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Impact of culture intensity and monsoon season on water quality in Thai commercial shrimp ponds

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Abstract

The present authors investigated the impact of farming intensity and the prevailing season on water quality in intensive tropical shrimp farms. The weekly water quality samples from the inlets and production ponds of two commercial shrimp farms operating partial water exchange schedules and representing low and high farming intensities in Thailand (with *Penaeus monodon* Fabricius production rates of 4 and 9 t ha^{-1} $cycle^{-1}$, respectively) were analysed over two consecutive production cycles, covering the wet (monsoon) and dry seasons. Significant differences in inlet water quality between farms occurred only in salinity, temperature and suspended solids. The present authors assessed impacts of farming intensity and season on production pond water quality parameters using: (1) an analysis of variance (ANOVA) of measurements in replicate ponds during the final month of the production cycle; and (2) a trend analysis which classified trends in parameters over the cycle as externally or internally determined. The prevailing season was found to have a strong impact on salinity, temperature, pH, nitrate, dissolved reactive phosphorus, total phosphorus and dissolved oxygen in the final month of the cycle. The trends in these parameters were largely externally determined or absent. Nitrite and chlorophyll a were affected by production intensity in interaction with season and showed mainly internally determined trends. This indicates that nitrogen transformation processes responded to input levels as well as seasonal influences. Ammonia was highly variable and no significant intensity or season effects were detected, but trends were internally determined only at high intensity and more pronounced in the dry rather than the wet season. The results indicate strong seasonal effects on water quality in tropical shrimp ponds, direct in some parameters and indirect in others, including those linked to nitrogen transformations. The mechanisms of seasonal variation and the implications of these changes for water quality management call for further investigation.

Introduction

Shrimp pond culture is one of the fastest growing sectors of aquaculture. World production of cultured shrimp in 1995 was estimated at over 700 000 t, of which more than 80% was farmed in Asia (Primavera 1997). The single largest producer is Thailand with over 220 000 t in 1995. The Thai shrimp industry is characterized by intensive production in relatively small farms, with high stocking densities and inputs of formulated feeds, intensive aeration, and relatively low rates of water exchange (Kongkeo 1997). The main species cultured in Thailand is the black tiger shrimp, *Penaeus monodon* Fabricius.

Environmental problems – both within and beyond the farm environment – are considered the major constraint to sustainable growth of the shrimp industry and have been implicated in recent production crashes in Taiwan (1987), the Philippines (1989), Indonesia (1991–1992) and China (1993) (Macintosh & Phillips 1992; Primavera 1997). Water quality is at the core of the environmental problems experienced on farms since shrimp are strongly affected by the conditions in the water and on the pond bottom (Boyd & Fast 1992; Chen 1992). The stress induced by poor water quality may result in reduced growth rates, weakened resistance to disease or direct mortality. Problems with water quality are often linked to culture intensity (Wang & Fast 1992).

Thai intensive shrimp culture systems are characterized by low rates of water exchange and the long retention time means that processes occurring within the pond will have a major effect on water quality. Intensive culture of single cohorts is characterized by rapidly increasing levels of inputs added to the ponds as the cycle proceeds. Pond processes may be expected to respond to these increasing inputs, resulting in changes in many water quality parameters, which may have important implications for management. Of particular interest in this respect are critical levels of inputs beyond which the capacity of the pond to maintain suitable water quality conditions is exceeded, and the impacts of natural and management factors in these critical levels.

Various management measures are used to maintain water quality in ponds, but the effectiveness of many common measures is disputed (Boyd 1995). Giovannini & Piedrahita (1994) observed that management of aquaculture ponds occurs on an intuitive and qualitative basis. The above authors attributed this to the difficulty and expense of regular measurement, and also to the lack of quantitative procedures for using the data to benefit farm management. Thus, there is an identified need for empirical analyses and the development of models which address the link between water quality and management. Many quantitative investigations have focused on short-term variation in key parameters, such as diurnal changes in oxygen, and appropriate short-term or 'tactical' management responses (Madenjian, Rogers & Fast 1988; Piedrahita 1991). Quantitative studies with a longer time horizon, which would yield insights into strategic aspects of water quality management (such as sustainable levels of farming intensity or seasonal effects on pond dynamics), are rare. Some exceptions are the empirical studies by Tucker & van der Ploeg (1993) and Seok, Leonard, Boyd, & Schwartz (1995), and the modelling study by Lorenzen, Struve & Cowan (1997).

