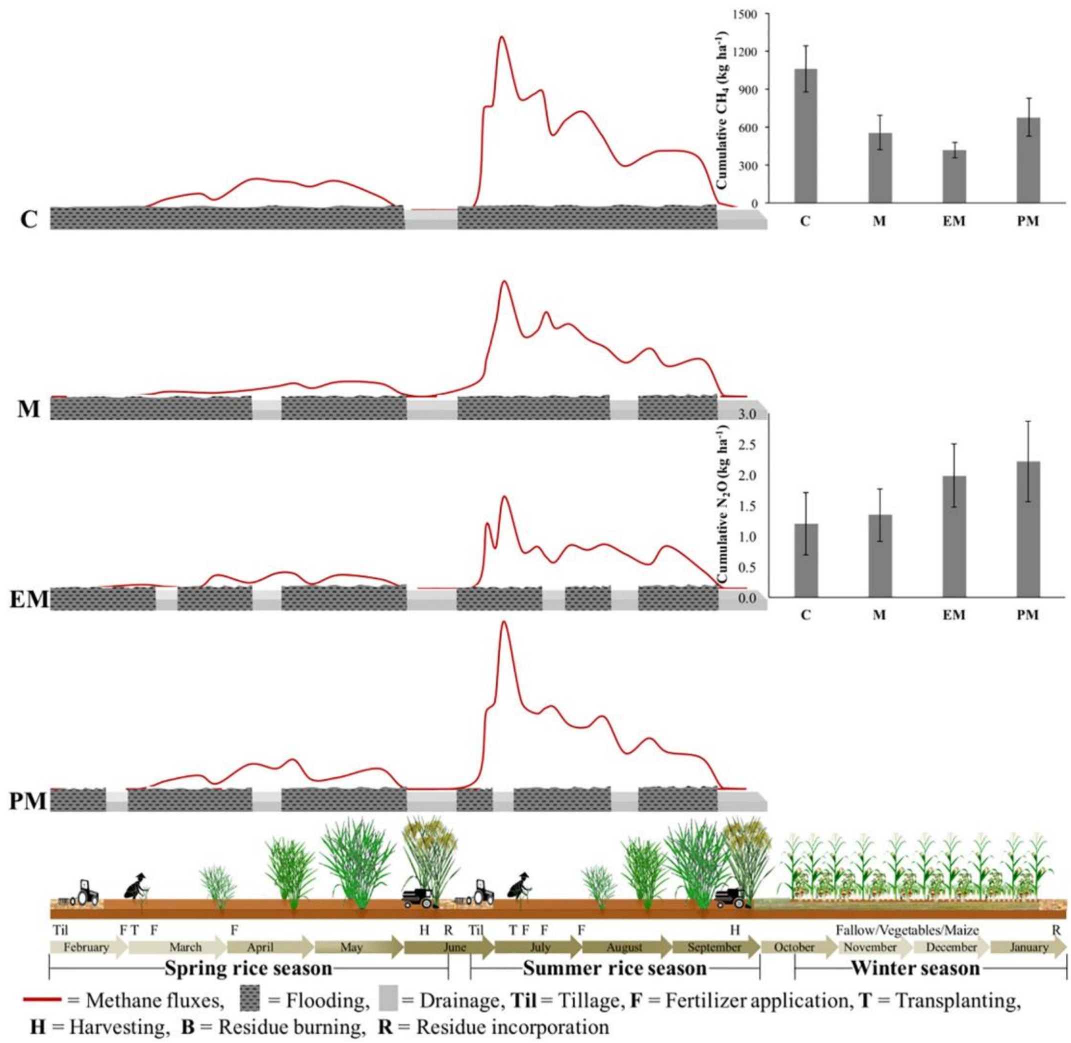

Fig. 4. Graphical presentation of farmers' existing practices (continuous flooding [C], midseason drainage [M]) and designed mitigation practices (early plus midseason drainage [EM], pre-transplant plus midseason drainage [PM]) on water management with full residue incorporation. The methane (CH_4) fluxes and cumulative CH_4 and N_2O (nitrous oxide) are adapted from Tariq et al. (2017b).

has less effective water control due to the lack of an adequate infrastructure to control the inflow and outflow of water.

