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2 Executive summary

Farming rice and shrimp in an integrated pond system is practiced widely in the Mekong Delta where dry season soil and water salinity is too high to continue with rice monoculture. These integrated systems involve farming rice in the wet season when soil and water salinity is normally negligible, and shrimp in the dry season when soil and water salinities exceed the tolerance of rice. In recent decades, these systems have been subjected to rising salinity due to climate variability and reduced freshwater flows into the Mekong Delta from upstream river regulation for dams and abstraction of water for other land uses. Consequently, wet season salinity is increasing and creating sub-optimal conditions for rice; dry season salinity is also becoming sub-optimal for shrimp at some locations due to hypersalinity. Nevertheless, these rice-shrimp systems, when risks are managed and location conditions are suitable, provide an opportunity for farmers to maintain production throughout the year.

This project was initiated at the request of the Ministry of Agriculture and Rural Development (MARD) to 1) test the farming system for scaling out; 2) identify risk factors for rice and shrimp production; 3) better understand the benefit of growing rice and shrimp together; and 4) create a basis for developing better management practices. Initially there was a focus on scientifically validating the efficiency of these systems; however, severe drought conditions caused recurrent rice crop losses and impacted on the research at Hoa My Commune in Ca Mau where farmers faced the challenges of severe salinity and acid sulfate soils. This led to more in-depth research on the risk factors for rice and shrimp production.

A review of the project recommended that the project should be extended to include research activities at study sites that were less impacted by severe drought. The project extension enabled the team to conduct field trials on system processes, farming risk factors and testing better management practices. Tan Bang Commune was selected as a second site. Site characterisation and risk factors for rice and shrimp production where evaluated along with data collection at Hoa My Commune for comparative purposes. Based on the findings of the risk factor studies, and the outputs of a scientific and expert (farmer) Bayesian Belief Network (BBN), a series of salt-tolerant rice trials were conducted, better farming practices were tested for rice and to a lesser extent shrimp, and shrimp health was evaluated and linked to farm conditions to create a knowledge platform for future research. The trials identified suitable salt-tolerant rice varieties, demonstrated that sludge from shrimp farming could be used to replace fertiliser for the rice crop, and rice platform conditions could be improved by tilling, washing and leaching of the residual salt and modifying the rice growing platform.

The project also made recommendations on the timing of sowing to address salinity issues that affect the early stages of rice growth. These practices reduce the need for fertiliser, have improved rice yields, and increased the profitability of rice-shrimp farming system. The study found that natural food production is low for shrimp due to water quality conditions that do not enable the conversion of nitrogen to natural food. Shrimp are also stressed by low dissolved oxygen concentrations and, periodically, by salinity and water temperatures outside their optimal range for growth and to maintain health. Further research is needed to test better management practices for shrimp nutrition and methods to increase dissolved oxygen concentrations and temperature conditions. Pilot trials demonstrated that shrimp yields could be improved e.g. supplementary feed can increase the value of the shrimp crop by USD 1500 annually.

The project was led by the University of New South Wales and the Research Institute for Aquaculture 2 (RIA2), and involved Can Tho University (CTU), Griffith University, Charles Sturt University (CSU), the Cuu Long Rice Research Institute (CLRRI) and the Department of Agriculture and Rural Development (DARD) in collaboration with farmers from Hoa My and Tang Bang Communes in Ca Mau, Vietnam. Farmers from Kien Giang and Bac Lieu also contributed to the development of the BBN that framed the research.

3 Background

The Mekong Delta is the most important rice-producing region in Vietnam and accounts for more than 50% of annual rice production (General Statistics Office, Vietnam, 2012). Approximately 70% of agricultural land in the Mekong Delta is under rice cultivation, but in areas influenced by dry season salinity, rice farming is restricted to the wet season when the salinity of canal and other surface waters is sufficiently low for the available rice varieties. In recent years, rice farming in the wet season has resulted in regular crop losses attributed to elevated salinity associated with high evaporation rates, modified canal networks, changes in how tidal gates are operated, expansion of brackishwater aquaculture, lower rainfall and shorter wet seasons (Nhan et al. 2007, 2011). Farmers are also changing water management practices to extend the shrimp growing season leading to longer periods of soil and water salinity that then impacts the rice growing season.

Shrimp is the most valuable commodity for the region and accounts for 42% of the country's earnings from seafood production. Approximately 76% of Vietnam's shrimp production occurs in the Mekong Delta. The Government of Vietnam advocated (Resolution No. 09/NQ-CP) the conversion of unproductive agricultural land to higher value shrimp production systems. In the last few decades, integrated rice-shrimp farming has been promoted to minimise the crop failure risks associated with a rice monoculture system, and the need to maintain rice production levels but offer farmers an additional crop (shrimp) for income (Preston and Clayton 2003). Rice-shrimp farming is now widely adopted by former rice farmers, particularly in parts of the Mekong where there is seasonal variation in water salinity. Shrimp monoculture is restricted to areas close to the coastline where marine water intrusion is sufficiently high year-round to ensure shrimp are not stressed by low salinity.

A key feature of rice-shrimp farming systems is that they are commonly operated by families rather than commercial enterprises and involve low stocking densities and low-cost farm inputs. However, despite the reduced risks to crops due to the low-intensity farming systems, there are still issues; profitability has been low and production failures still occur. This is due to factors such as rainfall variability, modifications of the canal networks and increasing pressure on water resources. Flooding, drought and unpredictable variations in water salinity are significant risk factors for rice and shrimp. Therefore, rice-shrimp systems have become increasingly difficult to manage, leading to environmental and livelihood impacts.

Recent research has identified new salt-tolerant rice varieties that have the potential to be used on farms affected by residual salt from shrimp production in the dry season (CLRRI, unpublished data). Additionally, a project funded by the Ministry of Agriculture and Rural Development (MARD), and coordinated by RIA2, designed new rice-shrimp farming systems to a preliminary stage which were then tested by this project. In a 2010 ACIAR Country Consultation process, the Government of Vietnam identified a need for research on the risk factors for rice-shrimp farming systems, the benefits of farming rice and shrimp in an integrated system, testing of the new farming systems and modification of pond and canal designs to manage constraints and improve both rice and shrimp yields. To date, there has been a lack of scientific investigation into risk factors for this farming system, particularly environmental constraints and ways to manage them. An understanding of the underlying processes and mechanisms was urgently needed to develop appropriate management strategies and to enable farmers to respond to increasing wet-season salinity.

The benefits of farming the two crops in the same system was, prior to this research, anecdotal with a paucity of research on processes that, if understood, could enable more efficient farming and determine the influence of one crop on the productivity of the other. The main aim of the project was to scientifically test the efficiency of the system and to more specifically identify and describe risk factors for poor production, to study the movement of nutrients and evaluate the benefits of farming rice and shrimp in the same system as a basis for improving the crop yields and reducing farming costs. The study commenced in 2013 in Ca Mau and involved capacity building, studies on soil and water quality, assessment of nutrient dynamics and growth performance of rice and shrimp, and eventually developing better management practices for rice that were assessed over several rice growing seasons. Trials on better management practices for shrimp were also undertaken following a comprehensive study of environmental factors identified key water quality variables that affected shrimp health and nutrition.

The main outputs of the project include scientific knowledge on pond/rice platform processes, a better skilled research team with expertise in evaluating soil, water, rice and shrimp interactions, scientific publications on risk factors for rice and shrimp production, a publication on better management practices for rice farming, extension materials for technical and extension officers, and guidelines for farmers. The project also captured and analysed socio-economic data on rice-farming systems, built strong partnerships between scientists, extension and technical officers and farmers, and facilitated partnerships and information exchange between farmers and farmer groups.

Figure 1: Rice-shrimp farming system showing the raised rice platform and surrounding ditch where shrimp and crabs are farmed. Source: J.Sammut, UNSW

4 Objectives

The overall objective was to understand the mechanisms, processes and functionality of rice–shrimp farming systems through rigorous scientific investigations in order to achieve sustainable production. The specific objectives were:

1. To better understand the key components of the sustainability of rice-shrimp farming systems;

2. To determine the sustainability of the rice-shrimp farming system by testing the identified key risk factors and system components;

3. To determine, explain and quantify the benefits to productivity of integrating rice and shrimp farming; and

4. To identify and promote better management strategies to improve productivity and sustainability of rice-shrimp farming systems.

Figure 2: Over 20 salt-tolerant rice varieties were tested at Tang Bang Commune. Several strains were selected for further trials and higher yields were achieved. Photo: J.Sammut (UNSW)

5 Methodology

Objective 1: To better understand the key components of the sustainability of rice-shrimp farming systems

1.1 Compile existing information held by researchers/publications

Information was sourced from peer-reviewed publications and government and non-government agency reports, and a comprehensive literature review completed. The findings of publications in Vietnamese were translated into English by RIA2 staff. Content of some materials was analysed using NVivo software to identify common themes. The resulting literature review will be revised to incorporate findings from the project and new knowledge from other research; a final review will incorporate findings from the literature review and project-based research to produce a manuscript on the status, challenges and management of rice-shrimp farming that will be submitted to a scientific journal.

1. 2 Conduct research focus group workshops to develop an initial BBN

Focus group workshops were undertaken over several stages with extension officers and farmers in each region (Ca Mau, Bac Lieu and Kien Giang). Groups of experts were formed to capture knowledge and experience critical to understanding the key aspects of the rice-shrimp farming system. These workshops occurred over three research trips in October 2013, July 2014 and November 2015. The main output of these workshops was the development of the BBN. We followed an iterative process of validation at each stage of the workshops to ensure specific regional biases did not affect the outcomes, and to ensure the BBN reflected the knowledge and experience of these participants.

The entire process began with a one-day introductory training workshop for facilitators from RIA2, CTU, CLRRI, who worked with the BBN developers to interact with the farmers and policy officers as facilitators and translators. The preliminary training workshop focused on the theory and application of BBNs and culminated in groups of researchers developing and presenting their own BBN for scrutiny by other workshop participants. This process ensured the training worked in two directions - the newly trained facilitators had a clear understanding of the BBN development process from beginning to end, and the BBN trainers and modellers were introduced to important environmental and agricultural processes, as perceived by the facilitators. Understanding the processes that were viewed as important by the facilitators also helped identify possible biases they may have unconsciously focused on in the subsequent expert elicitation workshops. Given the language barrier between the modellers and the experts, these biases may have otherwise been missed.

Following the training workshop and an initial research trip, a core group of facilitators from RIA2, CTU and CLRRI worked closely with the BBN developers to produce the prototype BBN.

While the final BBN was not completed until early in 2016, the initial focus groups held in October 2013 and July 2014 identified key insights and factors that affect the sustainability of rice-shrimp farming systems. From these workshops, we were able to develop and modify key components of research on the farms.

1.3 Conduct training in BBN development

We conducted four formal training sessions in BBN development over the life of the project, involving team members from RIA2, CTU and CLRRI. The training sessions are summarised in Table 1. Informal training was also provided to the team.

Table 1: Summary of formal BBN training sessions

Location	Date	Title	Attendees
RIA2 Sub-station Ca Mau	October 2013	Introduction to BBNs	All team members who attended project inception, approx 25.
RIA2 – Ho Chi Minh City	July 2014	Bayesian Belief Networks for agricultural decision making	Five team members including 3 staff from RIA2, 1 staff from CTU and 1 student from GU.
CTU – Can Tho	February 2018	Using Bayesian Belief Networks as a tool for making agricultural and environmental decisions	13 participants including 3 staff from CTU, 2 staff from CLRRI and 9 students from CTU.
RIA2 Ho Chi Minh City	November 2019	Using Bayesian Belief Networks as a tool for making agricultural and environmental decisions	5 participants who were all staff from RIA2

Objective 2: To determine the sustainability of the rice-shrimp farming system by testing the identified key risk factors and system components

2.1a Test the influence of key factors that will affect nutrient availability and rice yield

Soil surveys were conducted at both field sites (Hoa My and Tan Bang Communes) on farms involved in the project activities (n=18 and n=6, respectively). Profile descriptions, including chemical analysis for soil horizons, were recorded. Soil characteristics were examined to ascertain possible limitations to rice production. As salinity was ranked as the greatest risk factor during the BBN development phase, the salinity of canal water and field water was recorded at all farms throughout the rice and shrimp production seasons.
The relationship between surface water salinity and soil solution salinity was studied on a subset of farms at Hoa My Commune. This work demonstrated that soil solution salinity was a more useful metric for temporal studies relating to plant production. Consequently, soil solution salinity was included in basic measures at study sites, including Tan Bang.

The influence of salinity on rice production was studied in glasshouse trials and in the field. Rice variety trials were conducted at Hoa My and Tan Bang to test short duration, salt tolerant varieties against long duration traditional varieties. At Tan Bang successful varieties were short listed following a field trial (n=16) in 2017 for time of sowing (n=3) trials in 2018.

2.1b Quantify the improvement to rice production possible by platform preparation

Research conducted in years 1 to 3 at Hoa My identified salinity as the key limitation to rice production rather than nutrition. Prolonging the shrimp season, along with the conditions of drought at the end of the shrimp season, elevated salinity of the soil solution and ponded water. This caused a delay in establishing the crop, death of seedlings and plant stress at the start of season, and termination of grain formation at the onset of the dry season.

Greenhouse and lab trials indicated that removal of salt could be enhanced by facilitating leaching rather than the current farmer practice of horizontal washing (dilution) on the soil platform. Pot trials conducted at CTU, CLRRI and CSU examined the efficiency of decreasing soil solution salinity by soil management (liming, tillage) and water management (washing and manipulating water height). These findings were validated in field trials at Hoa My (tillage, water height management) and at Tan Bang (tillage and liming, improved drainage). Time of platform preparation was also studied in the field at Tan Bang in conjunction with time of sowing trials.

The method of sowing of rice was also tested in the field. At Hoa My commune, rice was either transplanted or directly sown on different farms. At Tan Bang, the farmers had begun to experiment with throwing seedlings onto the water covered rice platforms. This method was thought to provide the seedlings with more time in the less saline surface soil than transplanted seedlings that are pushed into the soil that may be saline below the surface. Field experiments were conducted to test the influence on rice yield of these two methods.

Platform preparation has also been shown to be compromised when shrimp are also grown in the wet season with rice. Even so, platform preparation remains a response sensitive management activity for farmers. Research in year 4/5, under the project extension, trialed low-cost management options for farmers at the Tan Bang site where only rice is grown in the wet season. Utilization of pond sludge generated from a shrimp crop as fertilizer in accordance with applying enhanced salinity washing techniques at the early wet season is promising to bring higher certainty for the rice crop, and as a consequence, sustain the integrated system of rice and shrimp. Farmers, researchers and DARD considered this a key research activity that required refinement under field conditions at Tan Bang. The potential transferability of this work should provide substantial benefits to large areas of the Vietnamese Mekong Delta at a time of predicted increases in salinization.

2.2 Quantify the fertiliser replacement value of shrimp pond sludge in rice cultivation

Shrimp pond sludge accumulates during the shrimp production phase because of waste from feed (when used – often not), faeces, algal production and accumulation of dead diatoms. Sludge can be used as a source of onsite fertiliser that supplements mineral fertiliser used in the rice production phase. At both Hoa My and Tan Bang, sludge was collected and quantified from a number of ponds to determine the chemical composition (e.g. available and total organic carbon, N, P, K, S, and salinity) of sludge within the system. Two methods of sludge collection were tested; direct collection or in-situ sludge traps at Hoa My.

Incubation experiments were carried out in the lab at CTU to examine N and P mineralisation from sludge from various locations within the field. Field trials, utilising micro-plots, were conducted in the rice crop to determine the fertiliser replacement value of sludge on selected farms. In Hoa My, field trials were continuously conducted in years 2014 and 2015, and we tested sludge use as full or partial replacement of inorganic fertiliser at full or fractional recommended rates. Experiments conducted at Hoa My in Year 1 of the project demonstrated that decreased fertiliser use might result in economic savings without any deleterious effect on rice yield in saline compromised environments. Severe drought and salinity caused trial failure in Year 2. As such, further field validation was required before results could be extended with confidence. DARD required at least two crop cycles before considering a modified practice thus trials were moved to Tan Bang Commune where conditions were more amenable to experimental work and more representative of the conditions faced by farmers across the rice-shrimp farming areas of the Mekong Delta. The same trial was thus repeated at Tan Bang in 2016 and 2017. The results from the repeated field trials demonstrated that sludge could fully replace chemical fertilizers applied as farmer's practice, even higher grain yield could be gained as supplying sludge combined with fractional amount of chemical fertilisers.

The outcomes of these trials informed the soil management component of the BBN. As for all activities, economic data were collected to feed information into the Economic BBN and to demonstrate costs to farmers and extension officers.

2.3 Train staff in laboratory and field research techniques

The Australian project staff trained research and technical staff in Vietnam partner agencies building their skills in soil and water assessment, the use of isotopic tracers, live food classification and other laboratory and field methods. A training needs assessment was undertaken in Year 1 to ensure that research and technical staff would be trained in relevant skills areas before research activities were implemented. The training program also built research and technical capacity that will continue beyond the life of the project. Staff of RIA2, CLRRI and CTU participated in the training, and one CTU team member was trained in nuclear techniques (Isotopic and elemental profiling) at UNSW and ANSTO. Moreover, staff were also trained in data analysis and report/paper writing in both languages. Farmers were trained to check water quality and shrimp health on-site, evaluate results and to collected shrimp and rice samples for analysis. Research students in Vietnam and Australia were engaged in projects aligned with the research of the project. Six UNSW interns were also hosted by RIA2, CTU and CLRRI; the interns participated in field work, surveys and focus group discussions. There was one PhD student from CTU working on analyses of nutritional values of sludge and determination of rice's N use efficiency from sludge in comparison to that from chemical N fertilizer. He successfully passed the internal defense round and is expected to present his dissertation in late 2020.

