**Concurrent rice-shrimp-crab farming systems in the Mekong Delta: are conditions
(sub)optimal for crop production and survival?**

Authors

Catherine Leigh^{1,2*}, Le Huu Hiep³, Ben Stewart-Koster¹, Duong Minh Vien⁴, Jason Condon⁵,
Nguyen Van Sang³, Jesmond Sammut⁶, Michele Astrid Burford¹

Affiliations

¹ Australian Rivers Institute, Griffith University, 170 Kessels Road, Nathan, Queensland
4111, Australia

² The Griffith School of Environment, Griffith University, 170 Kessels Road, Nathan,
Queensland 4111, Australia

³ Research Institute for Aquaculture 2 (RIA2), 116 Nguyen Dinh Chieu Street, District 1, Ho
Chi Minh City, Vietnam

⁴ Can Tho University, Campus 2, 3/2 Street, Can Tho City, Vietnam

⁵ Graham Centre for Agricultural Innovation, School of Agricultural & Wine Sciences,
Charles Sturt University, Wagga Wagga, NSW 2650, Australia

⁶ Centre for Ecosystem Science, The School of Biological, Earth & Environmental Sciences,
The University of New South Wales, Sydney, New South Wales 2052, Australia

*Corresponding author: c.leigh@griffith.edu.au; T: +61 7 37354421

Running title: Rice-shrimp farming in the Mekong Delta

Key words: aquaculture, extensive farming, prawns, saltwater intrusion, water quality

Abstract

The Mekong Delta is the most important rice and shrimp producing region for food and economic security in Vietnam. Rice-shrimp farming is practised where salinity fluctuates substantially between wet and dry seasons. Research points to several potential risk factors for rotational systems, but how these link directly to both rice and shrimp production remains poorly quantified for systems that stock and harvest animals year-round. We examined water and soil quality of 18 rice-shrimp-crab ponds, in which shrimp and crab are grown in both wet and dry seasons, in the Cà Mau Province of Vietnam. Multiple lines of evidence indicated that environmental conditions experienced by both rice and shrimp were suboptimal and contributed to low yields and survival. Year-round cropping of shrimp and crab was associated with sustained suboptimal salinity, intensified by drought, for the wet-season cultivation of rice. Although rice seedlings were sown in all 18 ponds, only three had a harvestable crop. Low shrimp production and survival was associated with sustained suboptimal water temperatures (too high), salinity (too high in the dry season, too low in the wet season) and dissolved oxygen concentrations (too low). Food availability and quality may also have affected shrimp production. Improving productivity of rice-shrimp-crab ponds in the study region may require (1) separation of rice and shrimp crops and improving efficiency of soil washing practices such that salinity conditions are more suitable for each when grown, and (2) management intervention to increase oxygenation of water as well as the availability and the availability and quality of food for shrimp.

Introduction

The Mekong Delta is the most important rice and shrimp producing region in Vietnam in terms of food and economic security, accounting for more than 50% of the country's annual rice production (Phong et al. 2015; Smajgl et al. 2015; Ho & Burny 2016). Modern rice-shrimp farming commenced in the 1980s in areas of the delta where traditionally only

rice was grown (Nhuong, Luu, Tu, Tam & Nguyet 2002). This shift was driven by policy reforms in agriculture, decline in the price of rice and increasing saltwater intrusion (Khiem & Khai 2008). The region has a complex network of channels and sluice gates and by opening the sluice gates in the dry season, farmers can allow saline water to enter the channels and fill ponds for growing shrimp. In the wet season, farmers rely on monsoon rains to desalinate the water and top soil layer in preparation for planting rice on raised platforms (Preston & Clayton 2003; Nhan, Trung & Van Sanh 2011; Nhan, Phap, Phuc & Trung 2012).

Since the 1980s, farming systems have evolved to improve production and today the black tiger prawn, *Penaeus monodon*, is the most commonly cultured shrimp in the dry season (Nhuong, Luu, Tu, Tam & Nguyet 2002; Joffre & Bosma 2009; Tho, Ut & Merckx 2011). Farmers also stock other animal species on occasion (e.g. mud crab *Scylla paramamosain*, Pacific white shrimp *Litopenaeus vannamei*, and even freshwater *Macrobrachium* spp. if salinity allows) and may stock both shrimp and crab year-round in attempts to increase or at least stabilise profits (Christensen, Macintosh & Phuong 2002; Joffre & Bosma 2009; Son, Phuong, Hai & Yakupitiyage 2011). However, profitability can be low and production is affected by a range of factors, including white spot disease (WSD), pond water quality, water exchange rates and shrimp-pond preparation practices (Walker & Mohan 2009; Tran, Zwart, Phuong, Vlak & de Jong 2011; Tho, Ut & Merckx 2012). In recent years, early mortality syndrome (EMS, also known as acute hepatopancreatic necrosis disease) has resulted in a high level of shrimp mortality (Lightner, Redman, Pantoja, Noble & Tran 2012).

In addition, rice production in the region is being threatened increasingly by sea-level rise and saline intrusion (Wassmann, Hien, Hoanh & Tuong 2004; Smajgl et al. 2015), driving a move towards development and cultivation of rice varieties with greater salt tolerance or shorter culture periods (Preston & Clayton 2003; Nhan et al. 2011, 2012).

However, significant issues with production reliability and profitability remain. Field trials in the region show potential rice yield reduction of 180 to 1270 kg ha⁻¹ per crop for every unit (1 g L⁻¹) increase in salinity for tolerant to sensitive varieties (Nhan et al. 2012). Like shrimp, rice production has also been impacted negatively by the outbreak and spread of viral disease (Hoang, Zhang, Yang, Chen, Hébrard, Zhou, Vinh & Cheng 2011).