Rice residues are traditionally burned (50 to 70% of total residues) in the open fields after harvest. Residue burning depends on the harvesting method (machine or manual), cutting height and crop rotation. The harvesting method depends on the crop rotation; nearly 30% of the rice farmers in the area grow vegetables or onions in the winter season, with the remaining 70% of farmers leaving their land fallow during the winter season. Farmers who grow vegetables in the winter adopt manual harvesting of the summer rice crop leave 60–70% of the residues as a mulch during the winter season. Farmers who follow the winter fallow rotation use a combine harvester for the summer rice crop and 40–50% of residues are left standing in the field due to the combine harvesters' fixed cutting height. Farmers partially burn and incorporate the winter mulched and standing rice residues (from the summer rice crop) before spring rice planting. Generally, spring rice is harvested with a combine harvester and all the remaining residues (35 cm stubbles) are burned in the fields for rapid land clearance before summer rice is planted.

3.1.3. Farmers' constraints

The practical and technical constraints faced by smallholder rice farmers in improving farm management operations for low GHG emissions include the following: (i) farmers in An Luong cannot use rice residues for alternative purposes (composting, biochar, biogas, animal feed) because they have concrete houses, natural gas and electricity for cooking, no livestock to feed straw, limited availability of labor due to increased off-farm activities and limited resources for alternative management of residues, (ii) the intensive double rice cropping system limits the alternative residue management options due to the short timespan (less than 14 days) between spring rice harvesting and summer rice crop transplanting, (iii) a lack of awareness among farmers and a lack of incentives to encourage climate friendly production systems.

In the present participatory study of co-designing the mitigation solutions, we first identified the possible GHG mitigation options for rice production systems. Then, based on the survey of farmers and local stakeholders, researchers agreed with the stakeholders to focus on designing mitigation practices for the rice production system based on restricted residue burning and residue incorporation into soil, and modification of current water management systems. The farmers and other local stakeholders supported this, because seemingly these interventions required no external investment. This diagnosis process was useful as an entry point for co-designing the mitigation practices, which apparently will not give any tangible benefits to the farmers. Furthermore, it helps to develop trust and confidence between partners, which strengthen the farmers' participation in the further process of design and assessment. However, this method of diagnosis is limited to the contexts where GHG mitigation is not direct concern for the farmers. For further agronomical diagnoses, other participatory approaches (Lançon et al., 2007; Le Bellec et al., 2012; Rossing et al., 2009; Van Calker et al., 2006) could be used, which focus on farmer oriented problems and would enable finer analyses of cropping systems. However, there is always a need to find a balance between an open innovation process and the key to get started (Le Bellec et al., 2012).

3.2. Transformation of objectives and design of mitigation practices

The actual design of the mitigation practices commenced after the possible mitigation options had been tested in the growth chamber by Tariq et al. (2017a). Conclusively, the results of first growth chamber experiment revealed that early-plus-midseason drainage could reduce CH_4 emissions by 89–92% and 37–61% compared to midseason drainage alone from residue- and compost-amended soils respectively. In the workshop with local stakeholders, the researchers discussed the results of the diagnosis and growth chamber experiment to achieve consensus on the design of the mitigation practices based on the farmers practical and technical constraints and implementation feasibilities. The five sub-objectives for the mitigation practices were defined in the workshop with local stakeholders as: (i) the restriction of open-air residue burning since it is increasingly being prohibited in Vietnam due to increased air pollution and the emission of harmful chemicals, (ii) the incorporation of residues into the soil due to a lack of alternative residue management options (composting, biochar, animal feed) for rice farmers, (iii) the modification of current water management practices since they have a strong potential to reduce GHG emissions from crop residues in addition to water saving, and (iv) the reduction in GHG emissions without farmers suffering yield loss since they are more concerned about their yield than about mitigation. Furthermore, low external investment and no yield loss would be beneficial for motivating rice farmers to adopt mitigation practices.

In the second workshop, all the stakeholders validated the defined objectives and three new practices (one on residue and two on water management) were collectively designed. The newly designed practices included: (i) the incorporation of all rice residues into the soil [F] instead of typical residue burning [R], (ii) pre-planting plus midseason drainage [PM] and (iii) early plus midseason drainage [EM] instead of farmers' practices of conventional continuous flooding [C] and midseason drainage [M]. The graphical presentation of the designed practices and farmers' current management practices is given in Fig. 4.

The primary principle of participatory design of mitigation practices is to proceed step by step and to only propose innovative management options that farmers are willing to adopt in their own fields. Le Bellec et al. (2011) and Le Bellec et al. (2012) used a similar approach to design the prototypes for sustainable citrus production in Guadeloupe. However, Lançon et al. (2007) designed the prototypes for sustainable cotton production in West Africa by drawing upon experts who were external to the regional system. Le Bellec et al. (2012) proposed to form the local multi-stakeholder dynamics before calling the external experts or using the models to design the innovations.