Objective 3: To determine, explain and quantify the benefits to productivity of integrating rice and shrimp farming

Detailed investigation of nutrient processes within the traditional rice–shrimp system and comparison with the new designs were conducted. This involved determining nutrient balances and using isotopic tracers to determine dominant inputs and outputs to explore linkages between rice and shrimp crops. These studies allowed the benefits of rice to shrimp farming and vice versa to be evaluated, as well as identifying where the current system is unsustainable and could be improved.

3.1 Determine nutrient (carbon, nitrogen, phosphorus) balance and of the rice–shrimp system in traditional and improved systems

Six traditional and six each of the improved pond designs were used in Cai Nuoc district (Hoa My Commune), Ca Mau Province, to determine carbon, nitrogen and phosphorus budgets for both the rice and shrimp cycles over one year. The total volumes of water in ponds, water exchange, nutrient concentrations in the water (including dissolved nutrients such as ammonium), and sediment biomass of particulate matter in the water column, the platform and stubble were determined. These data were important to refining soil leaching/soil washing methods to prepare rice platforms and underpinned trials at Tan Bang under the project extension. Additionally, rice and shrimp seed stock and harvest biomasses, and food/fertilizer inputs were assessed. This involved regular visits to ponds by researchers to undertake sampling and collate information from farmers. Whole-season, whole-pond nutrient and carbon budgets were constructed for both current and improved systems.

3.2 Quantify temporal water and soil quality parameters throughout current and improved rice–shrimp systems

Temporal changes in water and soil quality parameters were measured in the same ponds used for the nutrient balance estimates (Activity 3.1). This included assessment of the effectiveness of reservoirs in the MARD system to buffer high salinity during the rice production season. Water and soil samples were collected from the rice platform, surrounding trench, dyke walls, and associated nursery pond (improved farm design) to determine their specific influence on pond environment. This included samples for pesticide analysis by RIA2 and shrimp health assessment. Systematic or fixed interval sampling was used, but the frequency of sampling was increased during a change in farm practice, increased rainfall or other acute events. The number of samples and key variables were determined by the design of field experiments. The key soil and water variables were measured to describe spatial and temporal variations during the production cycles. This activity provided data for Activities 2.1, 3.1 and 3.3. Physical and chemical properties were determined using standard *in situ* and laboratory methods. Where possible, data loggers were used for basic variables such as water temperature, water depth, dissolved oxygen, pH, EC and turbidity. Additionally, soil parameters were measured including but not limited to REDOX, pH, EC, iron, aluminium, hydrogen sulfide. Regular, fixed interval, *in situ* spot measurements were also collected at logged sites as a backup.

Water depth was identified as a factor likely to affect food availability for shrimp. Water depth affects the water temperature on the platform, which in turn affects the likelihood of shrimp accessing the platform during the hot hours of the day. Additionally, water depth affects the scale of epiphyte growth on the rice stubble. Epiphytes and benthic algae provide a potentially important source of food for shrimp. Key parameters were measured in situ to determine the availability of the platform for shrimp, and the amount and quality of food available on the platform. This was done in the same ponds as those used for nutrient balance studies (Activity 3.1). Access points were built on a number of ponds for sampling and measurements on the platform. Temperature loggers were deployed onto platforms to measure temperature and water depth. Epiphyte biomass and nutritional composition were measured by sampling rice stubble structures and harvesting the epiphytes per plant, and benthic algal biomass, throughout shrimp grow-out seasons.

In years 3 and 4, sampling was undertaken in Tan Bang district, Ca Mau province in three farms to measure and analyse the same parameters outlined above.

3.3 Determine the contribution of an annual rice production cycle to production of shrimp, and vice versa, within the rice–shrimp system

A pilot study was undertaken to determine variability in key measures related to nutrient cycling within platforms and between ponds; this was conducted during the first year of shrimp culture when the carbon, nitrogen and phosphorus budgets were determined for the shrimp cycle. This involved sampling multiple quadrats for epiphyte, benthic algae and rice stubble biomass, and soil samples for nutrients at each site. This set the foundation for the spatial intensity of sampling required to capture the variability across platforms in the next shrimp season, when the labeling studies were done.

The contribution of rice crops to shrimp production was examined in the second year. This involved using infield microplots allowing the spiking of rice with ^{15}N-labelled urea fertiliser and allowing the incorporation of the signal into the plant. After harvesting, the ^{15}N values in the rice and stubble were determined, giving a measure of the efficiency of fertiliser to the rice crop. Importantly, the ^{15}N in the labeled stubble was then traced through the food chain to the epiphytes within those microplots. In a separate ^{15}N labeled field study, run parallel to the microplot trial, ^{15}N was added to the water and by sampling epiphytes and shrimp, the transfer of ^{15}N from epiphytes and benthic algae on the platforms to the shrimp was determined. This combined experiment was undertaken in a trial phase in the first year, then refined and repeated in the second year. The data were used to quantify the contribution of nitrogen from the rice crop cycle to the shrimp production.

During Years 1 to 3, rice crop failures at Hoa My Commune, due to excessive salinity, did not allow the contributions of rice production to the shrimp production component to be examined. The establishment of the Tan Bang study location enabled the research team to collect data from reliable rice crops and this enabled the broader influence of rice on shrimp production to be determined. Research in year 4/5 (under an extension) included field experiments conducted with and without rice establishment to determine the effects of rice on soil quality and associated nutritional dynamics influencing the following shrimp production season. At the end of the rice crop, rice stubble was also sampled to estimate the amount of rice residue remained in experimental plots.

The effects of pond sludge on the rice performance, which in turn affects the shrimp health and production in the following season, were also validated in the extension phase at the new location. Sludge addition combined with rice or without rice experimental treatments was designed at large scale in-situ. At harvest, grain was collected separately to measure the rice yields, whereas rice plant biomass and stubble were used to determine the effects of the rice planting and rice residue on the variation of soil and water chemical variables impacting on the following shrimp growth and production.

The production of hydrogen sulfide from contrasting pond sediments was studied in lab column studies. Hydrogen sulfide volume produced and the resultant concentration in the head water was reported during the incubation study.

This objective was also combined with Objective 3.5; see methods below.

3.4 Develop a growth model for shrimp in rice-shrimp ponds

In the first two years of the project, at Hoa My Commune, farmers grew shrimp throughout the shrimp season and into the rice season. Survival in all rice-shrimp ponds was poor, <10% but it was unclear whether this was representative of survival in rice-shrimp ponds in the Mekong Delta more generally or was specific to the management practices at this site. There was semi-continuous stocking and harvesting and information on stocking and harvesting was gathered. However, there were insufficient resources to monitor this at a scale that identified the factors causing poor survival. Additionally, the lack of a rice crop (due to high salinities) in both years in Hoa My resulted in less natural food for shrimp. In year 3, the study site of Tan Bang was the focus as this region has much higher rice production and does not grow shrimp into the rice season (an activity that compromises both rice and shrimp production). However, in the third year, drought conditions resulted in extreme temperatures and hypersaline conditions, both of which are likely to have contributed to poor survival by the shrimp.

In year 4/5 we proposed to continue work at the Tan Bang site but during the shrimp season the focus was on gaining more detailed information on shrimp growth by undertaking weekly measurements of weights of individual shrimp. A preliminary trial was conducted in 2016 to determine an optimal sampling strategy because farmers stock more than once during a cropping season, i.e. we trialed gear type, number of animals for statistical robustness and frequency of samplings. This was combined with continuous measurements of the key risk factors for production, i.e. salinity and temperature. Additionally, oxygen concentrations were measured regularly. Other key farm management data were also collected, e.g. stocking number, harvest and weights, and other inputs and outputs from ponds. The involvement of the extension service, DARD, was key to the success of this work and DARD officers committed support for the extension to the project. The combination of information on water quality, and shrimp growth and survival, helped us to determine whether poor shrimp survival was the result of chronic or acute water quality events over the shrimp season. From this preliminary trial in 2016, a substantial data collection effort was set up for 2017 to monitor water quality, densities of natural food and shrimp growth and condition. Water quality parameters, including salinity, temperature and dissolved oxygen were monitored daily throughout the shrimp growing season. Densities of aquatic biota that may provide natural food for the shrimp were monitored fortnightly as was the size of shrimp in the ponds. These data were integrated into a set of statistical analyses including a growth model for the shrimp at each farm, to quantify how growth and yield may be related to water quality and the availability of natural food. The combination of information on water quality and shrimp growth and survival was then used to identify whether poor shrimp survival was the result of chronic or acute water quality events over the shrimp season.

3.5 Determine the nutritional state of shrimp and food quality in rice-shrimp ponds

As outlined above, the first two years of the study identified poor shrimp survival in the rice-shrimp ponds but it was unclear whether this was the result of atypical conditions at the Hoa My site. In the third year, when the study included Tan Bang as a study site, the drought also compromised shrimp production but not as severely as at Hoa My. However, the ^{15}N-experiments conducted at both Hoa My and Tan Bang suggested that there was insufficient high-quality food available for shrimp. Most shrimp showed little evidence of feeding and the number of primary producers needed to sustain the food web was generally low. If shrimp were nutritionally compromised, this would result in increased susceptibility to disease, and hence contribute to poor shrimp survival. Therefore, in year 4/5 we measured the nutritional status of the shrimp in the Tan Bang ponds. We measured the lipid content of the shrimp using the Folch method (Folch et al., J Biol Chem 1957, 226, 497). This can be compared with the lipid content of the food sources. Additionally, samples of both shrimp and food sources were analysed for fatty acid fingerprints to determine whether the food was of poor quality. Sampling was conducted periodically during the shrimp season at ponds at Tan Bang.

Objective 4: To identify and promote better management strategies to improve productivity and sustainability of rice–shrimp farming systems.

4.1 Refine and apply BBN – this activity will draw on outputs from all other objectives

The BBN from Objective 1.2 was integrated into a draft smartphone app to apply the BBN and provide an avenue for farmers and extension officers to interact with it. Users of the app can explore probable outcomes given a set of decisions in a given scenario. This app is in draft form and not intended for use as the BBN it encodes reflects the knowledge and experience of the farmers rather than the research findings. Nonetheless, it provided a framework to examine the various environmental conditions, including climate, that are encoded in the integrated BBN. As such, the app forms the basis for the ongoing refinement of the integrated BBN below. Farmer interest in the app was high and the participated in discussions on its development. The main desktop BBN is also now used by RIA2 and CTU and they have been trained to refine it over time (ie beyond the project).

4.1a Develop an integrated BBN

The BBN that was completed under Activity1.2 incorporated the knowledge and experience of farmers and extension officers from Kien Giang, Bac Lieu and the Hoa My commune of Ca Mau. This BBN was specifically designed to model risks to production where both rice and shrimp are farmed simultaneously during the wet season. This practice is not used at Tan Bang. As such, in addition to incorporating data from our research into the existing BBN, in year 4 we developed an integrated BBN based on research from both Hoa My and Tan Bang to accommodate different farming practices, including the seasonal rotation of shrimp and rice. The integrated BBN provides an opportunity to model processes that are generally applicable beyond the study region itself and represents a general integration of all research findings from the project.

During 2018, we conducted several workshops with the research team in Vietnam. These workshops were structured to capture the understanding of the researchers, given the research that had been conducted (and in some cases was still ongoing) under the project. We held separate workshops with the team at CTU and the team at RIA2 so as to devise the network structure for the rice and shrimp. A subsequent workshop was held to bring the components together in a manner that reflected the collective understanding of the research team.

Having derived a network structure through these workshops, we then refined the network to a simpler structure that can integrate the data collected under the project. This final BBN is not yet complete; however, it will be brought into the smartphone app to be made available to farmers.

4.2 Communicate better management practices through workshops and publications

Better management practices were communicated to DARD and farmers during field-based workshops and some formal meetings and workshops that were held in the local commune halls. Following each field visit, discussions were held with farmers and DARD officers; the discussions focused on findings from past work, updates on progress, and practical measures and better management practices that we had validated. Several extension materials were published in a booklet. However, the final workshop was postponed due to COVID-19 restrictions in Vietnam. A project extension was sought and granted in the hope that the final workshops could be run once restrictions on travel and gatherings are lifted. This activity might now run post-project with support from the Soil and Land Management Program.

4.3 Conduct train-the-trainer courses for DARD staff and produce associated training manuals.

DARD staff have been trained during the research program on better management practices, and a major series of workshops in different locations was planned but postponed due to the COVID-19 pandemic. Materials have been produced and were going to be used in workshops that were scheduled for March 2020.

<u>Additional Socio-Economic Study</u>

Under the extension, the project team initiated a socio-economic study involving CTU, UNSW and Griffith University. Participatory community appraisals were conducted to identify enablers and barriers to sustainable development of rice – shrimp farming systems and to understand the impacts on poverty reduction and gender, building on an understanding of sustainable livelihood elements, rice-shrimp farming practices and expected outcomes of farm households under different contexts such as bio-physical and wealth conditions. The appraisals were conducted at four economically and biophysically different sites including: (1) Hoa Tu 1 commune (My Xuyen district, Soc Trang province), (2) Phong Thanh commune (Gia Rain district, Bac Lieu province), (3) Tan bang commune (Thoi Binh district, Ca Mau province) and (4) Tay Yen A commune (An Bien district, Kien Giang province) (Figure 3). Sites 1 and 4 were considered relatively more favourable than sites 3 and 4 in land and water for rice and shrimp farming. Rice – shrimp farming has been practised since 1990s, early 2000s, late 2000s and 2010s at sites 1, 2, 3 and 4, respectively.

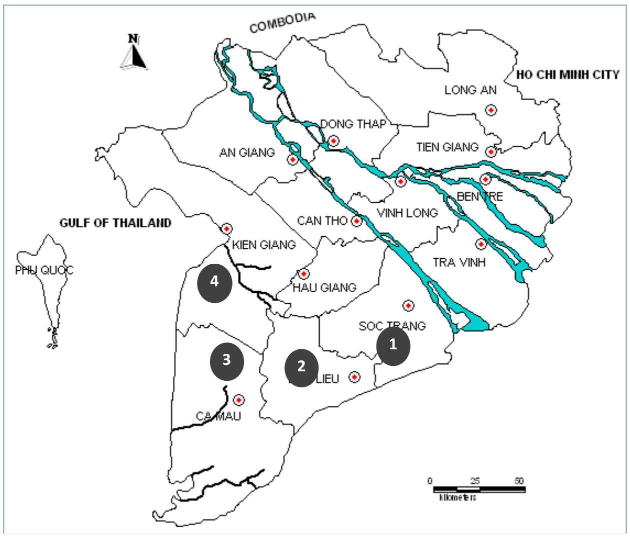

Figure 3: Mekong Delta map showing four appraisal sites: (1) Hoa Tu 1 commune (Soc Trang), (2) Phong Thanh commune (Bac Lieu), (3) Tan Bang commune (Ca Mau) and (4) Tay Yen A (Kien Giang).

Data were collected through three steps. The first step defined the context with local key informant panels to assess household wealth, which was conducted at three hamlets at each site, including a favourable, an intermediate and an unfavourable hamlet in terms of water and soil quality, and access to transportation roads and markets. A total of 3,557 households at the sites were assessed by local key informants, considering wealth types (rich, intermediate or poor), wealth mobility (improved, unchanged or declined) and major livelihood activities. In addition, strengths, weaknesses, opportunities and threats of rice – shrimp farming were defined, building on the sustainable livelihood framework (i.e. human, natural, financial, physical and social assets). The second step was understanding of expected outcomes and the enablers and barriers to rice-shrimp farming by households, using 16 focus-group discussions. A total of 133 local household members, which were represented level of wealth groups (i.e. rich, intermediate, poor and women), participated in the group discussions, four discussions at each site. The Analytical Hierarchy Process (AHP) method was applied to determine important enablers and barriers. The enablers and barriers were strengths, opportunities, weaknesses and threats of livelihood assets at household and community scales. Finally, individual in-depth interviews were done with 48 farm households, three interviews per group each site, participating in group discussions to collect input and output data of rice – shrimp farming practices. Combined with survey data of 26 households involved in rice – shrimp farming from CLUES in 2012, the dataset (n = 74) was statistically analysed to test for differences in yields and economic profits among household groups and relationships between resource inputs and outputs, applying univariate variance and multivariate canonical correlation analyses.

A second study, indirectly related to the project, was conducted by Ruby Annand-Jones (UNSW), an honours student under Jes Sammut's supervision; a manuscript is being prepared for submission to Ambio jointly with Jes Sammut and the CTU team.

6 Achievements against activities and outputs/milestones

Objective 1: To better understand the key components of the sustainability of rice–shrimp farming systems

No.	Activity	Outputs/ milestones	Completion date	Comments
1.1	Compile existing information held by researchers/ publications	Completed Literature review	November 2013	The literature review was undertaken over two stages, with one focussing on scientific papers and reports, and the other involving reviews of Vietnamese language papers, unpublished data and reports that are not accessible from search engines. The team intends to publish a review/status-of-industry paper, post project, after the remaining scientific papers from the project are all published; this is to incorporate new knowledge from the project. This activity is coordinated by Dr Sang and A/Prof Sammut.
1.2	Conduct research focus group workshops to develop an initial BBN	Complete prototype BBN Complete workshops	November 2013 Under the extension additional workshops will be completed by June 2018.	The original milestone was met in 2013. Additional *ad-hoc* workshops were included under a project variation because a BDN (economic BBN) was introduced as a new activity. BDN workshops commenced in August 2017 and completed in 2018. A paper documenting the process that was developed for this milestone was published in *Agricultural Systems* in October 2017 (See Appendix 1) We have completed an optimisation engine for this BBN, which assists farmers in making decisions through the growing seasons. It was presented at the International Conference on Computer Applications in Myanmar in February 2018 and a manuscript is under review. This BBN has also been integrated into a prototype smartphone app; it will be further developed to make the final BBN that integrates all of the project research findings (developed under Activity 4.1a) available to farmers.