The aim of the present study was to assess the impacts of production intensity and prevailing season on water quality parameters and pond dynamic processes in tropical shrimp ponds on the time-scale of a full production cycle. The present authors conducted an empirical analysis of water quality in two Thai shrimp farms of different production intensity over two consecutive production cycles, covering the wet and dry seasons.

Materials and methods

Data

The present study is based on the analysis of water quality data originally collected to calculate nutrient budgets. Details of the farms and sampling regime are described in Briggs & Funge-Smith (1994), and therefore, only a summary of the main aspects will be provided below. Water quality data were collected from two commercial shrimp farms representative of low and high farming intensities, with stocking densities of 50 and 100 postlarvae m^{-2}, and yields of 3919 and 8891 kg ha^{-1} $cycle^{-1}$, respectively. Both farms were located in the Ranod district of South-eastern Thailand. Table 1 summarizes the main features of both the physical nature and the management of the low- (L) and high-intensity (H) farms. The previous land use of both farms was as rice paddies, and the ponds were built on clay soil and were in the first year of cultivation. The grow-out ponds at farm H were smaller than those at farm L: 0.31 ha compared to 0.77 ha. Farm L was situated further from the coast and made use of inlet reservoirs, while farm H was closer to the coast and abstracted water directly from the sea. The feeding schedules on both farms followed the advice of the feed manufacturer: feed was added to trays four to five times each day, with minor adjustments being made according to the amount consumed in the previous feeding. Both farms followed partial water exchange schedules, exchanging on average 0.4%, 4%, 6% and 8% day^{-1} in the first, second, third and fourth month of the cycle, respectively. All ponds were harvested by

Table 1 Physical characteristics of the two sites and the differences in management which distinguish the two farms

	Farm	
Characteristic	**Lower intensity (L)**	**Higher intensity (H)**
Soil type	Clay	Clay
Distance from coast (m)	500	100
Previous land use	Paddy	Paddy
Year of cultivation	First	First
Source of inlet water	Inlet reservoir (10 000 m^2)	Abstracted directly from the sea
Aeration:		
time (h day^{-1})	19–20	19–20
paddlewheel type	Short arm	Long arm
power (kW ha^{-1})	0.62	0/31
Pond size (ha)	0.62	0.31
Stocking density ($n\,m^{-2}$)	≈ 50	≈ 100
Survival (%)	45	42
Culture period (weeks)	20	17
Production (kg ha^{-1} $cycle^{-1}$ wet weight)	3919	8891
Farmer experience	Some previous	Little previous

draining; the accumulated sediment was scraped out and the ponds were left to dry for a period of 5–10 weeks between production cycles. Both farms stocked post larval ($PL_{15–20}$) *P. monodon*. The culture period was, on average, 20 weeks for ponds on farm L and 17 weeks on farm H.

In the present study, the authors analysed data for two consecutive production cycles, sampled between August 1992 and August 1993. The main monsoon months for the South-eastern region of Thailand are from October to December; less intensive rains fall in May. The timing of the production cycles with respect to the main monsoon allowed the present authors to assign a wet or dry classification to individual cycles, according to the dominant season.

Water samples were taken weekly from inlets and grow-out ponds. Only morning (0900–1000 h) samples were analysed in the present study. Two replicate ponds were monitored at the farm L, while four replicate ponds were monitored at farm H. The following water quality parameters were determined: temperature, pH, salinity, turbidity as measured by Secchi depth (Secchi), total nitrogen (TN), nitrate (NO_3-N), total ammonia nitrogen (TAN), nitrite (NO_2-N), total phosphorus (TP), dissolved reactive phosphorus (DRP), chlorophyll *a* (CHL), biochemical oxygen demand (BOD), dissolved oxygen (DO) and total suspended solids (TSS). Details of the water analysis procedures can be found in Briggs & Funge-Smith (1994). Detailed rainfall and water exchange data were not included in the sampling programme.

Analysis

The analysis was carried out in four steps:

1 In order to ascertain that differences in pond water quality were attributable to management intensity rather than inlet water quality, inlet data were tested for systematic differences between farms. A two-way analysis of variance (ANOVA) with the factors 'intensity' (L and H) and 'season' (wet and dry) was carried out using the inlet data for the final month of each production cycle (four measurements in consecutive weeks).