3.3. Testing of mitigation practices

In this study, researchers tested and assessed the designed practices in participation with local farmers. The results were presented to farmers in simple local terms to convey the scientific findings on GHG emissions in a way that was easy to understand. Furthermore, farmers themselves assessed the economic benefits of improved management practices in term of their yields. This participatory approach of testing allowed the farmers to understand the potential benefits of the designed mitigation practices, which increased the farmers' confidence about adopting the improved practices on their fields.

The growth chamber experiments provided detailed understanding of the mitigation potential of farmers' existing practices (C and M) and the designed practices (EM and PM) (Tariq et al., 2018). Six water regimes (C, M, PM, EM, P (pre-planting drainage) and E (early-season drainage)) were tested to prove the theory that drainage early in the season oxidizes the residues' carbon, which reduces CH_4 emissions. Field trials were conducted to compare the mitigation and yield potential of the designed prototypes (EM, and PM) with farmers' existing practices (C and M) (Tariq et al., 2017b). During field trials, plots with C water regimes were continuously flooded with water from mid-January to mid-September, and only drained for 10 days before harvesting, *i.e.* 5 June and 14 September for spring and summer harvesting respectively (Fig. 4). In the M water regimes, irrigation was stopped at the end of the tillering stage in both seasons. During spring season, irrigation was stopped at start of April and re-flooded after mid-April. During the summer season, irrigation was stopped in first week of July and re-flooded after mid-July. In the EM water regimes, fields were drained in third week of transplanting in both seasons. In the PM water regimes, water was drained out from fields for five days before transplanting (*i.e.* during land preparation) in both seasons (Fig. 4). Crop residues were incorporated before the start of each season *i.e.* early February before spring season and end June before summer season. The rate of residue application and management on farmers field are presented in detail in Tariq et al. (2017b). In spring season, fertilizers were applied in end of February, 2nd week of March, and start of April. In summer season, fertilizers were applied in July and August (Fig. 4).

Table 2
Researcher-oriented assessment of designed practices with local practices in the growth chamber (Tariq et al., 2018) and farmers' fields (Tariq et al., 2017b), in absolute units for conventional practice and the relative change for adopted practice or design practices; positive values represent the percentage increase and negative values represent the percentage decrease from farmers' conventional practice.

Indicators	Units	Conventional practice	Adopted practice	Design practices			
		C	M	EM	PM	E	P
Growth chamber trials							
CH_4 emissions	(μg CH_4 g^{-1} soil)	331	−23%	−53%	−77%	−41%	−69%
N_2O emissions	(μg N_2O g^{-1} soil)	5.9	+70%	+97%	+92%	+77%	+80%
GWP	(mg CO_2-eq g^{-1} soil)	10.8	−10%	−31%	−53%	−24%	−47%
Farmers' fields trials							
CH_4 emissions	(t CH_4 ha^{-1})	1.06	−48%	−60%	−36%		
N_2O emissions	(kg N_2O ha^{-1})	1.2	+10%	+40%	+46%		
GWP	(t CO_2-eq ha^{-1})	30.1	−47%	−59%	−35%		
Grain yield	(t ha^{-1})	4.6	+2%	+5%	+10%		
N fertilizers	(kg N ha^{-1})	282	−8%	−1%	−9%		
GHGI	(kg CO_2-eq kg^{-1} yield)	6.9	−47%	−58%	−39%		

C = continuous flooding; M = midseason drainage; EM = early plus midseason drainage; PM = pre-transplant plus midseason drainage; E = early season drainage; P = pre-transplant drainage CH_4 = methane; N_2O = nitrous oxide; GWP = global warming potential; GHGI = greenhouse gas intensity.