Previous studies have examined water and soil quality in seasonally rotational rice-shrimp ponds (Tho et al. 2011, 2012) and identified potential risk factors for production, but how these factors link directly to both rice and shrimp production remains poorly quantified for systems where shrimp (and crab) are stocked year-round. To address this gap, we examined water and soil quality of 18 rice-shrimp-crab ponds, in which shrimp and crab were stocked in both wet and dry seasons, in the Cà Mau Province of Vietnam over a two-year period (2014-2015). We expected that ponds with poorer conditions (e.g. low dissolved oxygen concentration, high water temperature, sub-optimal salinity) would have lower shrimp production and survival. Additionally, we expected the year-round stocking of shrimp would be detrimental for rice production due to maintenance of salinity that favours shrimp but is sub-optimal for rice in the wet season. Knowledge on the environmental controls on the productivity of concurrent rice-shrimp farming systems is essential for environmental decision making, land-use planning and interventions that can improve production.

Materials and Methods

Study region and pond design

This study was conducted in the Hòa Mỹ commune, Cái Nước District, Cà Mau Province in the southern Mekong Delta, Vietnam (Fig. 1). The region has two main seasons, the wet season (~ May/June to October/November) and the dry season (~ December to April) (Tho et al. 2011). During the study period (2014-2015), total rainfall over the months

December to April (henceforth the dry season) and June to October (henceforth the wet season) ranged from 70-103 mm and 1518-1726 mm, respectively (Fig. 2). For purposes of analyses, the transitional months of May and November were not considered as falling strictly within either season.

Each of the 18 ponds in this study (Fig. 1) was managed by a different farmer and conformed to a 'ditch-platform' design. Raised central platforms are used to grow rice, typically in the wet season (mean depth of the 18 ponds = 0.3 ± 0.1 m). Shrimp, typically grown in the dry season, inhabit the deeper ditches (mean depth = 0.9 ± 0.2 m) surrounding the platforms during the day and use the platforms at night to access natural food sources. Twelve ponds (coded a-l) were sampled in 2014 and 18 ponds in 2015 (the original 12 plus six others coded m-r; Fig. 1). The 18 ponds (ditches + platforms) range in size from 3000 to 47900 m² (mean = 18500 ± 13800 m²), which is comparable to the size range of other rice-shrimp ponds studied in the Mekong Delta (e.g. Joffre & Bosma 2009). Source water for the ponds typically ranges in salinity from c. 0 to 40 g L⁻¹, depending on the season and tidal-flow direction, and comes from Muoi Phai canal, which connects to the My Binh River, flowing to the Gulf of Thailand via Thi Tuong Lagoon.

Pond management

Pond preparation for the dry season consisted of the addition of burnt lime with the amount varying from farm to farm (c. 300-400 kg ha⁻¹). Burnt lime and/or calcium carbonate and/or dolomite was then added to ponds periodically throughout the study period. Fertilizer in the form of a nitrogen-phosphorus-potassium blend (NPK), urea, and/or diammonium phosphate (DAP) was added periodically to stimulate primary production. In the dry season, water in the ponds was exchanged periodically with the adjacent canal.

Shrimp postlarvae were stocked periodically throughout both the wet and dry seasons of both years at an average density in the ponds of 2 ind. m⁻² (primarily *P. monodon*; PL15 in the dry season, PL25 in the wet season). Shrimp were harvested for market periodically throughout the study period using trap nets with mesh sizes that selected for larger individuals. The minimum individual harvest weight was 17 g in 2014 and 29 g in 2015. Under the *P. monodon* growth model of Jackson and Wang (1998), and given the mean monthly minimum water temperature of the ponds for 2014 (25 °C) and 2015 (27 °C), shrimp would take c. 120 d and 180 d to reach the minimum 2014 and 2015 harvest weights, respectively (comparable with culture periods reported elsewhere; Tho et al. 2011). Mud crab (*S. paramamosain*, crablet stages 1 and 2) were also stocked periodically throughout the study period at densities of 0.4 ind. m⁻². Study of pond-based aquaculture of mud crab in Vietnam indicates production of commercial size crab (c. 400 g) requires a growing period of 90-150 d (Keenan 1999). Farmers did not add formulated feed to ponds, but relied on natural feed to meet the nutritional needs of the animals.

At the end of each dry season, accumulated salt was removed from the platform of each pond by washing several times with rainwater falling at the start of the wet season. Rice seedlings were sown on the platforms of all ponds each wet season. Seedlings were nursery grown for 20-25 d before transplanting. Sowing rates and the varieties used differed between years. The 2014 rate was 100-120 kg ha⁻¹ for the OM9921 variety (high productivity, culture period 95-100 d). In 2015, the rate was 30-40 kg ha⁻¹ for a local variety 'Mot Bui Do', which has a longer culture period (115-120 d) but seedlings with higher salinity tolerance than those of OM9921 (Tiến, Liên & Thành 2011). Where there was sufficient rice present for harvest, this occurred at the end of each calendar year.

Sampling and laboratory analyses

Water quality of the ponds was characterised by several variables measured throughout the study period, excluding January and February (except for water temperature, which was measured in some ponds in January and February 2015). Water temperature ($^{\circ}\text{C}$) and salinity (g L^{-1}) were recorded in the early mornings and afternoons (*c.* 06:00 and 14:00) by loggers (Thermocron iButtons and Odyssey conductivity probes, respectively) placed below the water surface in the ditch of each pond. For dissolved oxygen (DO ; mg L^{-1}) and pH, weekly measurements were taken near the bottom of the ditch of each pond both early morning and afternoon (*c.* 06:00 and 14:00) using a calibrated TPS (90FLT) multiprobe device. Alkalinity (mg L^{-1}) of the water was measured *c.* fortnightly using a Sera test kit (Sera GmbH, Germany).