2 Management and seasonal effects on production pond water quality in the final month of the production cycle were assessed using a two-way ANOVA using individual ponds within the different farms as treatment replicates.

3 Trends in water quality parameters over the production cycle were analysed using linear regression, and trends in production pond parameters classified as internally or externally determined on the basis of a comparison with trends in inlet parameters. There were two stages to this analysis: firstly each water quality parameter was tested for trends in both inlet and grow-out ponds, and

Table 2 Impacts of intensity and season on water quality parameters during the final month of the production cycle: means and analysis of variance (ANOVA)

Parameter	Mean values: Lower intensity (L) Wet	Dry	Higher intensity (H) Wet	Dry	Source of variance (%): Intensity	Season	Interaction
Salinity	21	30	24	31	7	86	–
Temperature (°C)	28	31	28	30	–	89	–
Secchi (cm)	37	43	22	27	61	–	–
pH	7.7	7.2	7.7	6.9	–	83	–
TAN (mg L^{-1})	0.45	0.68	0.14	2.74	–	–	–
NO_2 (mg L^{-1})	0.05	0.01	0.07	0.09	51	17	32
NO_3 (mg L^{-1})	0.35	0.01	0.55	0.09	15	67	–
TN (mg L^{-1})	3.3	3.67	4.95	5.58	–	–	–
DRP (mg L^{-1})	0.06	0.01	0.12	0.01	–	79	–
TP (mg L^{-1})	0.39	0.28	1.03	0.28	19	50	19
CHL (μg L^{-1})	0.08	0.11	0.42	0.11	30	–	33
DO (mg L^{-1})	0.01	0.01	0.01	0.01	–	40	–
TSS (mg L^{-1})	115	144	240	153	43	–	31
BOD (mg L^{-1})	8.4	10.5	11.1	6.5	–	–	–

secondly, trends in inlet water and grow-out ponds were compared for significant differences. The water quality parameters were classified as showing no trend, an externally determined trend or an internally determined trend.

4 In a final synthesis, results from the statistical analyses were combined with a graphic interpretation of raw data on key water quality parameters.

The logarithmic transformation $\ln(x+1)$ was performed on all water quality data to meet assumptions of normality and homoscedasticity. Where average values are presented in the text, these were calculated using the transformed data and then reconverted to the linear scale. Plots of various parameters presented in the 'Results' were drawn from raw data. The level of significance used in all analyses was 95%, i.e. $P < 0.05$.

Results

Site and seasonal differences in inlet water quality

Significant site effects on inlet water quality were detected in only three parameters. Farm H was characterized by slightly higher salinity (31 versus 28), lower temperature (28 versus 30 °C) and a higher concentrations of TSS (223 versus 87 mg L^{-1}) than farm L.

With the exception of CHL, DO and BOD, all parameters showed significant seasonal variation. Compared to the dry season, inlet water quality in the wet season was characterized by: lower salinity (26 versus 31), temperature (27 versus 31 °C), Secchi (41 versus 100 cm), pH (7.6 versus 7.3), TAN (< 0.001 versus 0.06 mg L^{-1}) and TN (0.23 versus 1.23 mg L^{-1}); and higher NO_2-N (0.03 versus 0.002 mg L^{-1}), NO_3-N (0.32 versus 0.06 mg L^{-1}), DRP (0.07 versus 0.001 mg L^{-1}), TP (0.25 versus 0.03 mg L^{-1}) and TSS (223 versus 88 mg L^{-1}).

Impact of intensity and season on production pond water quality

Table 2 summarizes the impact of farming intensity and season on production pond water quality in the final month of the cycle. Table 2 shows the mean values for each parameter and combination of factors, and the percentage variation (i.e. sum of squares/total sum of squares) explained by each of the statistically significant factors. Overall, season was more important than production intensity in determin-