1.3	Conduct training in BBN development	Complete workshops and report	June 2013-October 2017	Completed on time but additional training was provided to new project staff from RIA2 and CLRRI who were not previously involved in this activity. In addition to the training workshops completed in 2013 and 2014 for RIA2 and CTU staff, this continued into 2018 and 2019. A large training course was delivered to staff from CTU and CLRRI in February 2018. A final training course was delivered to RIA2 staff in November 2019. These workshops provided theoretical and practical instruction and the early training sessions ensured Vietnamese staff were able to be active participants in the BBN development leading to their co-authorship of the first BBN manuscript, published in 2017.

PC = partner country, A = Australia

Objective 2: To determine the sustainability of the rice–shrimp farming system by testing the identified key risk factors and system components

PC = partner country, A = Australia

No.	Activity	Outputs/ milestones	Completion date	Comments
2.1 a	Test the influence of key factors that will affect nutrient availability and rice yield	Complete soil column experiments Complete report on soil characteristics and nutrient availability Complete report on salinity monitoring	April 2016 September 2016 December 2017	Completed – data were used to underpin new rice growing trials, and then integrated into a larger data set for further analysis and synthesis. Salinity in soil pore water was identified as a risk, and surface water salinity may underestimate the impacts on rice production. Monitoring salinity in soil pore solution and surface water in the rice growing phase during two consecutive years 2014 and 2015 highlighted that the yield loss was due to the sensitivity of rice production in the Hoa My commune to high salinity rather than nutrition. Prolonging the shrimp season due to conditions of drought at the start of the rice season elevated salinity of the soil solution and ponded water. This caused a delay in establishing the crop, death of seedlings and plant stress at the start of season, and termination of grain formation at the onset of the dry season. Besides salinity as a critical limiting factor to rice production, in both locations soil characterisation showed that sulfuric materials and hydrogen sulfide generation hamper production of both rice and shrimp.

2.1 b	Quantify the improvement to rice production by platform preparation	Complete field studies Scientific report on platform preparation management Report on rice varieties tolerant to salinity at Tan Bang	Dec 2018 April 2019 April 2019	Platform preparation techniques, with particular focus on salinity washing improvement interventions, were evaluated during the rice seasons in 2015 at Hoa My and during 2016 and 2017 at Tan Bang. There were two Master students from CTU and one Honours student from CSU working on this topic. These trials included: i) the use of small ditches to wash salt from the soil, ii) use of freshwater reservoirs or field bunds to enhance salt leaching, and iii) amendment of lime in combination of plough at the start of salinity washing phase. Data have been compiled for salinity washing management and a scientific manuscript is under preparation. Rice variety trials were not successful at Hoa My due to severe salinity. At Tan Bang, rice varieties and time of sowing trials were conducted in 2017 and 2018. This work allowed variety selection based on salinity tolerance and duration of growth characteristics. Short duration rice varieties OM2517, OM18, OM348, OM429 & OM242 were identified as being well suited to the shrimp-rice system at Tan Bang. Besides, some other saline tolerant rice varieties were also recommended to grow in rice-shrimp systems such as ST24 and ST25 (duration 103-105 days) Integrated application trial for salinity washing (ploughing, liming, enhanced leaching via ditches, rainwater reservoirs) were undertaken at Tan Bang in the wet season in 2018. Pot experiments indicated that rice variety OM2517 could not tolerate to soil EC higher than 8 dS/m. Yield testing of 20 salt-tolerant rice varieties in 2017 at Tan Bang (water salinity 2-4 ppt) showed that A2 rice group (OM18, OM242, IR15T1434, IR15T1466, IR15T1112) gave higher yields than A1 group (OM2517, OM348, OM4129). system. Enhancing salinity leaching for better rice performance by different techniques was also tested in both field and lab experiments. Increased draining ditches on the rice platform or storing freshwater to suppress salinity was proved to improving soil salinity leaching and rice production.

2.2	Quantify the fertiliser replacement value of shrimp pond sludge in rice cultivation	Report - characterisation of sludge variability and properties Complete the fertiliser value experimentation Scientific report on fertiliser replacement value Scientific paper for international peer review is in preparation	October 2018 June 2018 December 2018 (Dates reflect incorporation of additional trials at Tan Bang and an extension)	The characteristics of sludge quality and quantity were determined. The variation due to location within farm was studied. The mineralisation of nutrients from sludge of varied sources was studied under laboratory incubations. The replacement value of sludge was studied at Hoa My and Tan Bang. Sludge is a low-cost option for rice production without loss of yield. This work was presented in the 2018 National Soil Conference, Australia. A journal paper is yet to be completed. The findings of this component populate the BBN and underpin the improved management practices included in extension materials of the project. The hydrogen sulfide production from sludge was determined in column studies to identify possible risks of sludge use to subsequent shrimp production. This work was presented in the 2018 National Soil Conference, Australia.
2.3	Train staff in laboratory and field research techniques	Training materials Deliver training workshops	December 2013 December 2013-October 2019	Completed and skills were applied.

Objective 3: To determine, explain and quantify the benefits to productivity of integrating rice and shrimp farming

No.	Activity	Outputs/ milestones	Completion date	Comments
3.1	Determine nutrient (carbon, nitrogen, phosphorus) balance and of the rice–shrimp system in current and improved systems	Complete first two years of data collection for nutrient budgets and feed/fertiliser at Ca Mau (Tan Bang has now been added and one more year of data collection requested).	June 2018 December 2018	A conference paper has been published on nutrient budgets in Hoa My farms (Dien et al, 2017) (see Appendix 1) A paper on nutrient budgets in Hoa My farms, led by Luu Dien Duc (RIA2 staff, John Allwright PhD student) was published in the journal, *Aquaculture* in early 2018 (Luu et al. 2017, see Appendix 1) and another on seasonal nutrient cycling in the journal, *Marine Pollution Bulletin* in 2020 (Luu et al. 2020, see Appendix 1).

		Complete report on the nutrient budgets and feed/fertiliser use for the rice-shrimp systems in Ca Mau and Tan Bang		
3.2	Quantify temporal water and soil quality parameters throughout current and improved rice–shrimp systems	Complete two years of environmental data collection at Ca Mau for Hoa My (completed) and for Tan Bang (to be completed under an extension)	January 2019	Regular data collection was undertaken at 12 farms in year 1 and 18 farms in year 2 at Cai Nuoc district in the first two years of the study and three farms at Tan Bang with improved management practices. These farms were compared with three farms using traditional methods. Management practices, sediment and water quality were measured. A paper was published in the journal, *Aquaculture Research* (Leigh et al. 2018, see Appendix 1)
		Complete report on environmental data for both study sites	June 2019	Sample collection for salinity monitoring in soil solution and surface water during the salinity washing phase was regularly conducted in both sites Hoa My and Tan Bang, where the salinity ingression and farmer's practices on salinity washing are different.

3.3	Determine the contribution of an annual rice production cycle to production of shrimp within the rice–shrimp system	Complete first stage of sampling for the contribution of growing rice to shrimp and shrimp to rice production Complete scientific report on the contribution of growing rice to shrimp and shrimp to rice production	January 2018 January 2019	See Objective 3.5 for details of ^{15}N experiments. In 2016, a field trial was setup in Tan Bang to investigate the environmental effect of having rice versus not having rice. This trial was repeated in 2017, and also examined redox effects and nutrient processes. In the 2018 wet season, a study on the contribution of rice to the following shrimp season was implemented at a larger scale, i.e. on the whole three farms with having rice vs. with no rice, to validate the findings from the experimental trials. Data on environmental quality under the presence or absence of rice is linked to the data on shrimp production in the following season. The analysis is progressing to synthesise data and findings from all activities at this site. Column studies were conducted to determine the possible sulfide toxicity of sludge in the shrimp system. Results were presented at the National Soil Conference – Canberra in Nov 2018 (peer-reviewed conference). Dr Khoi and Dr Vien presented on behalf of the team.
3.4	Measure growth and survival of shrimp, and key risk factors in rice-shrimp ponds	Complete scientific report with growth model for shrimp and identification of key risk factors affecting survival	February 2018	Data were collected during the 2017 crop and a growth model was constructed for each of the three farms. The outputs of the model were compared to critical water quality parameters and a manuscript reporting paper by Leigh et al (2020) was published in the journal, Science of the Total Environment (see Appendix 1).

3.5	Determine nutritional state of shrimp and food quality throughout growth season in rice-shrimp ponds	Complete scientific report on nutritional state of shrimp and food quality	October 2018	^{15}N-tracer pilot experiments conducted at Hoa My to optimise methods. Then in 2017, two experiments were conducted at two farms in Tan Bang. These showed that shrimp feeding was insufficient for growth, and appears to be due to inadequate food supplies, but water quality stress may also have impacted on feeding. A paper was published in the journal, Aquaculture (Burford et al. 2020) Regular sampling conducted in Tan Bang and Hoa My to determine food availability for shrimp showed that algal production was relatively low in both the water column and sediment, and hence there would be less food available to feed animals consumed by shrimp (Leigh et al. 2017, Luu et al. 2019, Leigh et al. 2020, Burford et al. 2020).

Objective 4: To identify and promote better management strategies to improve productivity and sustainability of rice–shrimp farming systems

No.	Activity	Outputs/ milestones	Completion date	Comments
4.1	Refine and apply BBN – this activity will draw on outputs from all other objectives .	Report with the refined BBN and its use in identifying the key factors that drive sustainability of rice-shrimp farming and examines management scenarios	March 2017 (revised again in 2019 to capture more information) Jan 2019	This activity was delayed because we are integrating additional data collected in late 2019 from ongoing field trials and experiments at Tan Bang, and to include information from RIA2 studies. An initial expert elicitation exercise was conducted with the Australian team members to define key nodes for the BBN and important thresholds for those nodes. These were refined following workshops with the Vietnamese team members in June and November 2018.

4.1 a	Develop integrated BBN	Report the integrated BBN and its findings of key drivers affecting sustainability of rice-shrimp farming generally.	July 2018	A final scientific BBN was developed and presented to the research team in November 2019; however, the data collected over the duration of the project was not able to support this BBN. Consequently, efforts are ongoing to refine the scientific BBN to a model that reflects the scientific understanding and data collected throughout the project. The structure of this network has been finalised and the integration the final datasets collected in 2019 will be completed by June 2020. Subsequent to this completion, the model will be integrated into the smartphone app to distribute to farmers.
4.2	Communicate better management practices through workshops and publications	Produce draft manuals and other publications covering different farming scenarios under different environmental conditions. Produce an economic analysis of the different management practices. Publish and disseminate manuals Deliver workshops	2017/2018 December 2018 2017-2019 2017 - 2019	Findings have been communicated to farmers during and post trials, via farmer workshops and through combined DARD and farmer meetings at the relevant communes. Data collection for the coupled BBN-economic analysis was successfully conducted in August 2017. Dissemination materials named “Farming technologies for rice-shrimp system” were printed in March 2020 and was scheduled to be presented to stakeholders in a series of workshops with farmers in March 2020. However, with the COVID-19 pandemic and restrictions on gatherings and travel, we postponed the workshop. Completed Workshops, as part of the dissemination program, have been held annually, and workshops involving advice on how to use the extension materials commenced in early 2020 and will continue once the COVID-19 restrictions are eased, and post project by RIA2 and DARD.

4.3	Conduct train-the-trainer courses for DARD staff and produce associated training manuals.	Extension training materials Establish a team of Trainers Develop extension plans and conduct training	March 2018 to March 2019 2018 2017-2019	A workshop in November 2017 incorporated findings from trials in 2017 at Tan Bang Commune. This workshop also discussed broader extension plans and reviewed the adoption strategy that is now being implemented and will continue post project. DARD has committed to maintaining extension support to farmers. Extension material content and format was discussed with farmers and DARD. Extension materials were prepared for a workshop in March 2020 but was postponed due to the COVID-19 Pandemic.

7 Key results and discussion

7.1 Bayesian Belief Networks

The expert derived BBN

As part of the initial information gathering stage of the project, we developed an approach for integrating expert knowledge of multiple stakeholders and produced a Bayesian Belief Network (BBN) that represented the knowledge and experience of farmers and to a lesser extent, extension officers of the region. This approach allowed us to ascertain the farmers' knowledge and understanding of the system while we were developing a series of experiments and monitoring efforts. The final output from the approach was an expert derived BBN that identified a complex series of interactions among environmental and agricultural factors that showed farmers recognised a narrow set of conditions that would prevent crop failure in both crops (Figure 4).

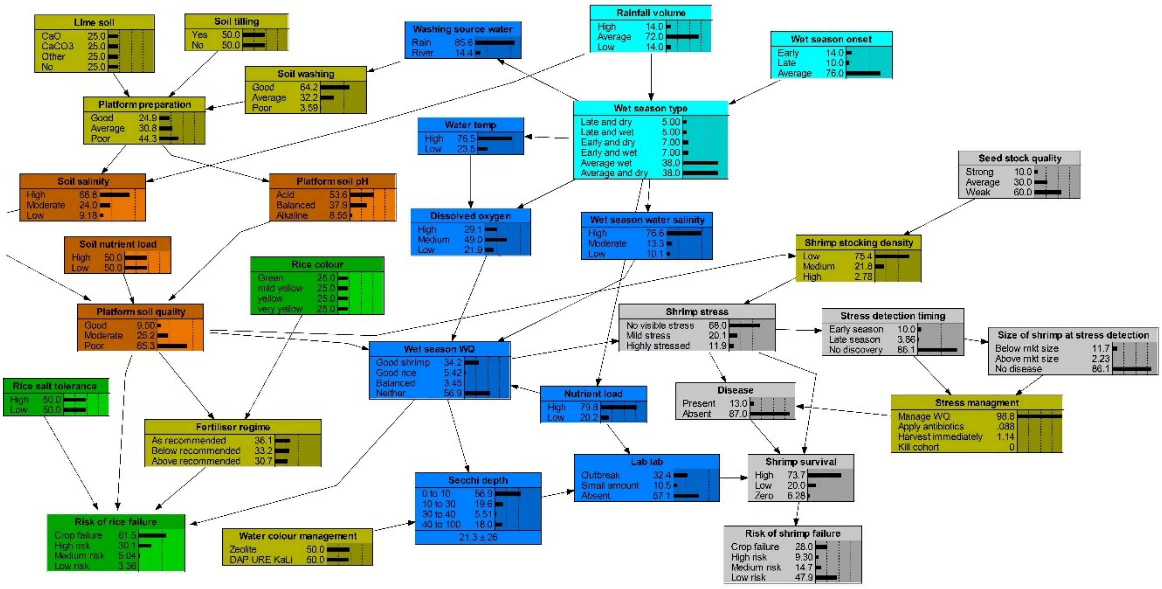

Figure 4. The final BBN representing the knowledge and experience of the participating farmers and extension officers

The key processes that the experts identified were generally consistent with available scientific evidence of processes that affect rice-shrimp farming in the region. However, it also ascertained some farming practices that the farmers were already trialling (e.g. soil tilling) but were uncertain of best practice for this technique. Consequently, this was integrated into the experimental work on the project to provide advice to farmers. Bringing this into the research program ensured the farmers were active participants in the research and secured their interest and support in the project. This BBN was encoded into the preliminary smartphone app, which will be updated with the scientific BBN (Figure 5).

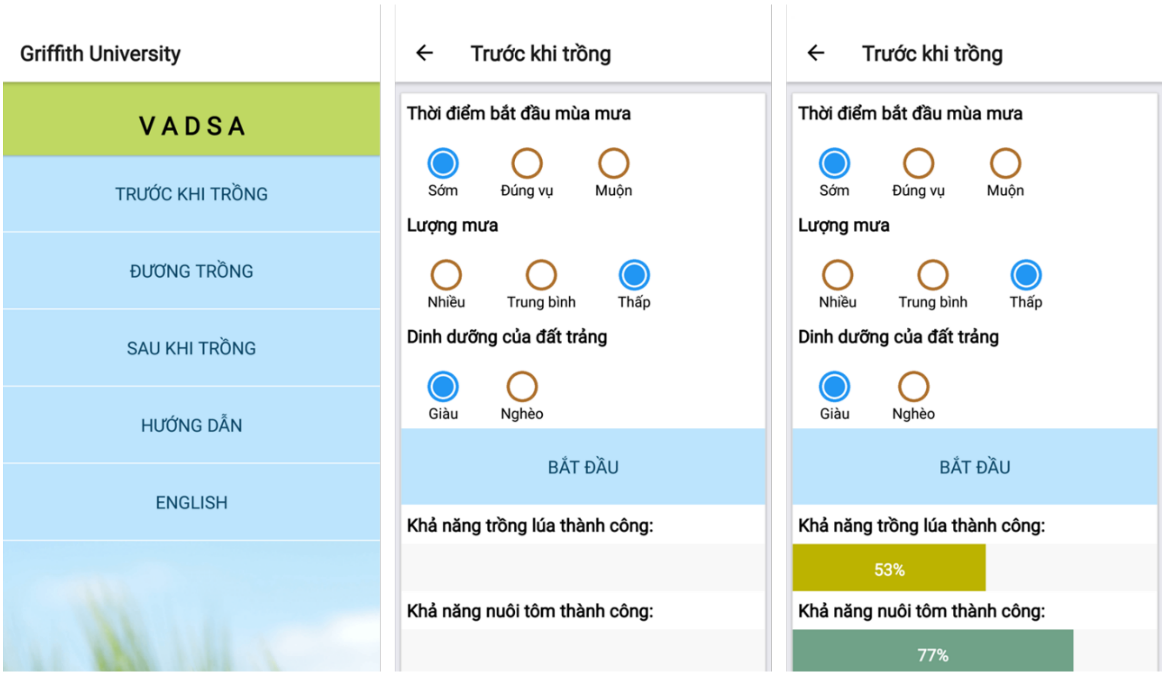

Figure 5. Screenshots from the draft smartphone app that provides an interface for farmers and extension officers to access the information in the expert BBN shown in Figure 4.