Concentrations of nutrients (total organic carbon, TOC; total nitrogen, TN; total phosphorus, TP; nitrite, $\text{NO}_2\text{-N}$; nitrate, $\text{NO}_3\text{-N}$; ammoniacal nitrogen, $\text{NH}_4\text{-N}$; phosphate, $\text{PO}_4\text{-P}$; mg L^{-1}), chlorophyll *a* (Chl *a*; $\mu\text{g L}^{-1}$) and total suspended solids (TSS; mg L^{-1}) were measured monthly, all using samples of water collected with buckets from five randomly selected locations in the ditch and platform of each pond. Water from the five locations at each pond was combined, from which two whole water subsamples and two 0.45- μm membrane-filtered subsamples (for $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$) were collected and then stored on ice during transportation to the analytical laboratories at Research Institute for Aquaculture No.2, Ho Chi Minh City, Vietnam. TOC was analysed using the chromic acid rapid titration method, $\text{NH}_4\text{-N}$ using the phenate method, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$, using the cadmium reduction and sulphanilamide method, $\text{PO}_4\text{-P}$ using the ascorbic acid method, and finally TN and TP were digested using the persulfate method, then analysed as $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ respectively (APHA, 2005). A spectrophotometer (Helios Alpha, Thermospectronic, UK) was used to measure absorbance (APHA, 2005).

About 20 samples of the top soil layer (depth 0-10 cm) were collected from the platform of each pond at the beginning of the study period (i.e. from ponds a-l only) and mixed in a composite sample for each pond for analysis at the Can Tho University laboratories, Vietnam. Composite samples were air-dried, pulverized to pass through a 2-mm mesh and analysed for electrical conductivity (1:2.5 soil:deionised water solution; dS m^{-1}) using a Schott lab 906 EC probe.

Monthly, seasonal and annual summary statistics

Because shrimp and crab were stocked and harvested continuously throughout 2014 and 2015, individuals harvested in early 2015 would likely have been stocked in late 2014. Given the estimated 120-d culture period for shrimp in 2014 and 180-d in 2015, we calculated production yield and survival for 2014 only using stocking data from January to August 2014 inclusive and harvest data from May to December 2014 inclusive, and for 2015 only using stocking data from January to June 2015 inclusive and harvest data from July to December 2015 inclusive. This also meant that the water quality conditions experienced by shrimp contributing to the 2014 and 2015 yield and survival data would be restricted to the 12 months of 2014 and 2015, respectively, and hence facilitate analysis. Annual yield (kg ha^{-1}) for each pond was therefore calculated as the total weight of shrimp harvested in the relevant annual period (see above) divided by pond area. We used total pond area to calculate production yields because shrimp use both the ditch and platform depending on the time of day; there was a strong, positive and linear relationship between total pond and ditch area ($R^2 = 0.96$). Annual survival for each pond was calculated as the total number of shrimp harvested during each of the relevant annual periods (May to December 2014, July to December 2015; estimated using the mean weight of samples of c. 30 harvested shrimp weighed individually each month and the total harvest weight for the relevant annual period)

divided by the total number of shrimp stocked during each of the relevant annual periods (January to August 2014, January to June 2015), expressed as a percentage (%).

Survival could not be calculated for crab because only the number stocked and total harvest weight was recorded (number of individuals harvested was unknown and could not be estimated because harvested crabs were not counted or weighed individually). Production yield in 2014 (and 2015) was estimated based on a 120-d growth period (median of the 90-150 d period reported in Keenan 1999), using harvest data from May to December 2014 (and May to December 2015) inclusive, and was calculated as the total weight of crab harvested in the relevant annual period divided by pond area (kg ha^{-1}).

Monthly, seasonal and annual summary statistics were generated for each pond from the water quality data. Monthly means, maxima and minima were calculated from water temperature and salinity (measured bi-daily), DO and pH (measured weekly), and alkalinity data (measured fortnightly). Concentrations of nutrients (TOC, TN, TP, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$), TSS and Chl *a* were all initially measured monthly. The generated monthly summary statistics for all the above variables therefore corresponded to means of duplicate monthly spot samples or the monthly means, maxima or minima of multiple (> 2) samples, as dependent on the sampling methods and time steps as detailed above. For each variable, seasonal (dry and wet) and annual means were also calculated from the monthly summary statistics, as relevant to each season and year.

For each pond, we then calculated the number of months in each year that the monthly summary statistic was outside (i.e. either above or below) the optimal range of values for shrimp, based on ranges provided in Anon. (2006) and Tho et al. (2011) and using the most conservative ranges where differences existed between these two sources, for water temperature, salinity, dissolved oxygen, alkalinity, pH, dissolved inorganic nitrogen ($\text{NO}_2\text{-N}$,

NO₃-N, NH₄-N) and TSS (Table 1). We performed the same calculation for water salinity based on the optimal range for rice production ($< 1.6 \text{ g L}^{-1}$, or $< 3.0 \text{ dS m}^{-1}$; Grattan et al. 2002). For each year and pond, we then determined the percentage of time each measure was outside the optimal range for either shrimp or rice. If a month had no data it did not contribute to the percentage, e.g. if salinity was measured for 11 months of the 2014 year only, and the mean salinity in each of those 11 months was $> 1.6 \text{ g L}^{-1}$, the resulting percentage for mean salinity would equal 100 % for rice. To visualise relationships between water quality and shrimp or rice production and survival, with respect to these optimal ranges, plots showing month-to-month fluctuation in water quality measures were produced using the monthly water quality data (for all ponds) for those measures for which optimal ranges were available (Table 1). Smoothing lines were added to plots using the `smooth.spline` function in the stats R package (R Core Team 2016).

Statistical analysis

Differences between the dry and wet seasons in water quality conditions were tested using linear mixed effects models in the R package nlme (Pinheiro, Bates, DebRoy, Sarkar & R Core Team 2016), using monthly data across both years and with farm code as the random effect to account for within-pond variation. Distributions of water quality measures were inspected prior to analysis and data were transformed as necessary to meet assumptions of the analysis. Salinity and DO data were natural-log transformed, PO₄-P, NO₂-N, NO₃-N, TP, TN and Chl *a* data were square-root transformed, and the fourth-root transformation was applied to NH₄-N and TSS data. Correlations between annual production yield and survival and annual and/or seasonal water and soil quality were tested for significance in the Hmisc package in R (Harrell, Dupont et al. 2016) using the Spearman rank correlation coefficient.