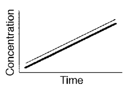
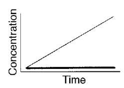
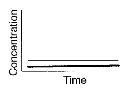
Key; (——) inlet (——) grow-out ponds	Lower-intensity farm		Higher-intensity farm	
	Wet	Dry	Wet	Dry
 **Trend determined externally**	SAL, TEMP, SECCHI NO_3-N TP, DRP	SAL, TEMP, pH TN, TAN, NO_2-N TP CHL	SAL, TEMP, pH, TSS, SECCHI NO_3-N TP	SAL TN, NO_3-N DO
 **Trend determined internally**	TN, NO_2-N CHL, BOD	TSS, SECCHI BOD	TN, TAN, NO_2-N DRP CHL, BOD	pH, SECCHI TAN, NO_2-N TP CHL
 **No trend**	pH, TSS TAN DO	NO_3-N DRP DO	DO	TEMP, TSS DRP BOD

Figure 1 Categorization of the trends in water quality parameters. The schematic graphs illustrate the categories defined in the text: the bold line represent trends in parameters in the inlets, while the fine line represents parameter trends in the grow-out ponds.

ing water quality. Variation in salinity, temperature, pH, NO_3-N, DRP, TP and DO was attributable primarily to season. Variation in NO_2-N, CHL and TSS was explained by production intensity in interaction with season, and only Secchi was determined by farming intensity alone; TAN, TN and BOD did not show significant variation with either season or intensity.

Trends in water quality parameters

Figure 1 summarizes the categorization of trends in water quality parameters over the production cycle: the results are presented by production intensity (low and high) and season (wet and dry). The schematic graphs illustrate the defined categories of trend (externally determined, internally determined and no trend). Only NO_2-N, CHL and BOD showed internally determined trends in most conditions. The TAN showed internally determined trends only at high intensity, regardless of season. Trends in Secchi were internally determined in the dry season and externally determined in the wet season, while TN showed the reverse pattern. Trends were primarily positive, i.e. concentrations increased as the cycle advanced. Secchi showed negative trends as it is inversely related to turbidity. Other parameters with negative trends were: salinity, which declined in the wet season cycles because of monsoon rains; temperature, which also declined over the wet season cycles; and pH, which decreased with time in the dry season cycles.

Description of key parameters

Total ammonia nitrogen

The ANOVA detected no significant 'intensity' or 'season' effects on TAN in the production ponds, while trend analysis indicated internally determined trends at high farming intensity only. Inspection of the raw data (Fig. 2) indicates a great deal of variation over time and between ponds which obscures intensity and season effects. However, it is interesting to note that the high intensity farm in the dry season displays a highly conspicuous trend and final month concentrations are higher than in all other cases. In the wet season, TAN levels in both farms appeared more variable than in the dry season, but not systematically different between farms. This hints at the presence of a complex seasonal effect on TAN levels, with TAN removal processes being more variable, but overall, more efficient in the wet season.

Nitrite

End-of-cycle NO_2-N in the production ponds was significantly influenced by farming intensity, season and the interaction of these factors, and trends were mostly internally determined. The highest NO_2-N levels occurred at high intensity in the dry season (Table 2; Fig. 3), probably in response to high TAN (Fig. 2). At low intensity, NO_2-N levels were higher and substantially more variable in the wet than in the dry season, a pattern that was not related to inlet nitrate levels.