There are many ongoing issues facing farmers across the Mekong Delta that increase the risk of crop failure and innovative modelling techniques are increasingly important to ensure the research process leads to improved crop production and land management. Working collaboratively with the producers helps ensure outcomes and changes to farming practices are more relevant and likely to be adopted in an ongoing manner. The process to develop the first BBN with the farmers helped to engage them in the research process and develop a network model that was specifically relevant. It also provided a framework for us to develop a scientific BBN based on the research conducted in subsequent years on the project.

<u>The scientific BBN</u>

Having completed several years of experiments and research, we began a process of expert elicitation with the scientists on the research team to produce a BBN that reflected the findings of the project. This provided an avenue to build a BBN that incorporates our research findings and reflects the up to date scientific understanding of the system. The expert elicitation process produced a very complicated network that represented the collective understanding of the project team of the rice-shrimp system (Figure 6).

The scientific BBN captured the processes affecting rice-shrimp farming each year and was divided into three sub-components; 1) early stages of shrimp growth, 2) late stages of shrimp growth and 3) the rice growing season. Included in the BBN were nodes that represented decisions and actions a farmer could take to change pond and platform conditions. While this BBN did represent the scientific understanding of the research team, it was not able to be supported by the data collected during the project alone. As such, we held supplementary workshops to simplify the BBN so that the relationships it included could be quantified based on project data (Figure 7). This second scientific BBN will be built into a revised smartphone app.

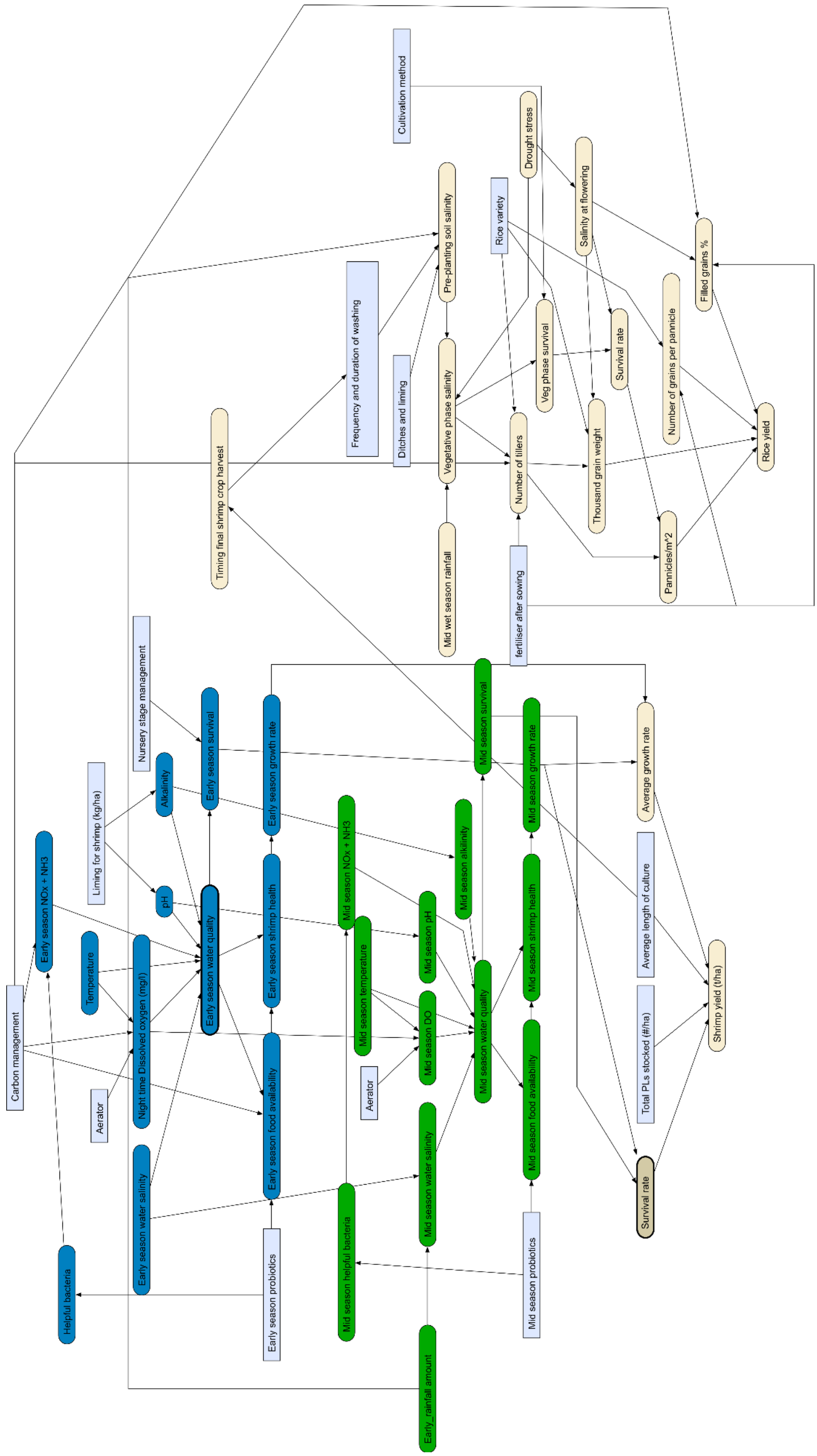

Figure 6. The first structure of the scientific BBN that captured the current scientific understanding of the system. Dark blue nodes represent processes that affect the early stages of the shrimp growing season while green nodes represent the later stages of the shrimp growing season. Cream coloured nodes represent the rice growing season and pale blue nodes represent the decisions that farmers can make at all stages of the season.

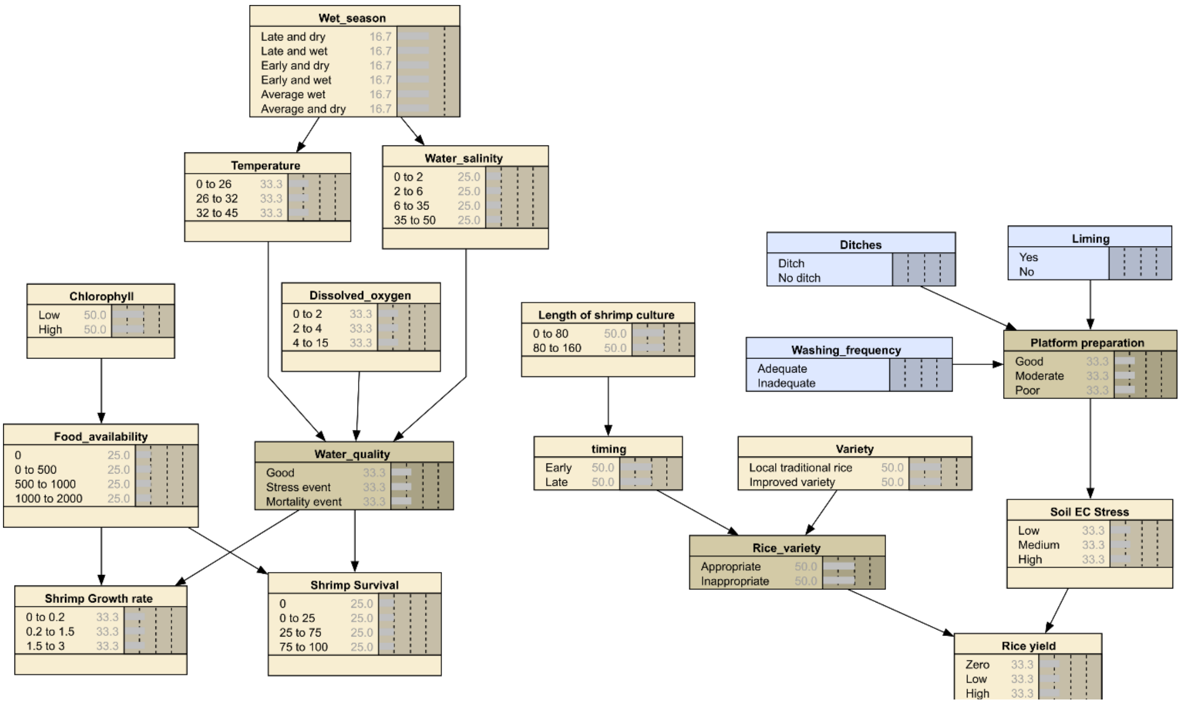

Figure 7. Revised BBN that captures the scientific understanding of the system and the data collected on the project.

7.2 Shrimp growth models

To understand the impact of water quality on key parameters for shrimp we collected data during the 2017 growing season at Tan Bang to investigate the links between the shrimp, their natural food sources and pond water quality. This work showed that there was a distinct increase in growth rate over the growing season, across multiple cohorts (Figure 8). These growth rates were significantly related to pond water quality, in particular dissolved oxygen, with growth rates increasing as pond dissolved oxygen increased through the season. There were also changes to the density and biomass of key natural food sources over the growing season.

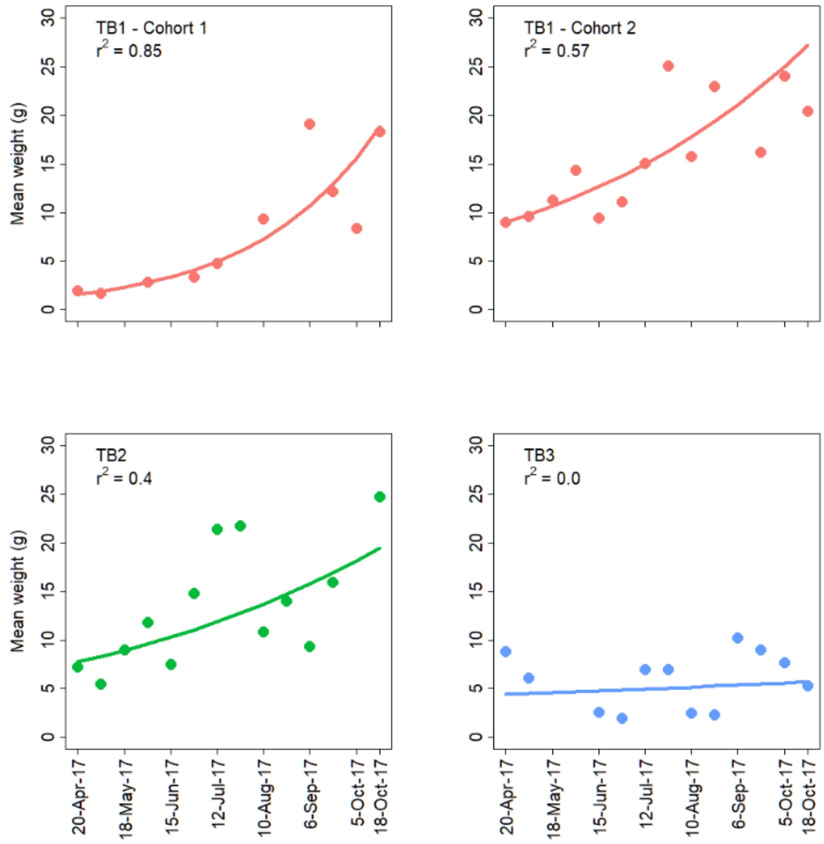

Figure 8. Mean weight (g) of each shrimp cohort (where identified) in the fortnightly cast-net samples at the three farms in Tan Bang province (TB1, TB2 and TB3). Regression lines represent the predicted values from the population growth models.

The overall findings from this study identified water quality and available food as key constraints on shrimp growth and risks to yields in the farms at Tan Bang. The findings also indicate that poor water quality, low benthic algal and invertebrate biomass, and shifts in the composition of phytoplankton and zooplankton are related to the alternating seasonal high and low salinity that occurs in the study region, which negatively affects the establishment and growth of natural food. From a management perspective, restricting shrimp inhabiting ponds to the dry season only may improve the ecosystem service of shrimp production in rice-shrimp ponds. While managing and improving dissolved oxygen conditions is a key step towards preventing losses of shrimp and improving production in the system.

7.3 Shrimp feeding trials 2019

In the first two years of the study, activities were based at rice-shrimp farms at Hoa My commune, Ca Mau province. A nutrient budget was developed for 12 ponds (on 12 farms) across a two-year period to determine the main inputs and outputs from the system. The study showed that the main nitrogen inputs (92%) and outputs (75%) were water from and to adjacent canals (Figure 9, Luu et al. 2017). This means rice-shrimp was not a primary source of nitrogen pollution in our study, and in fact, farms are reducing nitrogen load in waterways. This is likely to be because there was no feed supplementation, which is typically the source of excess nitrogen in shrimp ponds. Additionally, it means that the addition of nitrogen fertilizers is of little value as nitrogen levels from incoming water were already relatively high. Shrimp survival was very low (6.3%) which meant that little of the nitrogen inputs to the ponds translated into shrimp biomass. This suggests a very inefficient system of nutrient conversion, especially when compared with intensive shrimp cultivation, e.g. Jackson et al. (2003).

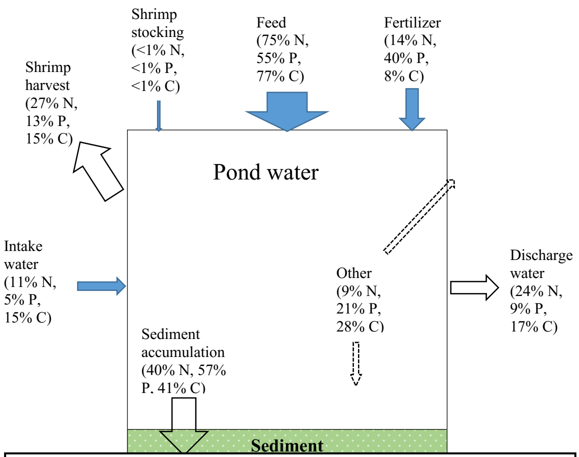

Figure 9: Nutrient and carbon budget for 12 rice-shrimp ponds in Cai Nuoc district

During the period of the nutrient budget study in Hoa My, the ponds were also sampled for sediment and water quality parameters to determine their effect on shrimp survival and production. Over the two-year period, environmental conditions contributed to low shrimp and rice yields, and low shrimp survival (~6%). Specifically, salinity was suboptimal – too high in the dry season and too low in the wet season, temperature was also suboptimal for shrimp, as were dissolved oxygen concentrations and alkalinity (Leigh et al. 2018). There was also evidence that food availability may have affected shrimp production. Rice production was also low due to excessively high salinities in the wet season.

As conditions were suboptimal for shrimp and rice production at Hoa My, the study site was moved to Tan Bang commune in Ca Mau province in 2017. This was recommended during the earlier 'final' review of the project. At this site, three ponds (three farms) were sampled for water quality parameters, and information was gathered on shrimp growth and survival, and rice production. Food availability was also determined, based on measures of algal production (chlorophyll *a* concentration in the water column and sediment), zooplankton and macrobenthos densities. At times during the year, salinity, temperature and dissolved oxygen levels were suboptimal but not to the same degree as in Hoa My. Shrimp survival in Tan Bang was also higher (30-41%) than Hoa My. A parallel study by John Allwright PhD student, Luu Duc Dien showed that sediment oxygen demand was responsible for low oxygen conditions in the ponds (Luu et al. 2019). Analysis of measures of food availability, combined with growth models, suggested that shrimp may not have sufficient food for optimal growth (Leigh et al. 2020). Growth rates were only ≤ 0.7 g week^{-1}, particularly compared to that measured in intensive ponds (1.3 g week^{-1} at 30°C; Jackson and Wang 1998). The biomass of primary producers was relatively low, possibly because they were stressed by the wide range of salinity conditions, ranging from 2-40.

Building on the results of the data collected from 2017, we conducted a pilot study in 2019 where two treatments were tested, with and without supplementary feed, to quantify the impact of feeding protocols on key parameters in the shrimp pond. This study monitored shrimp growth as well as densities of zooplankton, zoobenthos, phytoplankton in the two treatments.

With only three farms on which to conduct the pilot study there was considerable variability in the data collected. Nonetheless, there was evidence to suggest that higher yields may be possible from supplementary feeding. Additionally, there was evidence to suggest that farms with more zooplankton over the season produced a higher yield in shrimp. With only a small sample size, differences in shrimp growth between feeding treatments were not able to be identified during the pilot study. While these results were not conclusive, they do provide an avenue for further research across a larger number of farms to isolate the effect of supplementary feeding protocols on shrimp growth rates and yield.

^{15}N-nitrogen tracer experiments were also done to track natural food assimilation by shrimp on two ponds in both the wet and dry seasons. Six enclosures were used in each of the two ponds. The study supported the findings from the whole year study of pond management, water and sediment quality, i.e. there were little assimilation of natural food by the shrimp in either the wet or dry seasons (Burford et al. 2020). This was in part due to the low growth of benthic algae, which is a key food source for macrobenthos, that feed shrimp. A parallel study by John Allwright PhD student, linked to the project, showed that primary productivity rates in these ponds was low in both the water column and sediment (Luu et al. 2019).

Consistent with the nutrient budget studies in Hoa My, high nutrient inputs were also measured in Tan Bang ponds. A parallel study by John Allwright PhD student linked to the project showed that much of the nitrogen entering the ponds is not removed by denitrification processes (Luu et al. 2020). Therefore, there is scope to optimise this process and reduce nitrogen levels being discharged.