Results

Production and survival

Shrimp yields were highly variable among ponds in both years, as indicated by the standard deviations around the mean pond values ($111 \pm 53 \text{ kg ha}^{-1}$ in 2014; $114 \pm 92 \text{ kg ha}^{-1}$ in 2015). By comparison, the mean weight of harvested individuals was less variable within years, but substantially higher in 2015 ($31.0 \pm 1.8 \text{ g}$) than in 2014 ($24.5 \pm 3.8 \text{ g}$). Fewer but larger shrimp were harvested in 2015 ($32 \pm 2 \text{ ind. kg}^{-1}$) than in 2014, when more but smaller shrimp were harvested ($40 \pm 5 \text{ ind. kg}^{-1}$). Annual survival was similarly low in both years ($6.2 \pm 3.9 \%$ in 2014; $7.5 \pm 8.4 \%$ in 2015). Crab production yield in 2014 was half of that in 2015 but highly variable among ponds in both years ($41 \pm 21 \text{ kg ha}^{-1}$ vs $82 \pm 73 \text{ kg ha}^{-1}$, respectively). Rice harvests were only obtained from three ponds over the entire 2-y study period (300 kg from pond g in 2014, 250 kg from pond k in 2014, and 200 kg from pond e in 2015; equivalent to 179, 112 and 258 kg ha^{-1} , respectively, based on platform area). All other farms experienced rice crop failure with no harvestable yield.

Water and soil quality and conditions for shrimp and rice

Monthly water temperature (mean, maximum, minimum), salinity (mean, maximum and minimum), alkalinity (mean, maximum, minimum) and TSS (mean) were all significantly higher in the dry season than in the wet season, whereas DO (mean, maximum, minimum), TOC (mean) and $\text{NO}_2\text{-N}$ (mean) were all higher in the wet season (Fig. 3; $p < 0.05$).

Conditions were predominantly sub-optimal for rice production (see Fig. 4 for reference). Electrical conductivity of platform soil in ponds a-l at the beginning of the study period ($9.3 \pm 3.0 \text{ dS m}^{-1}$) was above the guideline threshold at which rice yields become affected negatively (3.0 dS m^{-1} ; Grattan et al. 2002). Furthermore, monthly water salinity

(mean, maximum and minimum) was not optimal (i.e. $\geq 1.6 \text{ g L}^{-1}$) for rice production > 90% of the time, on average across ponds, in both 2014 and 2015 (standard deviation was $\leq 14\%$ in all cases). The one exception was minimum salinity in 2014, which was suboptimal 75% of the time ($\pm 22\%$), driven primarily by occasional, low minimum salinity (i.e. $\leq 1.6 \text{ g L}^{-1}$) in ponds a-d and l during the 2014 wet season, but none of these ponds had rice harvests. By contrast, minimum salinity at pond e was within the optimal range through much of the 2015 wet season (i.e. each month from August to December 2015; mean and maximum salinity were also within the optimal range for some of these months) and this pond had a rice harvest that year (200 kg). All other ponds had mean, maximum or minimum water salinities outside of the optimal range for rice production for percentages of time similar to the percentages observed on average across all ponds (i.e. 90-100%).

For shrimp, monthly water quality values were, on average across ponds, outside the range of optimal conditions at least once during the study period; the only exceptions were minimum water temperature, mean $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in both years, mean $\text{NO}_2\text{-N}$ in 2014, and mean, maximum and minimum pH in 2014 (Table 1). Maximum water temperature, mean, maximum and minimum salinity and alkalinity, minimum DO and mean TSS were, on average across ponds, outside the range of optimal conditions more than 50% of the time in both 2014 and 2015, and the mean and maximum DO were, on average across ponds, outside the range of optimal conditions at least 50% of the time in 2014 (Table 1). In most ponds, maximum water temperature was frequently too high for shrimp, particularly in 2015, and minimum water temperature too low, particularly in 2014 (Fig. 4). Water salinity in the later months of the dry season was often too high, especially in 2015, and too low in the wet season (Fig. 4). Alkalinity of water was also too high in many ponds, especially in 2014, and for much of the year; although alkalinity of pond d tended to be too low, especially in the wet season of 2015 (Fig. 4). This same pond had low pH during the 2015 wet season, but pH was

otherwise within the optimum range for shrimp for most other ponds and times of year (Fig. 5). Many ponds had below optimum DO throughout much of the study period, regardless of season; in fact, minimum DO in 2014 was below optimum for all ponds all year (Fig. 6). TSS was too high for most ponds regardless of season and year, except for pond c, which seemed to retain optimum TSS concentrations throughout much of 2014 (Fig. 6). Figures are not shown for nutrient data; only one pond (g) was outside the optimal range for nutrient concentrations, in November 2014 and for NO₂-N only (the value being > 1.0 mg L⁻¹; Table 1).

There were few strong (i.e. Spearman $\rho \geq |0.8|$) but several statistically significant ($p < 0.05$) correlations between water quality (annual, dry-season and/or wet-season means) and the survival or production yields of shrimp (Table 2). In 2014, for example, shrimp survival and production yield increased with mean annual Chl *a*, mean dry-season PO₄-P and NH₄-N, and mean wet-season Chl *a* concentrations ($p < 0.05$; Fig. 7). Although ranges of these concentrations for each variable were comparable between years (Table 2), the same correlations were not observed in 2015. Shrimp production yield in 2015, for example, increased with minimum wet-season salinity ($p < 0.05$; Table 2). Correlations between the electrical conductivity of soil and shrimp survival or production yields were non-significant ($p > 0.05$).