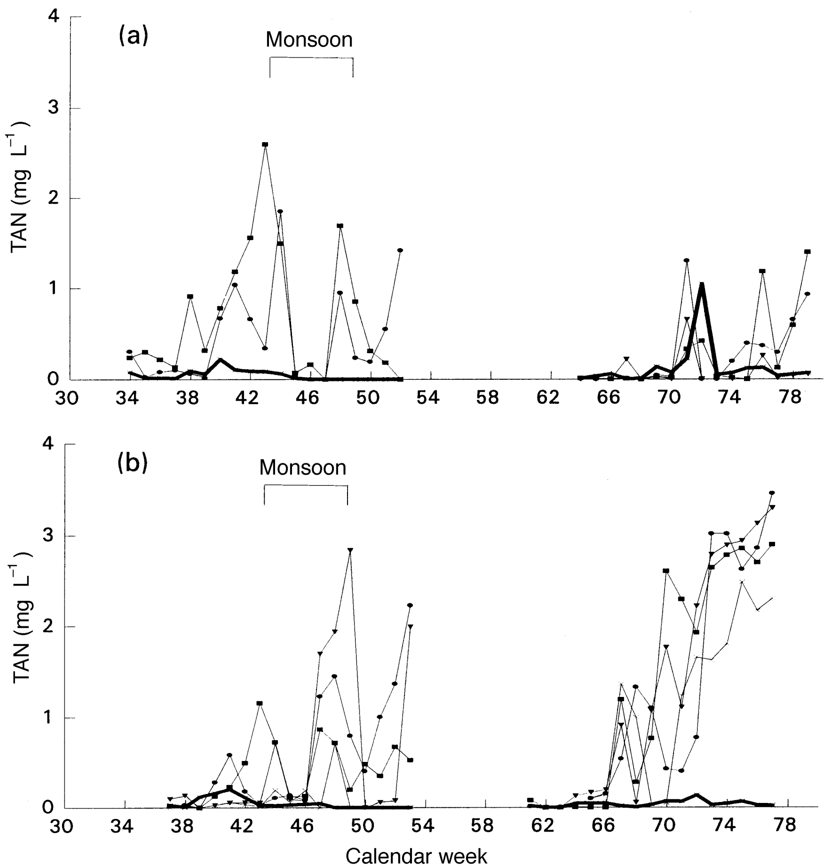


Figure 2 Total ammonia nitrogen (TAN) concentrations in inlets (bold lines) and production ponds (fine lines) of both (a) the less intensive farm and (b) the higher-intensity farm. The timing of the monsoon with respect to the two production cycles is indicated.

Nitrate

Levels of NO_3-N in the production ponds were influenced primarily by seasonality, and to a lesser extent, by farming intensity. This is strongly evident in Fig. 4, which shows much higher and more variable NO_3-N levels in the wet season than in the dry season. The strong apparent trends in the wet season were externally determined. A slight internally determined trend was evident only at high intensity in the dry season. The predominance of external processes in NO_3-N levels contrasts with the results for NO_2-N, the intermediate product of nitrification, where internal processes were dominant.

Dissolved reactive phosphorus

Levels of DRP were influenced exclusively by season and not production intensity. Average pond concentrations in the final month of wet season production were 0.08 mg L^{-1} compared to 0.01 mg L^{-1} during dry season production. Conspicuous trends occurred in the wet season (Fig. 5), classified as externally determined at low intensity and internally determined at high intensity, while there were no trends during the dry season.

Chlorophyll a

Chlorophyll *a* concentrations were influenced by intensity in interaction with season and trends were largely internally determined. An inspection of Fig. 6 shows that only the wet season concentrations at farm H were visibly different from the others, while dry season levels were not noticeably different between farms (intensities). The absence of seasonality in the inlet data