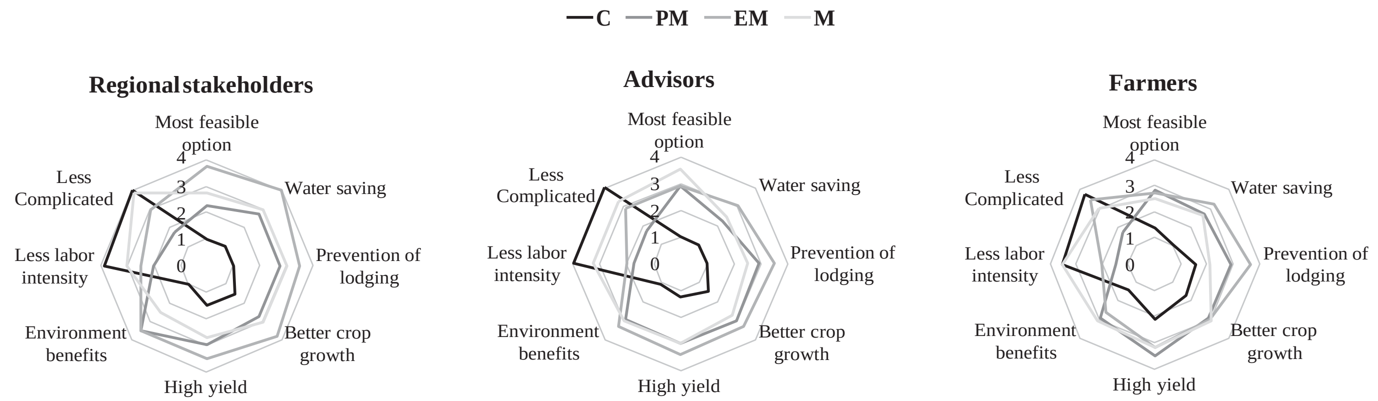

Fig. 5. Local stakeholders' assessment of design practices (PM and EM) with farmer practices (C and M). PM = pre-transplant plus midseason drainage; EM = early plus midseason drainage; C = continuous flooding; M = midseason drainage.

Table 2 shows the performance of designed practices compared to local practices in the growth chamber and in farmers' fields. The results show that EM and PM performed equally under controlled growth chamber conditions, with a small difference in overall GWP reduction that was due to the high N_2O emissions in PM. The obvious reduction in CH_4 and GWP in the P and E practices elucidated the importance of pre-planting and early-season drainage in PM and EM in lowering GHG emissions. The CH_4 mitigation potential of the PM was higher in the fully controlled growth chamber than in farmers' fields, where the mitigation efficiency of PM did not differ from the farmers' adopted practice (M), but EM lowered the GWP and GHGI (greenhouse gas intensity) due to the reduction in CH_4 emissions and high yield. The low mitigation efficiency of PM in farmers' fields was due to the intensive crop rotation cycle (two weeks between the rice seasons) (Fig. 4), and to the less efficient field drainage during land preparation, which limited the residue carbon oxidation and increased the CH_4 emissions. Farmers puddle (tillage operation in standing water) their fields in standing water two times before transplanting, which does not allow the fields to dry efficiently during this period. Furthermore, farmers were reluctant to drain their fields during land preparation due to the risk of late transplanting. However, field water drainage was efficient during early-season and midseason, because farm operations had no conflict with field drainage and irrigation could paused to allow the fields to dry by natural evapotranspiration.

3.3.1. Researcher-oriented analysis

The growth chamber experiments and farmers' field trials showed that EM reduced CH_4 emissions strongly compared to farmers' practices (C and M) without any adverse effect on yield. EM was also easy for farmers to manage, even with a low level of water control infrastructure. Lu et al. (2000) have reported that additional drainage during the vegetative growth period reduces CH_4 emissions by an extra 30% compared to single midseason drainage. Previous studies have suggested that pre-plant or fallow residue incorporation reduces CH_4 emissions up to 11% (Lu et al., 2000; Wassmann et al., 2000). In the northern Vietnam, the intensive crop rotation, labor shortages and cultural events (*e.g.* Tết, Vietnamese new year) limit farmers' opportunities for fallow residue incorporation before the spring rice season. However, farmers agreed to test the pre-plant residue incorporation with improved drainage practices, despite their limitations on time and labor. The CH_4 mitigation effect of pre-plant drainage was not obvious in the field (36%) compared to the controlled growth chamber (77%), due to inadequate drainage during puddling. The efficient soil aeration during the early drainage period increased the residue carbon mineralization which effectively suppressed the CH_4 emissions later in the season (Islam et al., 2018; Ly et al., 2015; Tariq et al., 2017b). Farmers have to adopt the improved drainage practices to mitigate the CH_4 emissions from added crop residues, otherwise more residue incorporation will lead to higher CH_4 emissions (Fig. 4). Further, farmers were also reluctant to drain water out of their fields during land preparation due to extra charges to re-pump water back and the uncertainty around water availability, especially in the spring (dry) season. Moser and Barrett (2003) and Krupnik et al. (2012) reported that additional labor requirement for SRI (System of Rice Intensification) may be a constraint for smallholders to implement alternate water management systems in their fields. The implementation of improved water management techniques is more complicated in the areas where irrigation is not individually controlled by farmers (Noltze et al., 2012). Despite the limited labor resources, less control over water and time constraints between the seasons, farmers were in favor of both EM and PM due to their extra yield (5–10%) compared to farmers' local practices.