Discussion

This study has provided multiple lines of evidence indicating that the environmental conditions experienced by rice and shrimp during 2014 and 2015 were suboptimal and contributed to low production yields and survival for both rice and shrimp. Only three of the rice-shrimp-crab farms produced a rice crop during the entire study, at production values (< 260 kg ha⁻¹) well under those achieved in field trials even when using salt-sensitive varieties

(> 2000 kg ha⁻¹; Nhan et al. 2012). The pond with the highest rice production (258 kg ha⁻¹, in 2015) maintained water salinity within optimal range (< 1.6 g L⁻¹) for much of the 2015 growing (i.e. wet) season; however, the two other ponds that produced a rice crop had suboptimal salinity which makes attributing variation in rice production to salinity alone, or at least primarily, somewhat difficult.

Nevertheless, salinity was suboptimal (> 1.6 g L⁻¹) for rice for > 90 % of the study period in most ponds. Salinity was often well above 4 g L⁻¹ (Fig. 4), the maximum threshold reported by Nhan et al. (2012) at which farmers in the Mekong Delta region should be able to maintain income and production of salt-tolerant rice varieties without use of other management interventions such as adjusting the rice-cropping season, improving desalinization, rotating rice crop with shrimp. In our study, shrimp were stocked and harvested year-round. Furthermore, drought associated with the 2014-2016 El-Niño phenomenon affected much of Vietnam during the study period, intensifying saltwater intrusion (CCAFS-SEA 2016). Rice plants, especially seedlings, are sensitive to increasing salinity, which imposes both ionic and osmotic stresses and can lower rates of photosynthesis (Grattan et al. 2002; Moradi & Ismail 2007). The electrical conductivity of the platform soil was above guideline thresholds at the start of the study period (in early 2014) and sowing commenced after the ponds had been used to grow shrimp (i.e. under saline conditions). Although platform top soil was washed with rain water prior to sowing rice seedlings, previous research in the study region has demonstrated the difficulty of effectively removing salt from soil in the rice-growing season (Tho, Vromant, Hung & Hens 2006). We can be reasonably confident, therefore, that pond management practices associated with year-round stocking of shrimp, combined with the drought and ongoing saltwater intrusion in the region, contributed to suboptimal soil and water conditions, primarily suboptimal salinity, for the wet-season cultivation of rice in the study systems.

Shrimp production was also low, the average yield across ponds in both years being < 115 kg ha⁻¹, which is well under the 300 kg ha⁻¹ 'low' yield value reported by Joffre and Bosma (2009). In fact, yields from individual ponds were all well under this value except just one pond (h) in 2015 (at 335 kg ha⁻¹). The disease, EMS, was prevalent in the region during the study period (pers. obs. L. H. Hiep) and may have contributed to the poor shrimp yields and survival in the ponds. However, even in rice-shrimp farms in the region known to be affected by (unspecified) disease, production has been recorded at levels (i.e. 146 ± 60 kg ha⁻¹; Joffre & Bosma 2009) well above those recorded by most farms examined here, on average and individually. Susceptibility to disease is closely linked with stress, which can be caused by factors such as poor water quality and nutritional imbalances (Kautsky, Rönnbäck, Tedengren & Troell 2000). Our study showed that shrimp were exposed to a range of potentially stressful water quality conditions, i.e. sustained suboptimal water temperatures (too high), salinity (too high in the dry season, too low in the wet season) and DO concentrations (too low). Sustained or recurrent (i.e. chronic) periods of sub-lethal DO, as opposed to short-term, acute events, are particularly stressful for shrimp (Allan & McGuire 1998) but are not uncommon in rice-shrimp farms in the region (e.g. Tho et al. 2011). Additionally, the combination of poor water quality conditions (beyond low DO alone), as measured in our study, likely exacerbates shrimp stress and ultimately poor production outcomes. Our study did not examine predation of shrimp by other species, such as snakehead fish (Channidae; e.g. Cagauan 2008), but this may also have impacted on shrimp stress and survival.

Poor food availability, and/or poor food quality can also affect shrimp survival and production. Our study showed that an indicator of food availability, i.e. Chl *a* (Burford, Preston, Minh, Hoa, Bunn & Fry 2004a; Burford, Sellars, Arnold, Keys, Crocos & Preston 2004b), was positively correlated with production and survival, at least in 2014. This suggests

that the natural food available in ponds may not have been sufficient to meet nutritional needs. Shrimp do not feed on water column algae, as measured by Chl *a*, but rather on microalgae growing on sediment and rice stubble, and fauna such as small crustaceans and molluscs (Burford et al. 2004a). However, water column Chl *a* can provide an indicator of food availability, particularly as shrimp yield and survival also correlated with nutrient concentrations the same year they correlated with Chl *a*. Extreme salinities and temperatures and low DO likely affect natural food resources negatively as well as the shrimp, particularly on pond platforms where conditions are likely to be most extreme due to the shallower water depth. The interaction between poor food availability and poor water quality may well have triggered outbreaks of EMS, contributing further to poor survival and production. Previous research on rice-shrimp ponds has pointed to lack of food availability for shrimp but that supplementation with homemade feed can reduce water quality rather than improve nutritional outcomes (Burford et al. 2004a; cf. Kumar, Anand, De, Deo, Ghoshal, Sundaray, Ponniah, Jithendran, Raja, Biswas & Lalitha 2015). Formulated feeds may be needed to supplement natural food, particularly during extreme conditions. The fact that the same positive correlations between shrimp measures, nutrients and Chl *a* were not observed in 2015 but a range of water quality parameters remained suboptimal suggests that water quality, rather than nutrition, was the key factor affecting production and survival that year.