The studies of nutrient budgets, water quality and ^{15}N-tracer experiments across Cai Nuoc and Tan Bang districts highlight significant issues with current rice-shrimp production systems. Firstly, there are areas and years where climatic conditions, e.g. droughts lead to excessive temperatures and salinities unsuitable for optimal growth and survival. High temperatures also exacerbated low dissolved oxygen conditions. The low oxygen conditions are caused by high organic matter in the sediment fuelling high sediment oxygen demand (Luu et al. 2019). This is particularly extreme at night. Another risk factor is the decision of farmers to grow shrimp in the wet season alongside the rice crop. Given that the optimal salinity conditions for these two crops is different, typically one or both crops are compromised. At the extreme end of this management decision, there was no rice crop in Cai Nuoc ponds, while in Tan Bang, rice production was variable. Conversely, lower growth rates of shrimp may be linked to lower salinities. Options for improving water quality, particularly increasing dissolved oxygen levels, needs to be explored.

Based on the findings using a range of scientific approaches, it appears that food availability is also an issue for shrimp production. There is evidence for this in both Hoa My and Tan Bang communes. The relatively low biomass of primary producers means that it is likely to limit macrobenthos biomass, with flow-on effects on shrimp. The low primary production cannot be improved with more fertiliser inputs. Therefore, to increase production, a potential option is to add supplemental feed.

7.4 Shrimp better management practices

Pilot trials for better management practices for shrimp were applied and included nursing post larvae for 15-20 days in hapas, removing sludge from the ditch before stocking, using probiotics periodically, water level and water exchange and checking for harmful *Vibrio* periodically. These appeared to help increase survival and yield of shrimp. Moreover, stocking more mud crab when mollusc abundance appeared to increase crab production as a third commodity that generates income for farmers. ^{15}N-tracer feeding experiments and abundance of live food in the system are correlated to status of shrimp in term of its body lipid or protein content. There was a higher frequency of bacteria-infected shrimp when mollusc numbers were higher in the sediment. The first supplemental feeding of commercial feed showed that nutrients in water (TN and TP), benthic chlorophyll a, zooplankton, phytoplankton, zoobenthos were not significantly different between feeding and no feeding treatment but generated a higher shrimp yield i.e. 893.4 kg/ha using supplementary feed versus 566.5 kg/ha with no feed.

7.5 Risk Factors relating to rice

Seasonal Salinity

The temporal pattern of salinity in the rice season is characterised by an initially high salinity associated with the dry season (Figure 10). The onset of the rainy season causes rapid decreases in salinity of the platform water. The soil solution salinity follows a similar pattern although values remain high relative to the platform water and there is no direct relationship between platform water and soil solution salinity. This reflects a lag in diffusion and dilution of salinity in water-filled pores within the saturated soil. In general, rice yield is negatively impacted when the salinity of the platform water exceeds 2 ppt. It can be seen that at Hoa My, the salinity of the system was not suitable for rice production. Only one farm at Hoa My was able to grow rice (maximum yield of 2.5 t/ha) in 2014; rice failed at that location in 2015-2017 due to high salinity at sowing. Rice did not survive beyond tillering.

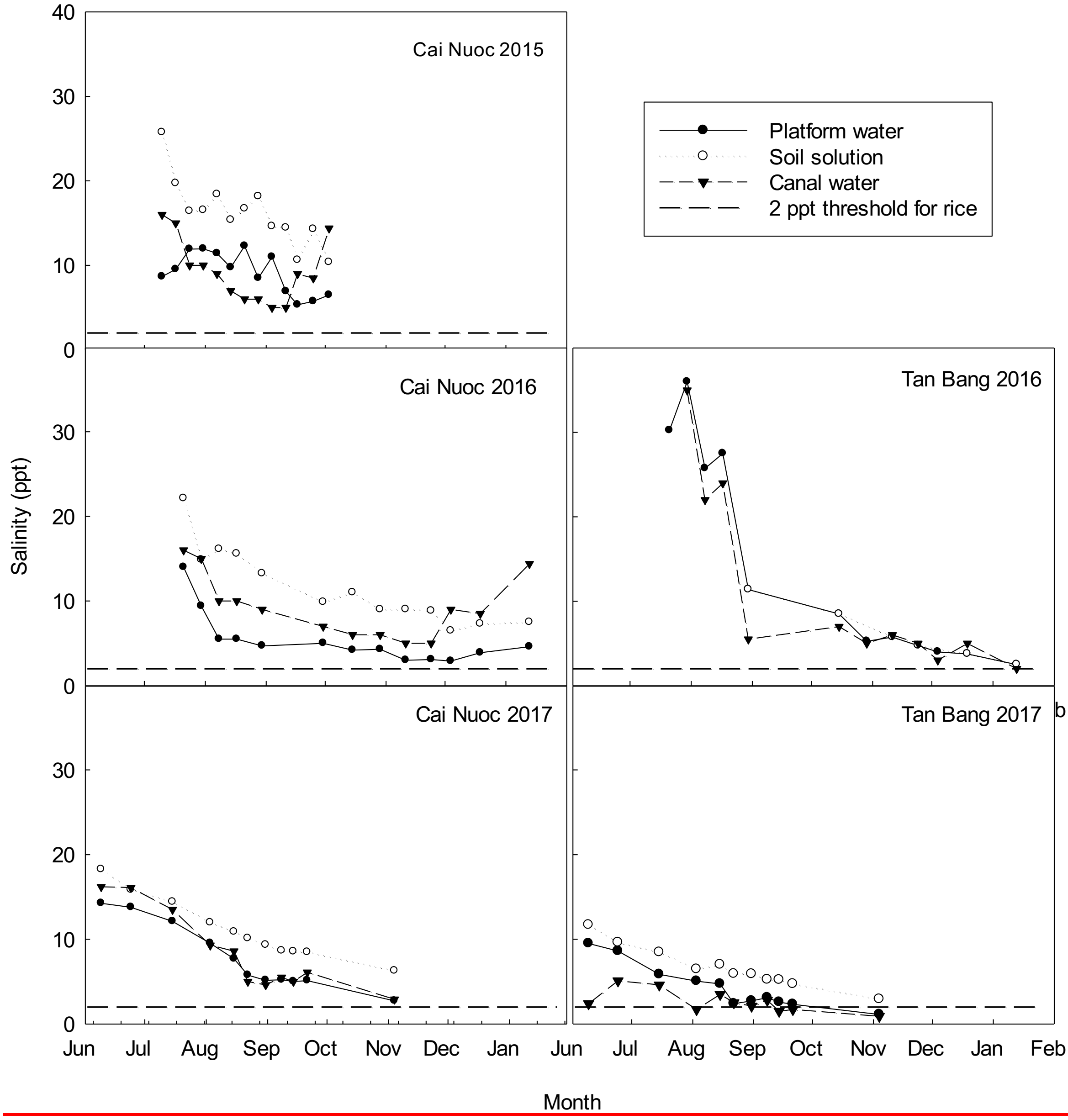

Figure 10. Salinity (ppt) of the platform water, soil solution (0-20cm) and canal water during the rice season at Cai Nuoc and Tan Bang from 2015-2017.

At Tan Bang the extreme drought-related, salinity event that impacted the Mekong Delta in 2016 was evident in the salinity data at the start of the rice season (Figure 10). The rainfall of the wet season was able to decrease salinity effectively for planting in September. Comparison of salinities recorded at the sites in 2017 indicates that Tan Bang is more suited to successful rice production than Hoa My. This difference is a product of the proximity to the sea (Cai Nuoc district being closer to the ocean) and use of saline canal water to favour shrimp production, which ultimately increases the salt load of the rice field.

The salinity of the system at Tan Bang can be influenced by both rainfall (dilution) but also regional groundwater (Figure 11). Weekly sampling of surface and soil solution (pore water) demonstrated that the salinity of deep (20-40 cm) pore water, variated greatly compared to the surface water. The gain in salinity at approximately 40 days is not related to changes in the 0-20 cm pore water or the surface water. It is therefore assumed that such changes are the result of influence of the regional groundwater. The management of surface water by drainages during rain events or supplementary irrigation from canals can be used to ensure that saline ground water is kept from the root zone of growing rice plants. This was the case in 2018 (data shown in Figure 12), the relatively low salinity of the surface system allowed rice yields of 4 t/ha. Towards the end of the rice season, increases in soil solution salinity may also be the result of saline groundwater increasing as the quantity of fresh water decreases within the region.

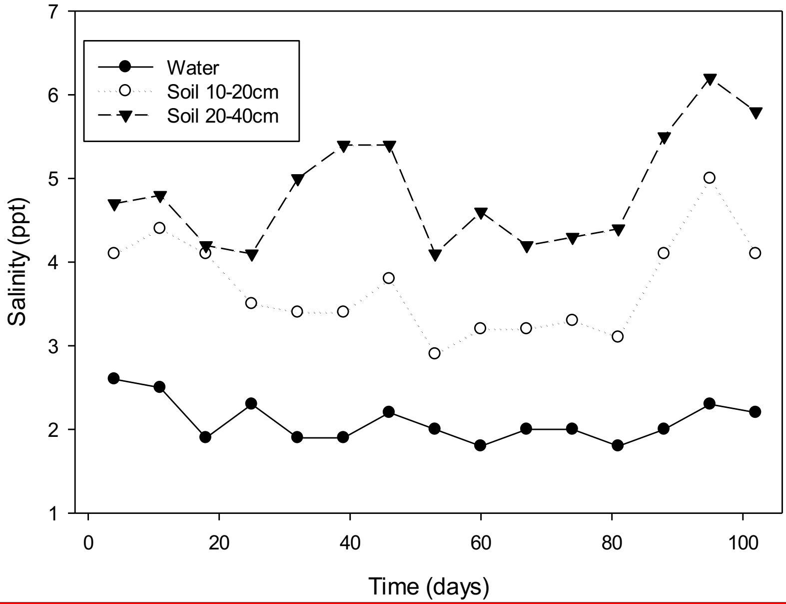

Figure 11. Weekly salinity (ppt) of Canal water and soil solution taken from the 0-20 and 20-40 cm soil layers at Tan Bang in 2018.

7.6 Soil Management to decrease salinity

Tillage

Green house trials determined that tilling the soil with the addition of lime (2 t/ha) resulted in significantly less salinity in the soil solution thus improving rice plant growth (Figure 10).

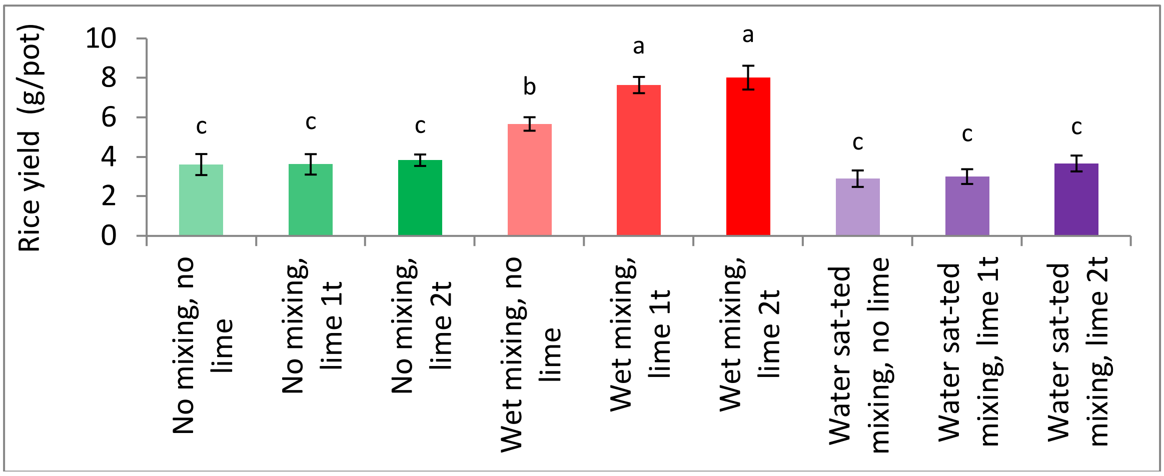

Figure 12. Rice yield from lime application without tillage (mixing) or mixed on drained (wet) or saturated (sat-ted) soil under glasshouse conditions. Columns marked with different letters are significantly different at $p<0.05$.

However the practical implications of tillage can impact the success of the practice. Effective tillage requires draining of the platform; this can increase the risk of acidification if rainfall doesn't occur when canal water is too saline for irrigation (common during platform preparation time). Prolonged draining of the rice platform increases weed burden. These two factors caused the failure of the rice crops on all 12 farms in the 2015 season at Hoa My when tillage was included in the platform preparation phase of rice production. Tillage needs to be completed rapidly to succeed and efficiency of timing may be gained with access to improved tillage machinery. Field validation has yet to be conducted over different sites and seasons and could be undertaken by a follow-on project.

Bunds to enhance leaching of salt

Manipulation of the field water height and creating platform bunds to provide a head of water to facilitate enhanced leaching was found to significantly decrease soil solution salinity by approximately 3 ppt (Figure 13). This technique was also enabled the platform soil to be covered with water for longer, thereby avoiding the risk of surface drying which can result in acidification due to oxidation of acid sulfide soils. Though the magnitude of salinity decrease with leaching may be sufficient to avoid total crop failure by avoiding a toxic threshold of salinity, the creation of bunds was believed to hinder the movement of shrimp from the safety of field ditches and the rice platform and vice-versa. The additional labour required to form bunds was also viewed unfavourably by farmers and potentially added to the cost of production.

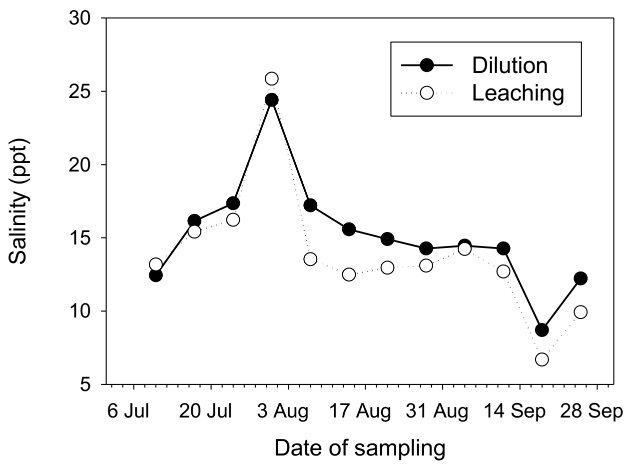

Figure 13. The soil solution salinity (ppt) at Cai Nuoc where conventional farmer practice of salinity management (dilution) was compared with enhanced leaching using platform bunds (leaching).

Time of platform preparation and sowing
The greatest decreases in soil salinity were possible when platform washing began more than 4 weeks prior to transplanting of rice at Tan Bang. Field experiments demonstrated that there were no differences in soil salinities when washing occurred 6 and 8 weeks before planting. Platform washing influenced salinity in both the 0-20 and 20-40 cm soil layers.

7.7 Rice farming options to mitigate effects of salinity

Sowing method
The farmers in Tan Bang utilise a transplanting method that involves throwing the rice seedling into the field rather than pushing the seedlings into the soil. Farmers believe this method enables the seedling to avoid the more saline soil solution (relative to the surface water) until the plant is larger and is growing roots. Experiments testing this method against traditional transplanting methods showed no significant difference in rice yield; 4 t/ha for throw and traditional methods in 2018.

Rice varieties
Rice varieties that offer tolerance to saline conditions and/or short growing duration suit the rice shrimp production system. In both Cai Nuoc and Tan Bang traditional varieties offer salinity tolerance but are long (135 days) duration varieties. The window of suitable growing conditions is not long enough to reliably produce adequate yield when the wet season starts late or finishes early. Short duration (<90 days) were found not to provide adequate yield at Tan Bang during 2017 (Table 2). However, it should be noted that salinity at Tan Bang was not as toxic as at Hoa My and therefore the yield resilience of saline tolerance may not have been such an important factor in the trials at Tan Bang in 2017, 2018.

Table 2 Rice variety trials at Tan Bang 2017, 2018. OM varieties are sourced from CLRRI. Yields with the same letter within a given year are not significantly different p<0.05.

Variety	Salt tolerance (ppt)	Growth Duration (days)	yield (t/ha)	
			2017	2018
OM380	<3.0	<90	2.0 ab	
OM Nếp 441	<3.0	<90	1.0 a	
OM439	3.0-4.0	<90	3.4 cd	
OM442	<3.0	<90	1.7 ab	
OM2517	4.0	<90	4.2 de	3.9 a
OM6976	3.0-4.0	90-105	2.7 bc	
OM449	3.0-4.0	90-105	2.7 bc	
OM108	<3.0	90-105	1.3 a	
OM429	3.0-4.0	90-105	4.0 de	4.5 ab
OM341	3.0-4.0	90-105	3.2 cd	
OM348	<3.0	90-105	4.9 e	4.7 b
OM376	<3.0	90-105	2.0 ab	
OM18	<3.0	105-120	4.6 e	4.1 ab
OM242	<3.0	105-120	4.3 de	4.1 ab

OM359	<3.0	105-120	1.9 ab	
Lun KG	4.0	135	5.0 e	4.7 b

Compared to the traditional variety, OM348, OM 429 and OM2517 offer no reduction in yield but allow for shorter growing duration; OM2517 was the shortest duration rice without yield loss. Further investigation of the salinity tolerance of OM2517 (Table 3) reported moderate tolerance to salinity of 4 dS/m.

The shorter (90 day) duration improves resilience to salinity intrusion at the end of the season or allows growers to allow more time in platform preparation (platform washing) prior to crop establishment. No rice quality factors were analysed during experiments though grain quality is a property that farmers ranked highly due to the associated marketability of the rice produced. Rice quality of OM348, OM429 and OM2517 warrants further investigation.

Table 3 Response of rice (OM2517) to controlled salinity concentrations in glasshouse pot trial.