3.3.2. Local stakeholders-oriented analysis

The stakeholders-oriented analysis was based on workshops with local farmers, agricultural advisors and regional stakeholders. The assessment indicators at this stage were directed at farmers and other stakeholders', in terms of technical complications, potential economic and environmental benefits, and future perceptions and possibilities for implementation of the mitigation practices. Farmers shared their personal experiences, implementation constraints and possible options for successful adoption of mitigation practices in their fields, agricultural advisors shared their personal experiences of field visits and their perception of the possible implementation of mitigation practices, while regional stakeholders provided feedback on performance and the feasibility of possible implementation. The performance of the designed practices and farmers' practices was assessed using eight composite indicators: (a) water savings, (b) prevention of lodging, (c) crop growth, (d) grain yield, (e) benefit to the environment, (f) labor intensity, (g) complexity of implementation, (h) most feasible management option for the future (Fig. 5). The comparative analysis by local and regional stakeholders gave the researchers supporting material to identify strengths and weaknesses for the future adoption of mitigation practices in rice production system. Furthermore, the experiments were conducted with local rice farmers on 24 farmers' fields, which provided an opportunity for strong local integration. The ongoing informal conversation with local rice farmers highlighted their practical and technical limitations.

In general, none of the stakeholders awarded high points to the conventional practice of continuous flooding (Fig. 5). The EM seemed equally beneficial to all stakeholders in terms of improved plant growth, increased resistance against crop lodging, water savings, high rice yield and being less complicated to integrate into farmers' current practices in the fields. From the perspective of local farmers, the PM could be the best management practice in the future if the government were to provide incentives for infrastructure and equipment for regulating water level during land preparation operations. Agricultural advisors proposed M as an effective management practice due to equal yields with EM and PM while being less complicated to implement and less labor intensive. Regional stakeholders favored the EM prototype for integration and implementation with farmers' current practices due to it being less complicated to implement in farmers' fields, water savings, reducing GHG emissions, offering better plant growth and high yield, or representing no loss for farmers. Furthermore, farmers could adopt EM with their current capacity and resources without requiring any additional support. EM may not work during the dry season due to the uncertainty of water availability, and farmers will be more careful about draining their fields. Despite this, farmers were happy to implement the EM because it is more economical and easy to implement. This was not only due to the positive effect of involving the farmers in the design and test of innovative practices, as demonstrated by other studies (Cardoso et al., 2001; Lançon et al., 2007), but due the active participation of local and regional stakeholders as well as conducting the pilot studies at farmers' fields, which inspires the farmers. It is important to develop a multi-stakeholder dynamics to design the innovative solution for complex agricultural problems. It is unlikely to find successful solutions if different dimensions of the problem are analysed and treated separately (Hall and Clark, 2010). Stakeholders participation in the design and assessment process provide better understanding of different aspects of the problem, and solutions that are both technically feasible, and economically and socio-culturally acceptable by the farmers (Faysse, 2006).

This study demonstrated an example of combining qualitative and quantitative methods with the participatory researcher and stakeholders' analyses to address the complex agricultural issue of GHG mitigation. Schut et al. (2015) also used a similar approach called RAAIS (Rapid Appraisal of Agricultural Innovation Systems). RAAIS is a diagnostic tool, derived from the agricultural innovation system approach (Hall et al., 2003) and the multi-level perspective (Klerkx et al., 2012), that aims to provide a set of entry points that can enhance innovation capacity of complex agricultural system. In our work, we use the same type of methodological approaches (multi-stakeholder workshops, semi-structured interviews, group discussions and participatory field trials), but our focused entry point is the co-design of a prototype (practice) with the stakeholders. We believe that prototyping allows us to go beyond workshops and interviews because it allows us to confront the speeches and the knowledge of stakeholders with the reality of innovation and what it is changing. Hence, prototyping builds innovation capacity by acting together.