To target management actions for improved shrimp survival and production, the key risks factors and their timing need to be more clearly defined. Published values for optimal ranges of water quality for shrimp have their limitations and are often based on laboratory studies which may not be good indicators for field conditions. However, the sustained conditions of suboptimal water quality in our study do point to stress factors for shrimp that may explain, at least in part, the poor production and survival. To address this more directly, future research should track cohorts of stocked shrimp to determine their growth and survival

throughout the growth season. This then can be correlated directly with poor water quality events or periods during the year. In the case of poor nutrition and poor food availability for shrimp, additional studies measuring shrimp condition and food quality are needed to substantiate whether the nutritional status of shrimp is being compromised.

In summary, our study has confirmed that poor water quality and food availability can be key risk factors affecting shrimp production and survival in concurrent rice-shrimp-farming systems. In the case of rice production, high salinity was a major risk factor. Rice-shrimp-crab ponds that follow the production model described in this study are unlikely to be sustainable systems in the long term, and management intervention will be needed to improve both rice and shrimp productivity. This may include measures such as (1) temporally and spatially separating rice and shrimp crops such that salinity conditions are more suitable for each crop when grown, (2) increasing the efficiency of washing practices that remove salt from soil prior to rice cultivation, and (3) applying management interventions that increase oxygenation of water as well as the availability and quality of food resources when growing shrimp. Cropping freshwater prawns (*Macrobrachium rosenbergii*) in rotation or concurrently with rice and/or shrimp (Quang 1993; Huong, Viet, Huong, Hai 2016) may also be an option in the Mekong Delta at times when, or in regions where, water salinity is sufficiently low.

Acknowledgments

We thank Graeme Curwen for producing Fig. 1, the many project team members in Vietnam and Australia for their help with data collection and logistics, and the farmers from the 18 study ponds for their hospitality and participation in this study. Funding for this study was provided through an Australian Centre for International Agricultural Research (ACIAR) project grant SMCN/2010/083.

References

- Allan G.L. & Maguire G.B. (1991) Lethal levels of low dissolved oxygen and effects of short-term oxygen stress on subsequent growth of juvenile *Penaeus monodon*. *Aquaculture* **94**: 27-37. doi:10.1016/0044-8486(91)90126-R
- Anon. (2006) Australian Prawn Farming Manual: Health Management for Profit. Department of Primary Industries and Fisheries, Queensland, Australia.
- APHA (2005) *Standard Methods for the Examination of Water and Wastewater*, (21st edn), American Public Health Association, Washington DC, USA.
- Burford M.A., Preston N.P., Minh T.H., Hoa T.T.T., Bunn S.E. & Fry V.M. (2004a) Dominant sources of dietary carbon and nitrogen for shrimp reared in extensive rice-shrimp ponds. *Aquaculture Research* **35**: 194–203. doi:10.1111/j.1365-2109.2004.01012.x
- Burford M.A., Sellars M.J., Arnold S.J., Keys S.J., Crocos P.J. & Preston N.P. (2004b) Contribution of the natural biota associated with substrates to the nutritional requirements of the post-larval shrimp, *Penaeus esculentus* (Haswell), in high-density rearing systems. *Aquaculture Research* **35**: 508–515. doi:10.1111/j.1365-2109.2004.01052.x
- Cagauan A.G. (2008) Exotic aquatic species introduction in the Philippines for aquaculture: a threat to biodiversity or a boon to the economy? *Journal of Environmental Science and Management* **10**: 48-62.
- CCAFS-SEA (2016) The drought and salinity intrusion in the Mekong River Delta of Vietnam: assessment report. CGIAR Research Program on Climate Change, Agriculture and Food Security- Southeast Asia, Hanoi, Vietnam.

- Christensen S.M., Macintosh D.J. & Phuong N.T. (2002) Enhancing income opportunities in mangrove–aquaculture systems by introducing semi-intensive mud crab aquaculture (*Scylla* spp.). *Quantitative Approaches in System Analysis* **24**: 73–84.
- Grattan S., Zeng L., Shannon M. & Robert S. (2002) Rice is more sensitive to salinity than previously thought. *California Agriculture* **56**: 189-198. doi:10.3733/ca.v056n06p189
- Harrell F.E. Jr, Dupont C., et al. (2016) Hmisc: Harrell Miscellaneous. R package version 3.17-3. <https://CRAN.R-project.org/package=Hmisc>
- Ho T.M.H. & Burny P. (2016) Impact of value chain governance on the development of small scale shrimp farmers in Vietnam. *International Journal of Business and Economic Sciences Applied Research* **9**: 93-98.
- Hoang A.T., Zhang H.M., Yang J., Chen J.P., Hébrard E., Zhou G.H., Vinh V.N. & Cheng J.A. (2011) Identification, characterization and distribution of Southern rice black-streaked dwarf virus in Vietnam. *Plant Disease* **95**: 1063-1069. doi:10.1094/PDIS-07-10-0535
- Huong H.K., Viet L.Q., Huong D.T.T. & Hai T.N. (2016) Evaluation of technical aspects and economical effectiveness of giant freshwater prawn and rice-black tiger shrimp farming in brackish areas in Bac Lieu province. *Science Journal of Can Tho University* **43**: 97-105. doi:10.22144/ctu.jvn.2016.030
- Jackson C.J. & Wang Y-G. (1998) Modelling growth rate of *Penaeus monodon* Fabricius in intensively managed ponds: effects of temperature, pond age and stocking density. *Aquaculture Research* **29**:27-36. doi:10.1111/j.1365-2109.1998.tb01358.x