Salinity (dS/m)	Tiller number	Height (cm)	Yield (g/pot)
0	13	92.9	27.2
4	12	85.1	19.7
5	7	79.9	10.1
6	6	74.7	5.5
7	5	44.4	3.4

7.8 Production efficiencies

Sludge use

As sludge is the organic debris that accumulates in the ditches of the rice/shrimp system, it is a potential source of nutrients for crops if applied to soil. Incubation experiments demonstrated that the magnitude of plant available nitrogen mineralised from sludge varied depending on the location from which it was sourced within the rice/shrimp farming system (Figure 14). The small and main ditches in or adjacent to the rice field are able to generate large quantities of mineral N which can substitute for mineral fertiliser in the production of the rice crop.

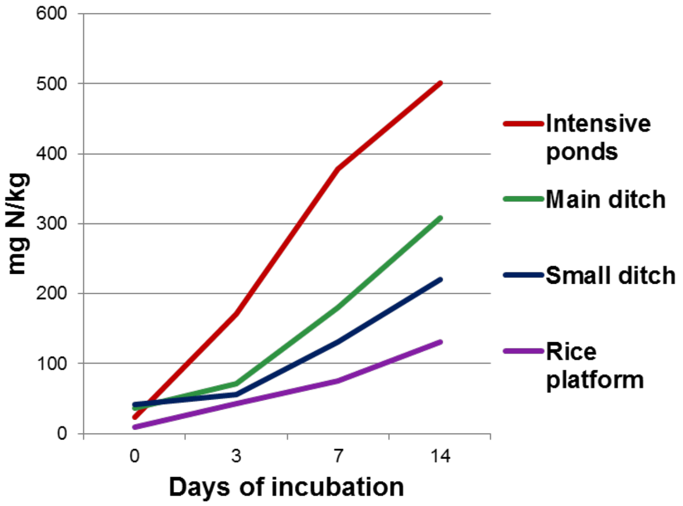

Figure 14 Ammonium (mg N/kg) mineralised during a 14-day incubation of sludge sourced from different locations within the rice/shrimp farming system

The fertiliser replacement value of the fertiliser was variable depending on salinity and seasonal effects. There were no significant differences between treatments at Hoa My (Figure 15) during the 2014 rice season and no yield was recorded during the 2015 season owing to complete crop failure due to salinity. Significant treatment differences existed in both 2016 and 2017 at Tan Bang (Figure 16). In both seasons, the combination of sludge and the lower percentage of the recommended fertiliser rate performed well. In 2016, the sludge treatment produced an equivalent yield to the reduced fertiliser rate. In 2017, the sludge treatment either alone or with a reduced fertiliser rate produced the highest yield, significantly outperforming the traditional fertiliser recommendation.

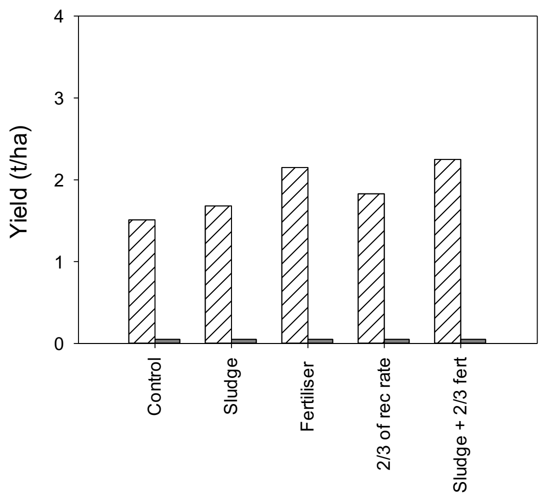

Figure 15 Yield of rice (t/ha) at Cai Nuoc in 2014 (white hashed).and 2015 (grey) due to sludge and fertiliser treatments. Data are treatment means of four replicates. There were no significant differences (p=0.05) within seasons.

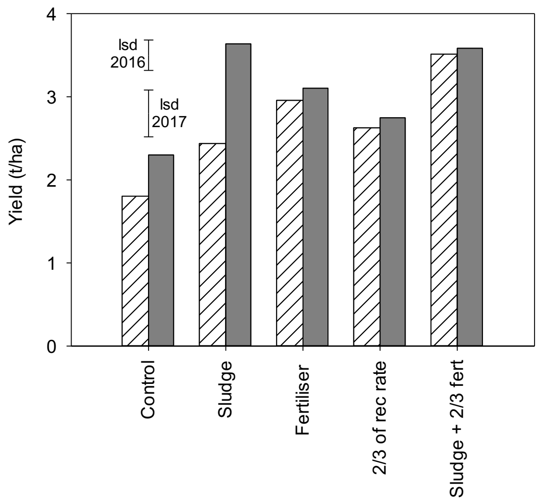

Figure 16 Yield of rice (t/ha) at Tan Bang in 2016 (white hashed).and 2017 (grey). Rice variety OM2517. Data are treatment means of four replicates. LSD (p=0.05) bar is indicated.

The important finding of this work is that yield is not compromised by the replacement of fertiliser by sludge. Its use has only the cost of labour for application but decreases the cost of rice production. It therefore represents an effective management option to increase economic resilience of farming households. If rice crop failure occurs due to salinity the economic loss is less if sludge was used rather than purchasing mineral fertiliser. The benefit of organic matter, via sludge application, to the physical condition of the soils and associated leaching efficiency remains to be determined. Additionally, farmers believe that removal of sludge from ditches is beneficial to the health of the shrimp system. This may be associated with changes to the magnitude of hydrogen sulfide production when the organics rich sludge is removed.

Hydrogen sulfide production

Rice/shrimp production commonly occurs on acid sulfate soils that produce sulfate as a common anion of the soil solution. When the oxidation status of the soil water is low, reduction of sulfate in sediments may result in the release of hydrogen sulfide (H_2S) gas which can be toxic to shrimp. It was expected that the presence of sludge would facilitate greater H_2S production by sulfate reduction owing to higher biological oxygen demand of organic wastes. However, it was found the quantity of H_2S released was driven by the total potential acidity (TPA) of the soil, with sludge presence having a smaller influence (Figure 17). Therefore, removal of sludge from ditches does not remove the risk of H_2S production.

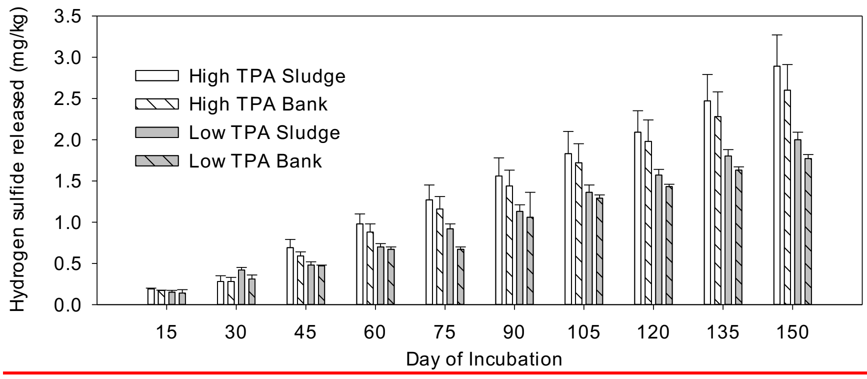

Figure 17 Release of hydrogen sulfide (H_2S) (mg/kg) from incubated soil of earthen banks or ditch sludge taken from high or low total potential acidity (high TPA and low TPA, respectively) farms. Error bars represent standard deviation.

Laboratory column studies demonstrated that regardless of the TPA or presence of sludge, the concentration of sulfide in the water column was in excess of the LC_{50} sulfide concentrations for the shrimp species grown in the rice/shrimp system (Goppakumar and Kuttyamma 1996) (Figure 16).

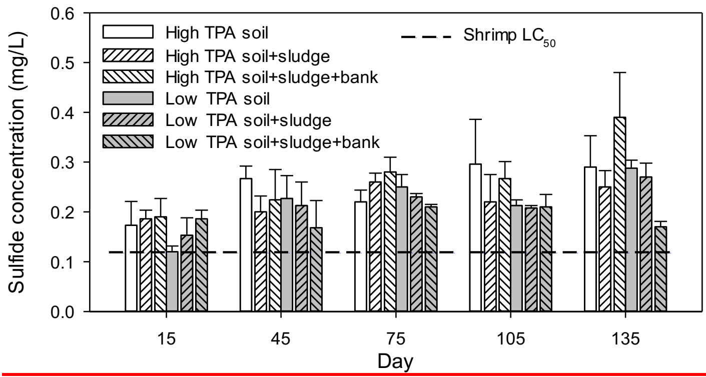

Figure 18. Sulfide concentration (mg/L) in water columns over soil, sludge, and sludge with eroded bank soil for two farms (high TPA and low TPA). Error bars represent standard deviation. The LC_{50} sulfide concentrations for shrimp are indicated by a horizontal line (Goppakumar and Kuttyamma 1996).

Therefore, low oxygen concentrations in the soil sediments are likely to create an environmental risk factor that may influence shrimp health. However, it is not known where sulfide toxicity is placed in a hierarchy of deleterious factors associated with low oxygen concentrations impacting on shrimp health.

7.9 Agronomic recommendations to farmers/advisors:

- Platform preparation should occur early (end of July). It should involve application of lime (1-2t/ha) to a drained surface soil and mixed using tillage, manipulation of water height should be used to minimise groundwater rise of soil solution salinity.
- Planting rice can occur without yield loss once soil solution salinity is around 4 dS/m (2 ppt). Soil solution within rice shrimp systems seldom decreases below that threshold. If soil solution in greater than 2 ppt, selection of varieties with salinity tolerance should occur.

- Rice varieties OM348 or OM2517 are suitable for the rice/shrimp system. The latter selected especially if platform preparation is not completed by mid-August as it has the shortest growth duration.
- Utilize sludge to partially replace chemical fertilisers to reduce cost in rice production.
- Once mechanical options, i.e. tractor specifically used for rice-shrimp farming system, are available, the advantage should be applied to platform preparation and sludge utilisation.

7.10 Research recommendations:

There is scope to improve understanding of the system efficiencies by testing and costing mechanisation for tillage and harvest. Although the project generated knowledge on how the timing of planting and selection of salt-tolerant strains can improve outcomes for rice, the grain quality of these rice varieties requires further investigation.

7.11 Socio-economic results

Participatory community appraisals showed that relatively fewer poor households have adopted rice-shrimp farming. Percentages of poor households practising the farming were lower than those of richer households (Figure 19). Relatively more poorer farmers practised rice - shrimp farming in less favourable hamlets (Figure 19b). Rice-shrimp farming is considered as a farming practice that needs lower external inputs and provides a stable income, compared to monoculture of shrimp with a higher intensity level. However, the wealth of many poorer households did not improve, particularly with the poor group in unfavourable hamlets, which highly contrasts with the rich group (Figure 18). These results raise two questions: (1) was rice - shrimp farming still difficult for resource-poor farmers to adopt ? If so, what were the reasons? and (2) why did rice-shrimp farming not help poorer farmers improve their wealth? Answers to these questions are of great importance, not only for improving the performance of current rice-shrimp farming systems applied by poorer farmers but also by contributing to sustainable development of future rice-shrimp farming as more rice land could be potentially shifted to rice-shrimp in view of the projected saltwater intrusion in the Mekong Delta.

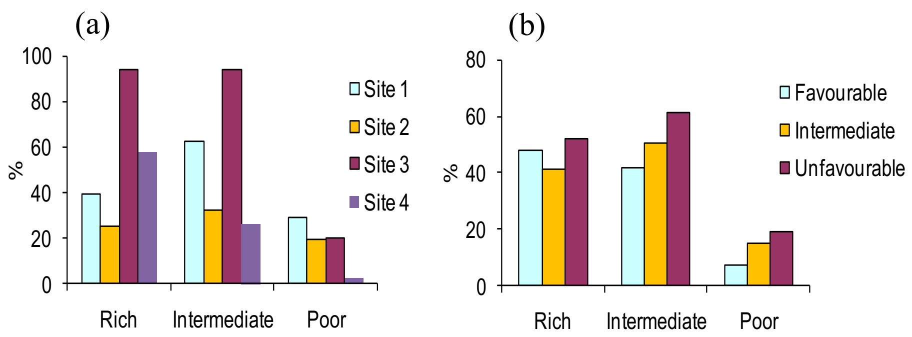

Figure 19: Percentage of households practising rice-shrimp farming by wealth group at different sites (a) and bio-physical conditions (favourable, intermediate and unfavourable hamlets) (b).

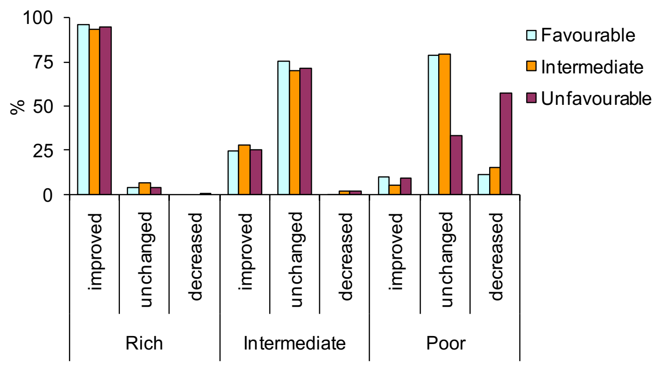

Figure 20: Percentage of households with wealth mobility (improved, unchanged and decreased) by group across bio-physical conditions.

2. Expected outcomes, enablers and barriers to rice - shrimp farming

Focus-group discussions revealed that the current rice – shrimp farming system provides multiple benefits to farm households. Common benefits reported by the farmers groups include higher farming income, a better environment at the farm and surrounding areas, economic risk is spread, and there is a more appropriate use of local natural resources compared to monoculture of rice cropping. The expected impact of these benefits include improved wealth of farm households. The effect of rice – shrimp farming on improving household food security was thought less important, except by women. A question was raised that, in order to achieve the benefits as expected by farmers, what are the enablers and barriers to sustainability of rice - shrimp farming currently and later on?

Key informant at the study sites suggested 27 enablers and 31 barriers, building on livelihood assets (i.e. human, natural, financial, physical and social assets). Results from AHP analyses showed important enablers and barriers by group at each site. Important enablers commonly considered by farmers at the study sites are related to financial elements (i.e. farming income diversity and stability, and low external inputs) and human elements (i.e. farming experience and family labour availability). By looking at differences in perception among the groups, we found that richer farmers at sites 1 and 2 (bio-physically favourable sites) considered natural enablers (i.e. suitability of land and water resources, rice and shrimp synergies) as potential drivers for further development of the farming systems. In contrast, poorer farmers highly appreciated physical and social elements at community level (i.e. availability of transportation facilities and technical information, access to private services for farm inputs and outputs, availability of communal regulations). The findings can explain the reason why resource-rich farmers have tended to further intensify shrimp farming or to shift rice – shrimp to shrimp mono-culture at some intensity levels given economic successes in previous crops. In addition, better physical and social enablers at community level can benefit many resource-poor farmers by improving their rice - shrimp farming and then wealth, particularly in relatively less favourable hamlets (as aforementioned).

Like for enablers, AHP analyses showed important barriers to rice – shrimp farming by group each site (Figure 21). The common issue that concerned all groups included the challenges of dealing with uncertainties such as weather and markets for farm inputs and outputs. Important barriers commonly agreed by farmers were a lack of advanced technical knowledge and skills to deal with climate change and resource use efficiency, lack of seasonal farm labour (i.e. human elements), weather anomalies (i.e. natural element), increased costs of farm inputs, instability of output prices for rice and shrimp (i.e. financial elements). In addition, some groups at all the sites complained barriers like unavailability of certified input materials for rice and shrimp culture, and the unavailability of rice harvesters (physical elements), poor cooperation within a community, lack of trust and information sharing to better manage natural resources, risks from shrimp diseases, and shrimp poaching (social elements). Moreover, poorer farmers at sites 2 and 3 (with relatively less favourable conditions) considered poor quality of canal water for shrimp and the decline of natural fish resources as important natural constraints. The findings imply that a package of solutions is needed to solve problems not only at farm household but also the whole supply and value chains of rice and shrimp at landscape level, which are context-specific.

So far, individual farmers have played around with rice and shrimp farming with a trial and error approach. Resource-rich farmers have tended to gradually intensify shrimp farming by increased inputs, particularly at sites 1 and 2. Public agricultural extension staff and private service technicians have provided farmers short-trainings and demonstrations on component farming technologies. The aforementioned findings show a need for building adaptive capacity of many rice – shrimp farmers, particularly the resource-poor , and further improving natural resource management at the landscape level. A participatory technology development and value chain approaches are therefore necessary, promoting participation of relevant actors and constant social learning, as public resources for supporting farmers are still limited.