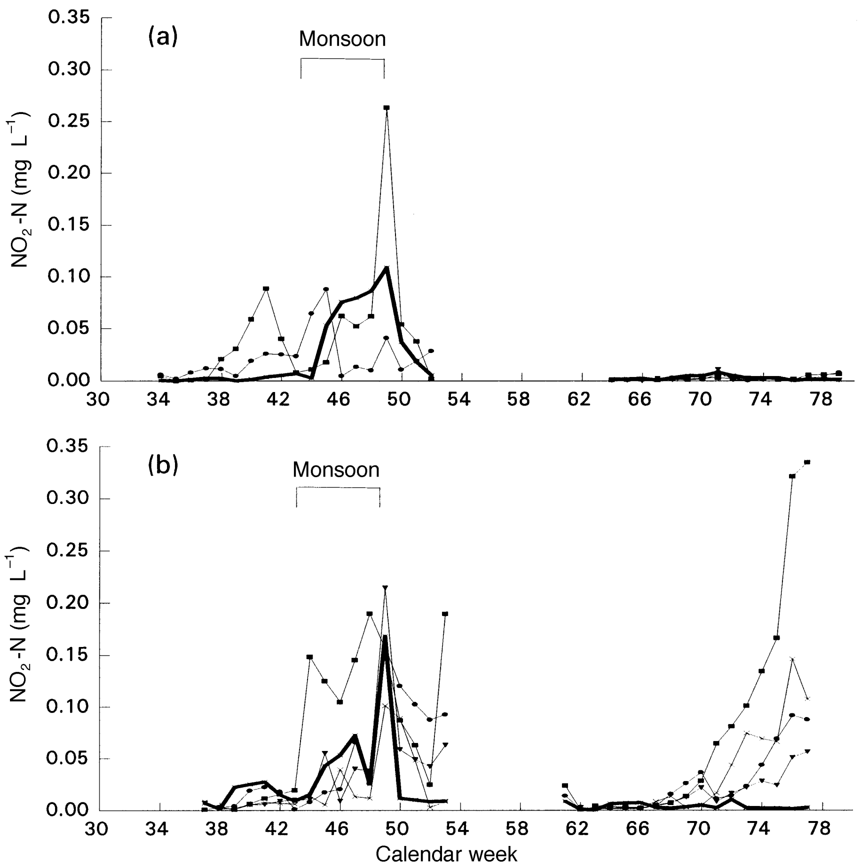


Figure 3 Nitrite (NO_2-N) concentrations in inlets (bold lines) and production ponds (fine lines) of both (a) the less intensive farm and (b) the higher-intensity farm. The timing of the monsoon with respect to the two production cycles is indicated.

combined with an intensity–season interaction in the grow-out ponds indicates an indirect seasonal influence: the prevailing season affected conditions in the ponds which, in turn, affected the growth of the phytoplankton bloom.

Discussion

The present study aimed to assess differences in water quality parameters caused by farming intensity levels and seasons through the analysis of data originally collected for the purpose of calculating an average nutrient budget. As a result, the present study suffered from certain design limitations, i.e. low numbers of replicate ponds, an unbalanced design, and a lack of specific data on water exchange and precipitation. It would also be desirable to replicate the study over several wet and dry seasons, and across several farms of comparable production intensity, in order to eliminate potentially confounding effects of long-term variability or site-specific conditions. Nevertheless, the data set used is among the most extensive data available from commercial shrimp farms, and while accepting the limitations outlined, the analysis provides significant new information in particular on seasonal effects.

Seasonality has been identified as a major influence on water quality in inlets and production ponds. While seasonality affected most water quality parameters in the inlets, site differences occurred only in salinity, temperature and TSS, and were most likely related to the use of an inlet reservoir in one of the farms. The lack of site differences in most inlet parameters implies that the site differences detected in production pond water

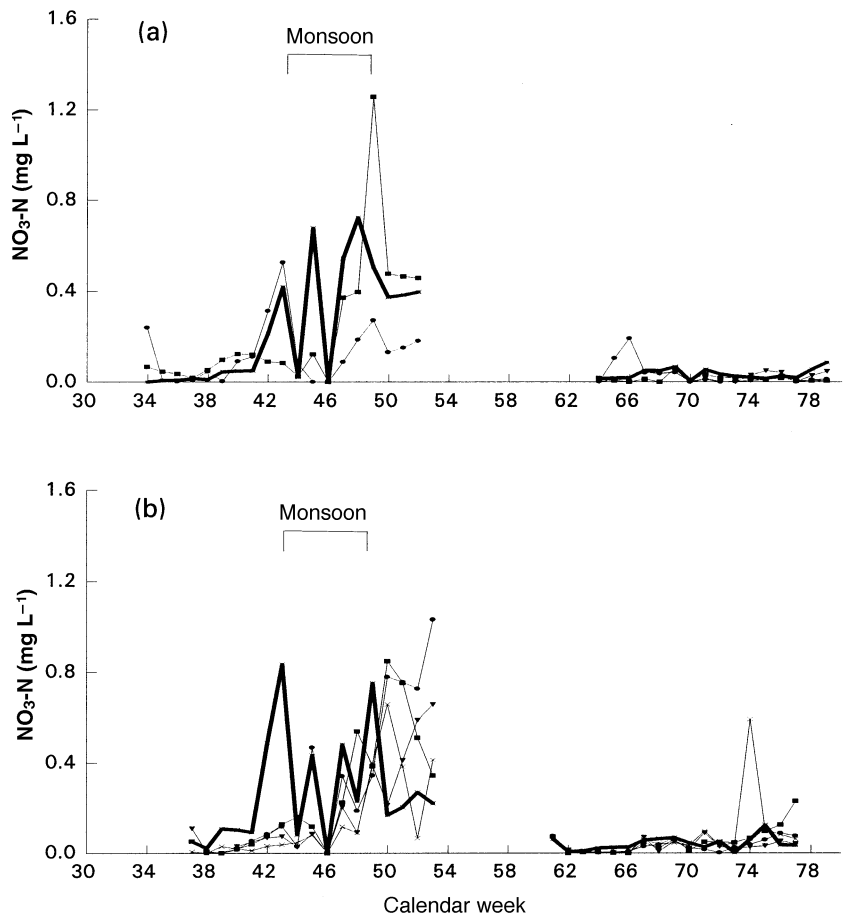


Figure 4 Nitrate (NO_3-N) concentrations in inlets (bold lines) and production ponds (fine lines) of both (a) the less intensive farm and (b) the higher-intensity farm. The timing of the monsoon with respect to the two production cycles is indicated.