- Joffre O.M. & Bosma R.H. (2009) Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. *Agriculture, Ecosystems & Environment* **132**: 153-159. doi: 10.1016/j.agee.2009.03.010
- Kautsky N., Rönnbäck P., Tedengren M. & Troell M. (2000) Ecosystem perspectives on management of disease in shrimp pond farming. *Aquaculture* **191**: 145-161. doi:10.1016/S0044-8486(00)00424-5
- Keenan C.P. (1999) Aquaculture of the mud crab, genus *Scylla*: past, present and future. In: *Mud Crab Aquaculture and Biology* (ed. by C.P. Keenan & A. Blackshaw), pp. 9-13. ACIAR Proceedings, Canberra.
- Khiem N.T & Khai T.T. (2008) Technology change in rice production and rice farmer income in Vietnam Mekong Delta lowland. Proceeding of the Forum on Rice Policy Research: Key Issues from National Perspectives Workshop. International Rice Research Institute. 18-19 Feb 2008. Los Banos, the Philippines.
- Kumar S., Anand P.S.S., De D., Deo A.D., Ghoshal T.K., Sundaray J.K., Ponniah A.G., Jithendran K.P., Raja R.A., Biswas G. & Lalitha N. 2015. Effects of biofloc under different carbon sources and protein levels on water quality, growth performance and immune responses in black tiger shrimp *Penaeus monodon* (Fabricius, 1978). *Aquaculture Research*. doi:10.1111/are.12958
- Lightner D.V., Redman R.M., Pantoja C.R., Noble B.L. & Tran L. (2012) Early mortality syndrome affects shrimp in Asia. *Global Aquaculture Advocate* **15**:40.
- Moradi F. & Ismail, A. M. (2007) Responses of photosynthesis, chlorophyll fluorescence and ROS-scavenging systems to salt stress during seedling and reproductive stages in rice. *Annals of Botany* **99**: 1161-1173. doi:10.1093/aob/mcm052

- Nhan D.K., Trung N.H. & Van Sanh N. (2011) The impact of weather variability on rice and aquaculture production in the Mekong Delta. In *Environmental Change and Agricultural Sustainability in the Mekong Delta* (ed. by M. A. Stewart & P. A. Coclanis), pp. 437-451. Springer Netherlands, Dordrecht, The Netherlands. doi: 10.1007/978-94-007-0934-8_24
- Nhan D.K., Phap V.A., Phuc T.H. & Trung N.H. (2012) Rice production response and technological measures to adapt to salinity intrusion in the coastal Mekong Delta. Mekong Delta Development and Research Institute, Can Tho University, Vietnam.
- Nhuong T.V., Luu L.T., Tu T.Q., Tam P.M. & Nguyet T.T.A. (2002) Vietnam Shrimp Farming Review. Individual Partner Report for the Project: Policy Research for Sustainable Shrimp Farming in Asia. European Commission INCO-DEV Project PORESSFA No. IC4-2001-10042, CEMARE University of Portsmouth, UK, and RIA1, Bac Ninh, Vietnam.
- Phong N.D., Hoanh C.T., Tho T.Q., van Ngoc N., Dong T.D., Tuong T.P., Khoi, N.H., Hien N.X. & Nam, N.T. (2015) Water management for agricultural production in a coastal province of the Mekong River Delta under sea-level rise. In: *Climate Change and Agricultural Water Management in Developing Countries* (ed. by C.T. Hoanh, R. Johnston, V. Smakhtin), pp. 120-134. CABI, Wallingford, UK.
- Pinheiro J., Bates D., DebRoy S., Sarkar D. & R Core Team (2016). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-125. <http://CRAN.R-project.org/package=nlme>

- Preston N. & Clayton H. (2003) Rice-shrimp farming in the Mekong Delta: biophysical and socioeconomic issues. ACIAR Technical Reports No.52e, ACIAR, Canberra, Australia, 170pp.
- Quang, N. (1993) Rice-freshwater prawn (*Macrobrachium rosenbergii*) farms in the Mekong Delta, Vietnam. *Naga, the ICLARM Quarterly*, **16**: 8-20.
- R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Smajgl A., Toan T.Q., Nhan D.K., Ward J., Trung N.H., Tri L.Q., Tri V.P.D. & Vu P.T. (2015) Responding to rising sea levels in the Mekong Delta. *Nature Climate Change*, **5**:167-174. doi:10.1038/nclimate2469
- Son V.N., Phuong N.T, Hai T. N. & Yakupitiyage A. (2011) Production and economic efficiencies of intensive black tiger prawn (*Penaeus monodon*) culture during different cropping seasons in the Mekong delta, Vietnam. *Aquaculture International* **19**: 555-566. doi:10.1007/s10499-010-9371-2
- Tho N., Merckx R. & Ut V.N. (2012) Biological characteristics of the improved extensive shrimp system in the Mekong delta of Vietnam. *Aquaculture Research*, **43**, 526-537. doi:10.1111/j.1365-2109.2011.02858.x
- Tho N., Ut V.N. & Merckx R. (2011) Physico-chemical characteristics of the improved extensive shrimp farming system in the Mekong Delta of Vietnam. *Aquaculture Research*, **42**, 1600-1614. doi:10.1111/j.1365-2109.2010.02750.x
- Tho N., Vromant N., Hung N.T. & Hens L. (2006) Organic pollution and salt intrusion in Cai Nuoc District, Ca Mau Province, Vietnam. *Water Environment Research*, **78**, 716-723. doi: 10.2175/106143006X101755

Tiến L.V., Liên Q.T.A. & Thành V.C. (2011) Selection of Mot Bui Do rice varieties of good quality in the greenhouse of Can Tho University. *Tạp Chí Khoa Học* **18b**: 157-162.

Tran T.T.H., Zwart M., Phuong N.T., Vlak M.J. & de Jong M.C.M. (2011) Transmission of white spot syndrome virus in improved extensive shrimp production systems: a molecular epidemiology study. *Aquaculture* **313**: 7-14.

doi:10.1016/j.aquaculture.2011.01.013

Walker P.J., & Mohan C.V. (2009) Viral disease emergence in shrimp aquaculture: origins, impact and the effectiveness of health management strategies. *Reviews in Aquaculture* **1**: 125-154. doi: 10.1111/j.1753-5131.2009.01007.x

Wassmann R., Hien N.X., Hoanh C.T & Tuong T.P. (2004) Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. *Climatic Change* **66**: 89-107.

doi:10.1023/B:CLIM.0000043144.69736.b7

Figure captions

Figure 1: The 18 study ponds (labelled a-r) in the Mekong Delta region of Vietnam.