3.4. Dissemination and evaluation

Given the national legislation prohibiting residue burning and the lack of sustainable residue management options and incentives available to farmers, local stakeholders collectively agreed on residue incorporation into the soil rather than residue burning. With the conventional practice of continuous flooding, residue addition will result in an increase in CH_4 emissions. Continuous flooding of rice fields will result in the increased GWP of the rice production system, and will be less economical in terms of water consumptions. Furthermore, local stakeholders pointed the benefit of drainage during the season in term of reduce lodging losses and water saving (Fig. 5). The local agricultural advisors favored the M practice as being a more feasible improved practice, due to its ease of implementation on farmers' fields, however M is not enough to reduce the GWP of rice production with added residues. The design drainage practices have the potential to reduce GWP, but are constrained by farmers' limited labor resources, intensive crop rotation cycle and inadequate water control system in their fields. However, EM performed well in term on reducing the GHG emissions in fields and farmers observed no yield losses (Fig. 4 and Table 2).

The main drivers identified for possible future implementation of EM prototypes in rice farmers' fields on the Red River Delta include environmental regulation, economic benefits in terms of water savings and high rice yield, and no extra costs to smallholders. EM could be implemented successfully in farmers' fields, even with the farmers' limited resources, poor field water control infrastructure and absence of incentives. The PM also has the potential to reduce the GWP of the rice production system, but its implementation conflicts with farmers' field operations due to their tight cropping rotation (two weeks between spring and summer season), limited labor and traditional festivals (before start of spring season). Furthermore, farmers' reluctant to drain their fields during tillage operations due to uncertainty of water availability, extra charges for re-pumping water in their fields and possible delay in transplantation. PM could be successfully adopted on farmers' fields if the government were to provide incentives for developing the field canal infrastructures and assist farmers with re-pumping water into their fields during land preparation. The participatory approach of design and assessment was useful for developing the site specific and feasible mitigation practices, which have potential to implement in farmers' field conditions. The EM could be adopted as a mitigation practice in an area with similar constraints. Furthermore, the participatory approach used in this study can be adapted in other growing areas to design the site-specific feasible mitigation practices for crop production systems.

In this study, participatory co-design and assessment approach deal with the specific and generic entry points, to increase the awareness of complex agricultural issue of climate change mitigation and increase the stakeholders' collaboration at different level (*e.g.* farmers, local advisors, provincial level) to find innovative mitigation solutions. Furthermore, the methodology used in the present study was useful for designing site-specific mitigation practices for rice production systems. Krupnik et al. (2012) also conducted a study for three seasons with a farmer-researcher collaborative method to develop rice management systems that fit the local conditions. They showed that farmer participatory technology development needs several cycles and seasons to lead to improvements. Our methodology led to results in two growing seasons; it would be doubtless most beneficial in multi-season efforts, in which stakeholder's work closely with farmers to improve the practices. We believe, as written by Krupnik et al. (2012), that experiential learning-based approaches could yield similar benefits elsewhere. The use of simulation models with participatory approach may also increase the confidence in the stability of results across the various cropping rotations, land management, soil types and climate.

4. Conclusions

We adapted the participatory method of prototype design and assessment to address the complex issue of GHG mitigation in rice production with a wide range of stakeholders of different levels and interests. The participatory approach was used to collect information on local indigenous knowledge, resources and constraints, and then this was combined with scientific knowledge in order to propose and assess mitigation solutions through the co-design and the test of mitigation practices. In this case study, the involvement of local stakeholders, especially farmers, from the design to assessment of mitigation practices build a confidence to implement mitigation techniques in their fields. Furthermore, multi-stakeholders' participation and analyses provide the basis to design feasible and acceptable mitigation practices.

The present study also indicates that mitigation practices should be adapted with the local conditions. The smallholder in the study area have special constraints for sustainable management of crop residues due to the intensive cropping cycle and limited labor. The results showed that early plus midseason drainage (EM) is more feasible and acceptable mitigation practices under farmers' conditions, since it considerably reduced the GHG emissions from added residues without reducing the farmers' rice yield. However, the broader promotion of EM as a feasible mitigation practice is not appropriate, nor was it the goal of this study. While, the participatory approach used to develop the EM are likely to be of broader value. This participatory approach can be used as an entry point to develop the innovative and feasible mitigation solutions according to the local circumstances.

Therefore, we emphasize the involvement of researchers, farmers, local and regional stakeholders, and adaptation of local practices to design innovative mitigation practices. Hence, whereas the current study was limited to just one cycle, this participatory approach may be improved in particular through long-term, and broader studies under different cropping rotations. Furthermore, there is a potential to integrate the analytical modeling methods into the participatory approach to design a future feasible scenario for low emissions crop production systems.

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