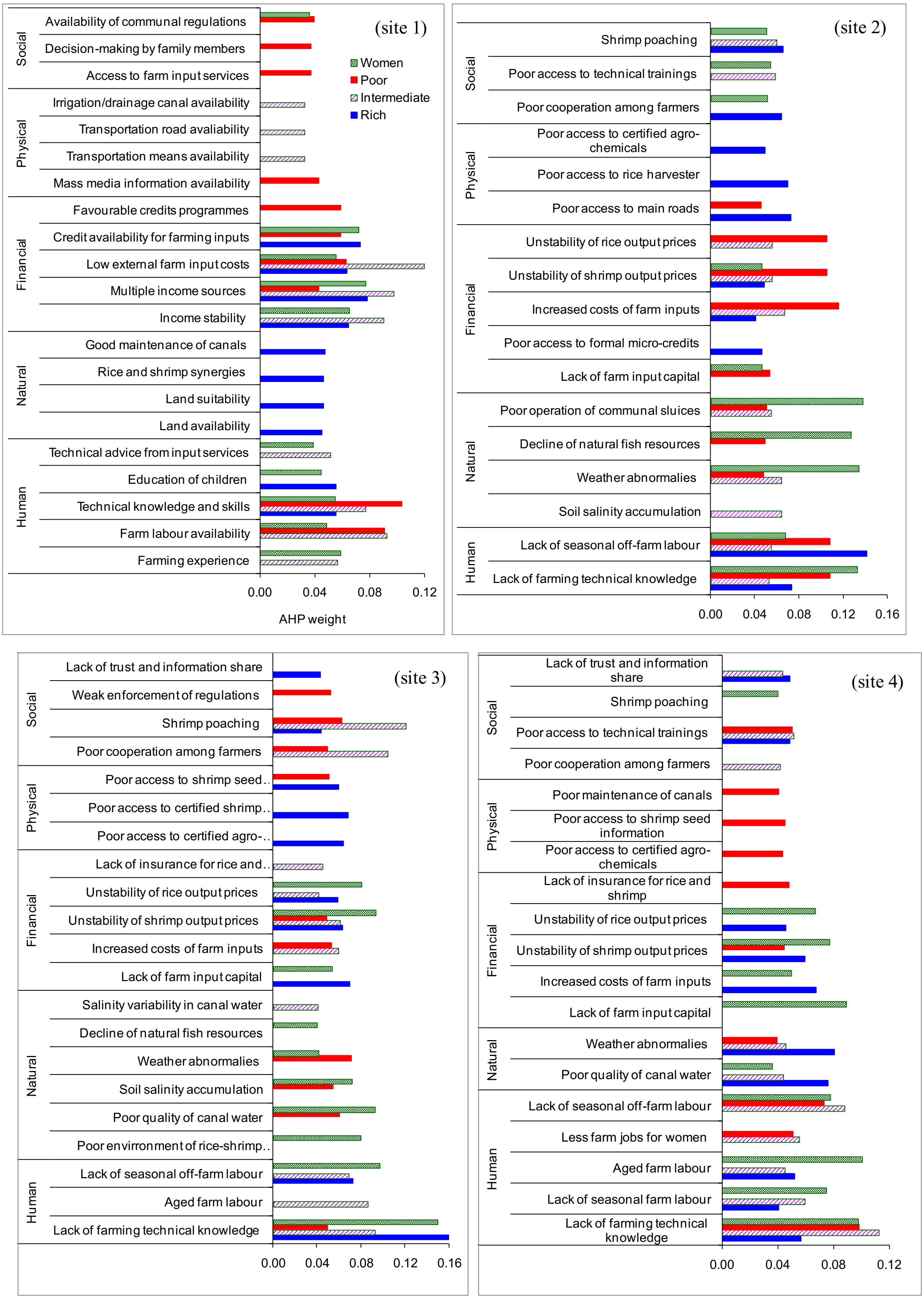

Figure 21: Results from AHP analyses indicate top 10 important barriers to rice – shrimp farming by group each study site, based on AHP weight.

3. Impacts on food security, poverty reduction and livelihoods

Rice – shrimp farming has both positive and negative impacts on food security, rural poverty reduction and livelihoods of local households (Figure 22). On the one hand, rice – shrimp farming provides multiples benefits (aforementioned), which contribute to better uses of farm resources. Combined with improvement in locally social and economic infrastructure systems (transportation, electricity, information, education, health care and private services markets) from governmental investments, rice – shrimp farming improves educational attainment of children, food security and livelihoods of rural communities. The term “food security” is based on four dimensions: availability, quality, accessibility and affordability of/to food. On the other hand, development of shrimp farming facilitates salinity intrusion with longer durations and higher levels, which result in reduced diversity of terrestrial crops and a decline in freshwater fishes. In addition, shrimp farming requires lower labour inputs than rice farming, which causes fewer opportunities for on- and off-farm employment. Consequently, many resource-poor households face food insecurity and low income, and hence move to urban and/or industrial areas for jobs. For women, shrimp farming provides women with more free time, which was considered an important barrier by poorer groups at site 4; this also contributes to rural out-migration.

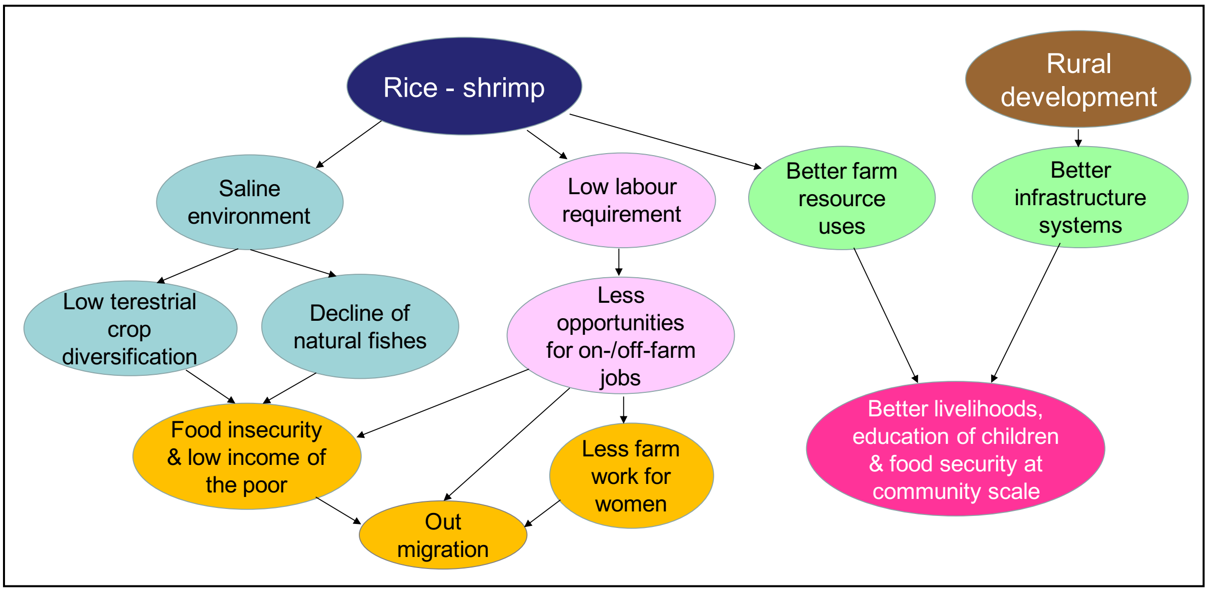

Figure 22: Causal relationships showing the impact of rice – shrimp farming on food security, poverty reduction and livelihoods of local households.

4. Shrimp yields and income

Rich farmers achieve higher shrimp yields and higher economic returns than poorer farmers (Figure 23). Shrimp yields were, on average, 353 kg/ha (paddy field plus trench) for the rich farmers and 233 kg and 302 kg/ha for the intermediate and the poor farmers, respectively. Rich farmers had lower input costs for shrimp than poor farmers and hence earned higher profit. Sites 1 and 2 had higher shrimp yields than sites 3 and 4 (363±86, 346±80, 281±37 and 204±46 kg/ha/year, for sites 1, 2, 3 and 4, respectively). There is still room to improve shrimp yields to an attainable level for poorer farmers at sites 3 and 4.

Shrimp is the main component in terms of income, accounting for an average of 60 – 80% of the total farm income. Rice was considered secondary, contributing about 20 – 28% of the farm income. Dykes cover a range of 14–20% of total area of rice-shrimp field but they shared an average of 6% of farm income. Efficient use of dykes by growing cash crops or grasses for livestock feed to add more farm income is necessary.

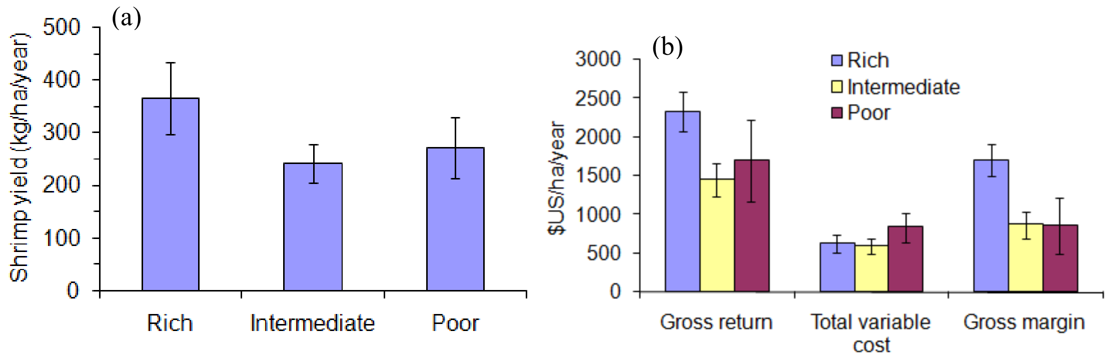

Figure 23: Shrimp yields (a), economic input cost and profit (b) by farmer group (mean ± SE)

Multivariate canonical correlation results reveal important relationships between income and household resource inputs. Farm households, who owned larger farms and rice – shrimp areas, had higher income per household, capita and labour (Figure 24a). This occurred with many rich farmers (in lower-left quadrant), opposite to the poor group (in upper-right quadrant). In addition, households with smaller household size and fewer farm labour had higher income per labour and per capita (Figure 24b). This occurred with a range of farmers, regardless of wealth type.

Similarly, looking at the relationships by site, the results show many farm households at site 1 had relatively smaller farm size and rice-shrimp area and hence lower income per household, per labour and capita (Figure 24c). Many households at site 3 had larger household size and/or more farm labour and hence lower income per labour and per capita (Figure 24d). The result also indicated no relationship between shrimp or rice yield and total farm income or household income but a positive relationship with farm-gate prices of shrimp. This is because of shrimp yields were below 400 kg/ha/year and rice yields were below 6 tonnes/ha/year in most cases at the time of the investigation.

These findings imply that higher shrimp yields through increased farm inputs could not result in higher income for farmer. Reduced input costs, reduced risks and improved farm-gate prices for shrimp and rice production are therefore most significant. For poorer farmers, improved rice-shrimp farming can help stabilise their livelihoods and labour shift can allow them to improve their income.

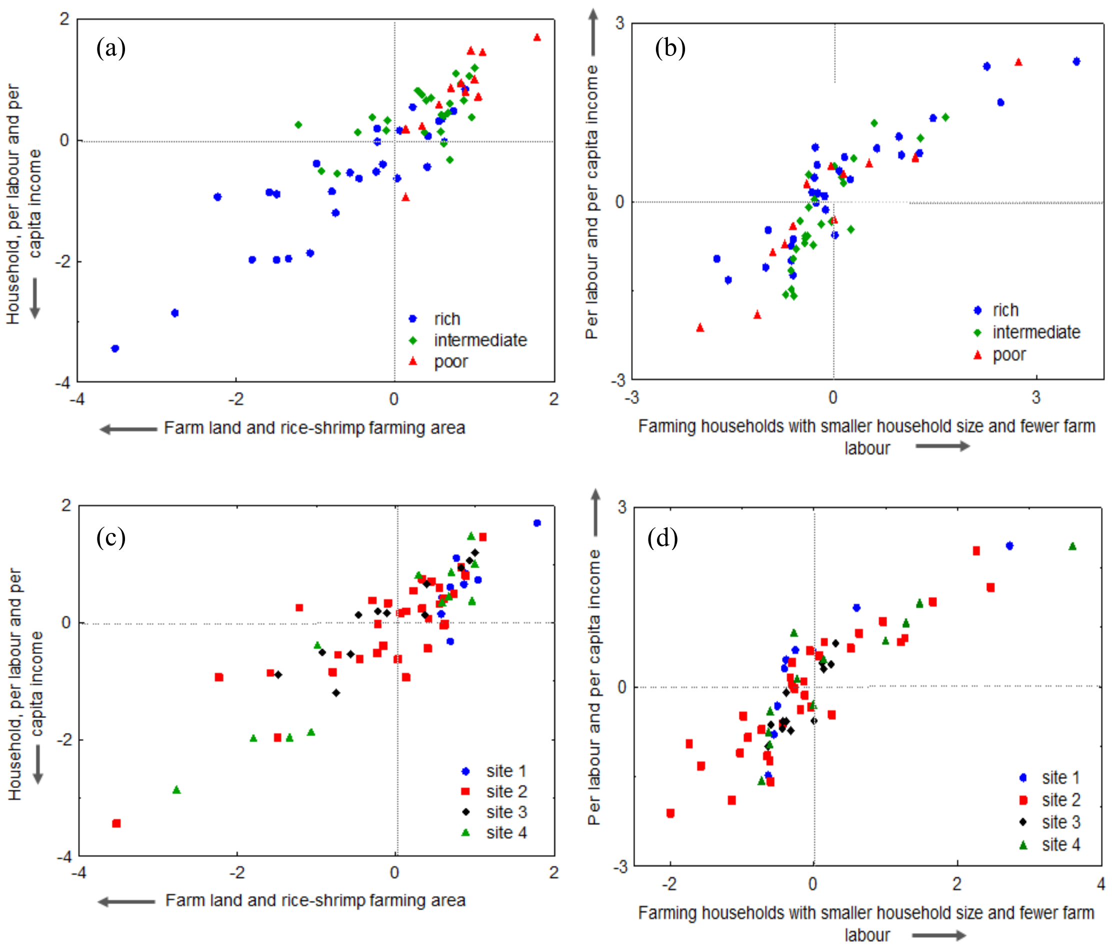

Figure 24: The distribution of investigated households along the exploratory (income) and response (farm, household size and labour) axes by farmer group (a and b) and site (c and d).

8 Impacts

8.1 Scientific impacts – now and in 5 years

The project has generated over 10 peer-reviewed publications, mainly from the BBN, farm processes and shrimp components, with more under review and in pipeline (soil, rice and better management practices which have only, so far, been published in conference proceedings). The publications were jointly prepared by the collaborating scientists and has enabled Vietnamese partner agencies to publish in English and in high impact journals. Through training and workshop in 2016 and 2017, the better management practices for shrimp introduced by project was adopted by Camau Extension Centre to test at different locations in Camau province, Mekong Delta in 2018-2019. The adoption of the practices was facilitated by trust in the scientific rigour used by the project team. Tan Bang authorities and experimental farms are communicating the scientific findings and working with other farmers to apply the better management practices. In 2020 a larger group of farmers was formed at Tan Bang following the success of the trials and the confidence that was built through the scientific approach to test new ways of managing the risks.

The research in this project points to the need for supplementary feeding to enhance productivity and future research could investigate supplementary feeding as a new practice for rice-shrimp farms, provided high quality feeds are used.

This study provided detailed new published information on the links between water quality, food availability and shrimp production. By undertaking the study across two districts and multiple ponds, an understanding of the climatic and pond management effects on production was developed. Multiple lines of evidence were also used to ensure the scientific robustness of results. This involved detailed studies of water quality drivers and nutritional status, as well as pond and season-wide monitoring of a wide range of parameters. The study has highlighted limitations to the sustainability of rice-shrimp farming systems, and pointed to potential testable methods for improving production. Of note:

- Successful rice production is not only determined by salinity in the pond water that can be alleviated by freshwater from rain, reservoir or the canal network; it is also highly affected by salinity in the soil pore solution. This is a significant finding because it demonstrates that the traditional reliance on surface water salinity is imprudent. This knowledge has been communicated to DARD and farmers to raise awareness of the limits of measuring salinity of the surface water as a guide for rice planting. Further research is needed to develop alternative, low-cost and farmer-friendly approaches to evaluating conditions given that farmers do not have access to laboratory facilities to measure soil pore water salinity.

- Pyritic materials present in the soils present a risk to farming. Once Oxidised, they create acid sulfate soils which can impact aquaculture and agriculture. These soils also generate hydrogen sulfide during the flooding stage when shrimp are grown and generate acidity and release aluminium when soil dries, thus presenting a risk to shrimp and rice production. Thus, improved management approaches, e.g. aeration to suppress H_2S generation, need further study to improve the system.

- The research has shown that sludge application can replace or supplement fertiliser use in rice production benefiting yield and profitability of production. Besides reducing cost, limiting use of chemical fertilizer could depresses environment pollution and growth of pathogens. This creates an opportunity for the farmers to produce higher quality and/ or cleaner (more organic) products from such a unique integrated cropping system. There is the potential to apply stable isotope analyses to trace the origin of the products, to enable the farmers to sell their products in higher valued markets. The impacts of the sludge application and rice residue on the variation of soil and water chemistry leading to shrimp growth and development in the following season need to be tested further.

- Through the development of the initial BBN, the project team established an approach for successful stakeholder engagement that ensured participating farmers were active participants in the research and enhanced their support for the project. In addition to bringing the farmers into the research process, the approach helped identify key issues of concern felt by the farmers which could be addressed in the subsequent development of experiments and monitoring (both on-farm and in the laboratory).

- The finding that water quality is suboptimal for shrimp grown in this system is new and important. The key factors are temperature, salinity and dissolved oxygen. There may be scope for management actions to increase dissolved oxygen. Temperature is climate related but future proofing farms may include strategies such as increasing the depth of ponds and improving water circulation. Salinity may be problematic by being too high during drought periods, or too low during the wet season. There are strategies for improving sustainability in the wet season (see below) but during the periods of high salinity, there are limited options.

- Some farmers are also growing shrimp and rice simultaneously which can have negative effects on the production of both rice and shrimp, since rice require freshwater and shrimp are not a freshwater species. Future sustainability needs to address the issue of using freshwater aquaculture species during the rice growing phase, rather than a marine/brackish water species. Work is already underway by RIA2 to test alternative species such as freshwater prawn *Macrobrachium rosenbergii*.