Figure 2: Total monthly rainfall during the study period (2014-2015), as recorded by a tipping-bucket rain gauge at pond g, Hòa Mỹ commune, Cà Mau Province, Vietnam.

Figure 3: Box and whisker plots of monthly mean, maximum or minimum water quality values for measures that differed significantly ($p < 0.05$) between the wet and dry seasons.

Figure 4: Monthly mean, maximum and minimum water temperature (left panel) and salinity (right panel) of ponds during the study period. Different ponds are shown as different letters (a-r), with 2014 in black and 2015 in red (letters have been jittered within months to show overlapping data points); the months January to December indicated numerically 1 to 12. The

blue line shows the smoothed curve, based on the average value across ponds per month (see text for details of methods). The lower, dashed grey line shows lower limit of the optimal range of conditions for shrimp; upper dashed grey line shows upper limit of the optimal range of conditions for shrimp.

Figure 5: Monthly mean, maximum and minimum water alkalinity (left panel) and pH (right panel) of ponds during the study period. See Fig. 4 for details of colour coding and symbols.

Figure 6: Monthly mean, maximum and minimum dissolved oxygen and mean total suspended solids concentrations of pond water during the study period. See Fig. 4 for details of colour coding and symbols; here, only one dashed line is shown, indicating the lower and upper limit of optimum conditions for shrimp for DO and TSS, respectively.

Figure 7: Examples of statistically significant bivariate relationships between indicators of resource availability and annual shrimp survival (left panel) or production yield (right panel), as observed in 2014.

Tables

Table 1: Water quality conditions experienced by shrimp as a proportion of the year conditions were suboptimal (i.e. outside the optimal range) for growth. Proportions were calculated using monthly water quality data for each pond in each year of the study period, considering only the months for which the relevant water quality variable was sampled, from which the presented means and standard deviations were then calculated. Bold typeface indicates conditions were suboptimal $\geq 50\%$ of the time.

Variable	Optimal range	Suboptimal proportion of 2014	Suboptimal proportion of 2015
Water temperature (mean)	26-32 °C	0.13 $\pm$ 0.11	0.05 $\pm$ 0.05
Water temperature (max)	26-32 °C	0.69 $\pm$ 0.16	0.98 $\pm$ 0.04
Water temperature (min)	26-32 °C	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
Salinity (mean)	10-25 g L ⁻¹	0.69 $\pm$ 0.14	0.94 $\pm$ 0.08
Salinity (max)	10-25 g L ⁻¹	0.70 $\pm$ 0.14	0.88 $\pm$ 0.11
Salinity (min)	10-25 g L ⁻¹	0.76 $\pm$ 0.12	0.90 $\pm$ 0.08
Alkalinity (mean)	50-100 mg L ⁻¹	1.00 $\pm$ 0.00	0.78 $\pm$ 0.09
Alkalinity (max)	50-100 mg L ⁻¹	1.00 $\pm$ 0.00	0.80 $\pm$ 0.12
Alkalinity (min)	50-100 mg L ⁻¹	1.00 $\pm$ 0.00	0.58 $\pm$ 0.16
pH (mean)	7-9	0.00 $\pm$ 0.00	0.07 $\pm$ 0.16
pH (max)	7-9	0.00 $\pm$ 0.00	0.04 $\pm$ 0.16
pH (min)	7-9	0.00 $\pm$ 0.00	0.15 $\pm$ 0.19
DO (mean)	> 3.5 mg L ⁻¹	0.51 $\pm$ 0.51	0.42 $\pm$ 0.19
DO (max)	> 3.5 mg L ⁻¹	0.50 $\pm$ 0.52	0.32 $\pm$ 0.10
DO (min)	> 3.5 mg L ⁻¹	1.00 $\pm$ 0.00	0.53 $\pm$ 0.17
NO ₂ -N (mean)	< 0.2 mg L ⁻¹	0.01 $\pm$ 0.05	0.00 $\pm$ 0.00
NO ₃ -N (mean)	< 1.0 mg L ⁻¹	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
NH ₄ -N (mean)	< 1.0 mg L ⁻¹	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
TSS (mean)	< 50 mg L ⁻¹	0.83 $\pm$ 0.19	0.99 $\pm$ 0.06

Table 2: Significant correlations between pond water quality and the survival or production of shrimp during the study period.

	Correlated with	Relevant annual or seasonal period	Range (min-max)	Spearman rho	p-value	n
Survival 2014	Chl <i>a</i> (mean)	Annual	12-60 $\mu\text{g L}^{-1}$	0.69	0.013	12
		Wet	8-65 $\mu\text{g L}^{-1}$	0.59	0.045	12
	PO ₄ -P (mean)	Dry	0.01-0.04 mg L^{-1}	0.69	0.014	12
	NH ₄ -N (mean)	Dry	0.04-0.22 mg L^{-1}	0.76	0.004	12
Production 2014	Chl <i>a</i> (mean)	Annual	17-82 $\mu\text{g L}^{-1}$	0.80	0.002	12
		Wet	14-72 $\mu\text{g L}^{-1}$	0.73	0.006	12
	PO ₄ -P (mean)	Dry	0.01-0.04 mg L^{-1}	0.71	0.009	12
	NH ₄ -N (mean)	Dry	0.07-0.49 mg L^{-1}	0.80	0.002	12
	Alkalinity (mean)	Annual	137-182 mg L^{-1}	0.60	0.039	12
	Alkalinity (min)	Annual	131-176 mg L^{-1}	0.66	0.018	12
	Salinity (min)	Wet	3.8-10.2 g L^{-1}	0.49	0.039	18
Production 2015	Alkalinity (max)	Dry	90-180 mg L^{-1}	0.60	0.009	18
	Alkalinity (min)	Dry	65-150 mg L^{-1}	0.58	0.012	18