8.2 Capacity impacts – now and in 5 years

The research involved farmers at two locations, and as a result of their participation in the field trials, there was an increase in farmer capacity. Farmers had also formed small groups to work together to apply research findings, which was most notable at Tan Bang. This included women meeting to share knowledge with most meetings led by women lead farmers. The lead farmers at experimental farms now know how to record farming data and implement better farming practices, and this knowledge has been shared to other farmers. DARD was also engaged in the project and extension staff have been providing technical assistance, drawing on knowledge generated by the project, to support farmers. Farmers from other districts have also visited the project trial sites to learn about the improved management practices. DARD and RIA2 will be exploring ways to improve information exchange beyond the project.

One staff member from RIA2 completed his PhD at Griffith University and nine masters and honours thesis students from CTU, CSU, Griffith University and UNSW also completed their studies in parallel to the project’s core activities. Six UNSW interns were hosted by RIA2, CTU and CLRRI. One intern, Ruby Annand-Jones has since been employed by ACIAR under the graduate program.

One PhD student from CTU joined the study on using sludge for replacement of chemical fertilizers in rice production. His thesis passed the internal round successfully. The final defence is expected to happen in late 2020.

One staff member from the Agricultural Extension Centre in Ca Mau, who was trained at Can Tho University, conducted his thesis research using data from the project and will apply the results to Ca Mau province.

Training in laboratory analyses was conducted early in the project with RIA2 staff to ensure the most up-to-date methods for chemical analyses of samples were conducted throughout the project. The shrimp research team continued to improve skills on natural foods and microbes measurements in 2017-2018. This involved field, laboratory and class-based activities, as well as training in shrimp growth modelling by Griffith University. Vietnamese and Australian researchers have also jointly written research papers for international journals, which has improved research writing skills across the team. One CTU staff, Ms Doan Thi Truc Linh, visited UNSW and ANSTO in 2019, hosted by UNSW's Aquaculture Research Group, to develop skills in nuclear techniques in environmental and aquaculture/agricultural research and laboratory methods.

We note that in the last 3 years of the project, the project team endeavoured to increase the number of women researchers. We now have 7 more Vietnamese women researchers participating on the project and have had 5 Australian women interns from UNSW.

The rice research team, based at CTU and CLRRI, have continued to develop quantitative skills in statistical modelling and BBN development, following a two-day intensive training workshop on BBN development in February 2018 at CTU. Additional workshops to develop the project BBN under activity 4.1a, in February and June 2018, have helped solidify the capacity in model development of Vietnamese researchers across all teams.

A key strength of the project is the solidarity of the team and the effectiveness of the multi-disciplinary profile. Australian and Vietnamese project team members are building each other's capacity scientifically and culturally – Australian team members are developing better skills in working collaboratively in a different cultural and environmental setting, and Vietnamese team members are learning about different research approaches that can benefit their work across other programs of research. The partnership model has worked well for this project and extends to the success with stakeholder engagement.

Jason Condon benefited from mentorship by J. Sammut in international multidisciplinary, multi-agency research, and ACIAR project development and management, and since commenced leading a project of his own. Michele Burford also developed skills in how ACIAR projects are developed, implemented and managed.

9 Community impacts – now and in 5 years

9.1 Economic impacts

Our pilot trials on modified shrimp farming practices help to increase yields from 242 to 303 kg shrimp/ha. Application of supplementary feed can achieve 326.9 kg shrimp/ha and a benefit of 1,500 USD/ha annually. 1,500 USD/ha is the gross return (excluding costs). With the current practice, farmers can earn an average 4 USD per kg shrimp, thus an increase in profit.

About 200,000 ha of rice – shrimp systems are currently spread across the Mekong Delta MD such that a large amount of benefit can be gained from adoption of our findings, even if only 20% of this area adopt the recommendations.

9.2 Social impacts

The project findings will have contributed to improving the performance of rice - shrimp farming and hence livelihoods of about 50,000 resource-poor farmers practicing the farming system.

About 45 local governmental staff (commune and district level), 35 communal key informants and 133 local farmers have improved perceptions and attitudes on ways of facilitating their local potential and overcoming barriers to further improve rice – shrimp farming systems and livelihoods of local people, through participating in local focus-group discussions and validation of preliminary study results.

The project findings will contribute to the successful implementation of the resolutions of the Vietnamese government policies and strategies on agricultural transformation and sustainable rural development in coastal Mekong Delta, where saline/brackish aquaculture industry is the most important domain. About 100,000 hectares of double rice cropping in the interface zone, ie between the freshwater and the brackish water, would be shifted to rotational rice and shrimp farming in the future under projected salinity intrusion from the estuary.

Our project also created opportunities for women to become local lead farmers, and this was most evident at Tan Bang where women were taking over the role of running the farm and enabling men to take on other forms of income generation. Women were involved in our field trials (data collection), participated in our workshops, and were also involved in planning meetings at trial sites. Farmers reported that the change in gender roles for some households was positive, and women became important disseminators of the research findings and had organised meetings for women involved in rice-shrimp farming to strengthen their role.

9.3 Environmental impacts

At the commencement of the study, the intention was to identify the positive and negative effects of rice-shrimp farm on the surrounding environment. Our study has clearly shown that eutrophication, i.e. high nutrient loads, are not a result of rice-shrimp farming, but resulted from pollution of canals from other human activities, e.g. sewage. Overall, rice-shrimp farms were actually reducing nutrient loads in the environment, which contrast with other forms of shrimp farming where they contribute significant loads which can negatively impact on the environment (Jackson et al. 2003, Burford et al. 2003). As a result of these findings it is also clear that fertiliser addition to stimulate algal growth, and rice production, may not be needed. However, if further research can improve water quality conditions, the high nutrient loads may stimulate much needed natural food production for shrimp growth. There is also scope to use rice-shrimp ponds for nitrogen removal, if denitrification processes are enhanced. This has greenhouse gas implications….millions dollars are spent in the ag industry to decrease denitrification in an attempt to limit nitrous oxide emissions

Quantifying nutrients in sludge collected from rice-shrimp farms demonstrated that low N and P contained in sludge as compared to other mono-shrimp cultured farms. This comes from the fact that feeding inputs in this system is minor, which minimize environmental pollution risk as sludge is flushed out from the farm. On the other hand, utilizing sludge as fertilizer for rice production help reduce cost, water pollution risk and eventually, sustain the production system.

There are many challenges to rice-shrimp farming in the Mekong Delta, particularly as other land uses draw on the water resources and industry and agriculture add pollutants to the environment. This is particularly true from potentially contaminated canal water. The chemicals and microbial communities in the canal water may negatively impact shrimp production, and the quality of the product. Therefore, examination of the broader issue of pollutant loads in canals in needed to address this.

10 Communication and dissemination activities

Dissemination activities

The project team regularly engaged with stakeholders at all stages of the project. Before each trial, the project team met with DARD officers, commune leaders and farmers to discuss the research objectives, capture lay knowledge, agree on selection of farms, and outline the research methods and the level of participation required from farmers. Feedback was then provided during each site visit to ensure stakeholders were kept updated on progress and to revise research plans and farmer roles in the research. At the end of each trial, and whenever research findings were generated, the project team conducted feedback sessions during which the results were explained and their relevance to the next stage of research or changes in farming practices were discussed. These sessions were held at DARD offices, the RIA2 Substation in Ca Mau, farms and commune halls. Better management practices were demonstrated on-site with farmers and DARD officers from other provinces.

Informal training of farmers occurred during field trials and was facilitated by the participatory approach of the research. Farmers were trained to collect and record data, and gained skills in applying better management practices. Formal training was provided via workshops on-site or at the local commune meeting hall. Plans to workshop extension materials have been postponed until the COVID-19 travel and meeting restrictions are lifted. We plan to organize the program for October to December 2020 before a new shrimp crop starts but this is likely to be pushed into 2021 if there is a second wave of COVID-19 cases in Vietnam. This year, better management practices are being applied by a large group of farmers, eg there are 11 farmers in Tan Bang who are promoting the practices with help from commune technical staff.

Communication

Project findings were communicated more broadly through Facebook and twitter accounts managed by UNSW, and the twitter accounts of the Australian research team. The following social media and web accounts were used:

1) UNSW Aquaculture research group Facebook Page: https://www.facebook.com/UNSWaquaculture/
2) UNSW Centre for Marine Science and Innovation Facebook Page: https://www.facebook.com/unswcmsi/
3) UNSW School of Biological Sciences Facebook Page: https://www.facebook.com/unswbees
4) UNSW Science Facebook Page: https://www.facebook.com/UNSWScience/
5) UNSW Global Water Institute: http://www.globalwaterinstitute.unsw.edu.au
6) Griffith University Australian Wetlands and Rivers Institute: https://www.griffith.edu.au/australian-rivers-institute
7) Team Twitter accounts: @JesSammut, @AquacultureUNSW, @michele_burford, @BStewartKoster, @Cleigh-rivers

Figure 25. Dissemination session with farmers and DARD officers occurred before, during and after field trials, and under a program of workshops. Most dissemination activities were undertaken at farm sites to demonstrate better management practices and for farmers to provide feedback on the modified farming practices. (Photo credit, J.Sammut, UNSW)

Table 4: Summary of formal training workshops; 2020 workshops have been postponed due to COVID-19. Informal training, which was regularly conducted, is not shown here.

No.	Activity	Type of activity	Date	Where (location, country)	Participants				# of ♂	# of ♀
					Government (not in team)	Farmer	INGO, NGO, private sector (not in team)	Project team		
1	BBN farmer Workshop	Presentation of initial results and collection of economic data for additional BBN development	31 Jul-5 Aug 2017	Can Tho on 31Jul, Ca Mau on 1-5Aug.2017	3	23	0	12 CTU, CLRRI, RIA2 team, Jes Sammut, Ben Stewart-Koster, Dieu Anh Nyguyen	29	9
2	Annual meetings	Presenting project findings, field visit, planning for remaining activities.	Annually every October	Ca Mau, Vietnam	6-10	2-30	0	27 Entire Team	>30	>10
2	Disseminatio n workshop	Extension workshop: inform provincial official of DARD, Directorate of Fisheries and famers project findings	23-24 Nov 2017	Ca Mau	8 Provincial officers from division of agriculture in Kien Giang, BacLieu, Ca Mau and directorate of fisheries	20	0	18 CTU, CLRRI, RIA2 team	30	16
3	BBN smart phone app workshop	Workshop	30 Jan 1 Feb 2018	Ca Mau, Vietnam	5 local officers in Thoi Binh and Cai Nuoc district	16	0	12 CTU, CLRRI, RIA2 team, Ben Stewart-Koster, Andrew Lewis, Dieu Anh Nyguyen	25	8
	BBN training for agricultural decisions	Training	2-3 Feb 2018	Can Tho, Vietnam	0	0	0	13, CTU and CLRRI teams, Ben Stewart-Koster	8	5
4	Social economic workshop 1	Workshop	7-8 Feb 2018	Ca Mau, Vietnam	1	40	0	5 (Dang Kieu Nhan, Ben Stewart-Koster, Jes Sammut, Alice McGowan, Nicola Clare Johnson)	30	16
5	Growth model training 1	Training	8-9 Feb 2018	Ca Mau, Vietnam	0	0	0	8 Ben Stewart-Koster, Nguyen Van Sang, Le Van Truc, Le Huu Hiep, Nguyen Minh Duong, Ngo	5	3

								Thi Ngoc Thuy, Vo Bich Xoan, La Thuy An		
6	Guiding farmers to estimate the quantity of natural food, identifying the harmful bacteria in shrimp, and water pond	Training farmers workshop	26-27 Mar 2018	Ca Mau, Vietnam	1	10	0	8 RIA2 team	10	9
7	Dr. Sang was Interviewed by VTC16 on importance and status of project	Promotion	25 years of ACIAR in Vietnam 11Apr2018	Hanoi, Vietnam	1	0	0	8 CTU, CLRRI, RIA, Jes Sammut, Jason Condon, Trieu My Hoa	5	4
8	Scientific BBN development	Workshop and training	4-8 Jun 2018	Can Tho and Ca Mau, Vietnam	3 Ca Mau DARD officers	0	0	21 CTU, CLRRI, RIA2 team, Jason Condon, Ben Stewart-Koster	15	9
9	Growth model training 2	Training	7 Jun 2018	Ca Mau, Vietnam	0	0	0	9 Ben Stewart-Koster, Nguyen Van Sang, Le Van Truc, Le Huu Hiep, Nguyen Minh Duong, Ngo Thi Ngoc Thuy, Vo Bich Xoan, La Thuy An, Hoang Thi Thuy Tien, Nguyen Thi Ngoc Tinh	5	4

11. Conclusions and recommendations

10.1 Conclusions

The multiple-methods approach of the project identified risk factors for production and utilised the scientific outputs as a baseline to develop better management practices and to guide future research on technologies to improve the system further. Salinity was identified as the key risk factor for rice production, and to a lesser degree, acid sulfate soils and farming practices. Importantly, the project demonstrated that the timing of planting, remediation of soil salinity in the rice growing platform, and selected salt-tolerant rice varieties can improve rice yields at Tan Bang Commune, and likely at other sites were soil salinity is not severe. By contrast, the severity of soil salinity at Hoa My Commune, which represents an extreme level of salinity for the Mekong, rice crop losses are difficult to prevent. Acid sulfate soils and farming practices (tendency to prolong the shrimp crop by allowing saline water into the system), compound the salinity issues at this location.

Further research into transitioning to shrimp monoculture or alternative livelihoods is recommended for locations, such as Hoa My Commune. Such research should also investigate the financial challenges of a change in livelihood, and interventions that can enable a transition in practice to occur. Our socioeconomic studies showed that farmers consider climate change and the uncertainty of the environmental conditions as challenges for rice production. Drought and associated increases in soil salinity were a significant concern.

Salinity, low dissolved oxygen concentration and high temperature were identified as the main water quality risk factors for poor shrimp production in the system. These water quality factors were also linked to the poor nutritional status of shrimp via two mechanisms. Firstly, suboptimal water quality for shrimp is a known cause of reduced feeding. Secondly, the high salinity and water temperatures limit the conversion of nutrients into natural food sources for shrimp. Accordingly, we theorise that optimising water quality can improve shrimp yields to reduce stress on shrimp, and to increase the natural food production. We have shown that nutrients in the system are abundant but natural food availability is too low for the density of shrimp in the ponds. Based on experiences in other countries, where extensive farming of shrimp has long transitioned to improved extension systems, supplementary feeding may help to further improve yields. Our pilot trials on supplementary feeding during the final stages of the project indicated that the potential to increase yields needs to be tested under a series of replicated studies. Given that improved extensive systems in other countries, such as Indonesia, are based on large extensive ponds rather than the design of the Vietnamese rice-shrimp system, field-based trials would be required to test the feasibility, and to modify feeding practices for the Mekong context. At present, the rice-shrimp farming systems we have tested are not widely scalable until further improvements are made to the shrimp farming component. There is also scope to more effectively investigate the benefits of farming rice and shrimp together, which was difficult under the present study because of inconsistent shrimp yields, and recurrent rice crop losses at Hoa My. Sites similar to Tan Bang would be useful for future research because the potential to optimise both rice and shrimp is high, whereas sites such as Hoa My Commune can provide opportunities to explore transition from rice-shrimp to shrimp monoculture as an alternative livelihood for struggling farmers and to address future impacts of climate change.

10.2 Recommendations

This study has clearly highlighted some key challenges with the sustainability of rice-shrimp farming systems. This has set a solid scientific foundation for testing new approaches for improving the sustainability of these systems, in terms of improved reliability of production and poverty alleviation. These include:

1) Assessing the effectiveness of supplemental feeding with formulated feed to improve shrimp productivity.
    - The published studies in both districts in Ca Mau point to inadequate natural food supplies for shrimp in the rice-shrimp ponds. Building on these findings, preliminary studies where formulated feed was added to ponds, suggest that there could be benefits of this approach, but a broader scale study is needed to test this. Therefore, it is proposed that a scientifically robust study comparing natural food vs supplementing with formulated feed be conducted with multiple farms across the Mekong. Previous research has established that homemade or trash fish will not provide benefits (Burford et al. 2004b). Therefore, the higher quality formulated feed must be tested. The effect of formulated feed on water quality also needs to be determined. This study needs to be coupled with a cost-benefit analysis of supplemental feeding.
2) Assess methods for reducing low oxygen conditions
    - Our study demonstrated periods of low oxygen concentrations at night. This is likely to be a major stress in shrimp, affecting growth, disease susceptibility and ultimately survival. Our study also identified sediment oxygen demand caused most of the oxygen reduction. Therefore, cost-effective methods for increasing oxygen during periods of identified high risk, e.g. high temperature periods, need to be tested. This then needs a cost-benefit analysis to ensure the benefits are clear.
3) Evaluate changes to pond designs and water management
    - Our research has demonstrated that high temperatures are also a risk factor for shrimp. Possible solutions may include changes in ditch dimensions, inclusion of water aeration or circulation, and modified water exchange practices. As for all possible solutions, economic analysis is required.
4) Testing of the above under different conditions in the Mekong to address a highly variable landscape with different degrees of salinity, access to freshwater resources, impacts of droughts and links to water availability, and livelihoods assets.
5) Testing the physical effectiveness and economic benefit of mechanized tillage and rice harvest in the rice-shrimp system.
6) Investigate the benefits of farming rice and shrimp together under an improved rice-shrimp farming system.
7) Investigate an effective way for using sludge as nutrient-supplying pool. The findings from the project revealed that sludge may partially replace chemical fertilizer, nevertheless further investigation on how frequency of use and how soil physico-chemical properties change over time is needed.
8) With the availability of mechanical systems that can be applied to this farming system (e.g. Yanmar has recently trialed a tractor to work on the rice platform), more investigation is needed on the improvement of salinity leaching and the turnover of soil organic matter in the system.
9) Investigate opportunities for a shift from rice-shrimp production to shrimp monoculture in areas that are too saline for rice production or are at risk of increasing salinity based on climate change forecasts.

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12 Appendixes

12.1 Appendix 1: Publications list (see Excel file)

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