quality are attributable primarily to production intensity rather than inlet water quality. In the production ponds, substantial differences in farming intensity impacted significantly only on NO_2-N, CHL, TSS and Secchi, and in all of these (except for Secchi), there was a significant interaction with season.

The long retention time of water in shrimp ponds means that water quality is the net result of pond management, processes occurring within the pond and external influences. The occurrence of internally determined trends in NO_2-N and CHL, parameters related to the removal of TAN through nitrification and phytoplankton uptake, highlights the importance of pond processes in the maintenance of water quality throughout the cycle. Increases in the transformation of nitrogen were sufficient to offset the increasing inputs throughout the production cycle at low intensity, and consequently, TAN itself did not show a trend. At high intensity, increasing inputs eventually exceeded the assimilation capacity of the pond and gave rise to a positive trend in TAN. The relationship between farming intensity and nitrogen dynamics has been explored in more detail by Lorenzen *et al.* (1997), who used a water quality model calibrated for the dry season cycles on the same two farms as analysed here. The present study shows that seasonality may also have a strong influence on water quality, including nitrogen dynamics. The external influences on water quality during the monsoon imply that water quality dynamics may be inherently less predictable during this period than

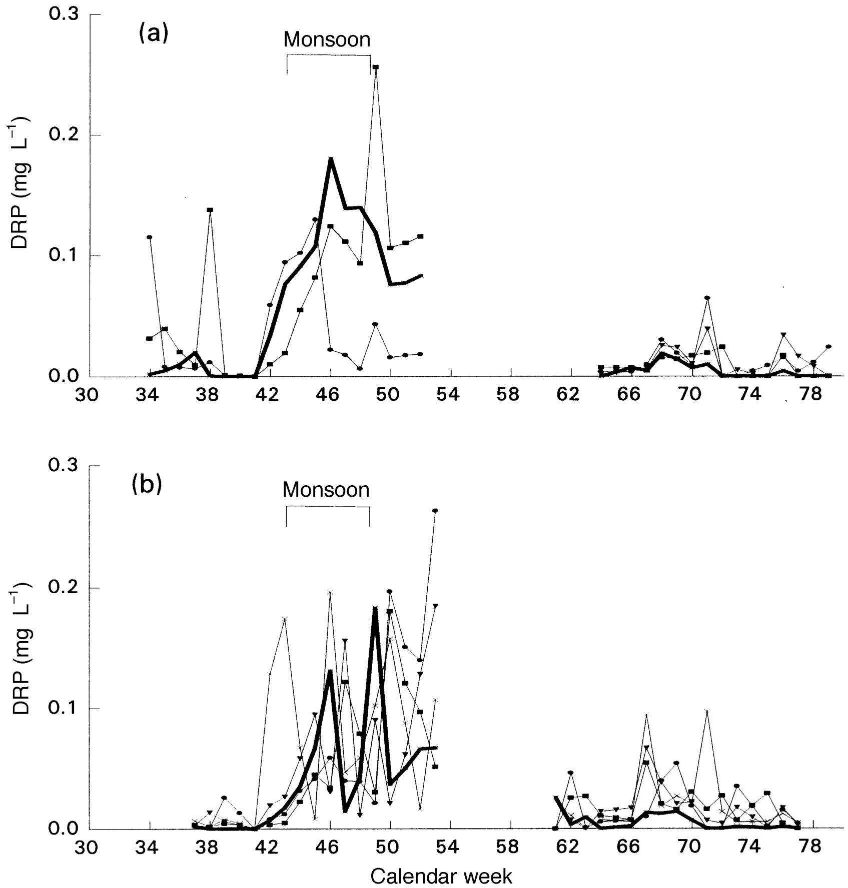


Figure 5 Dissolved reactive phosphorus (DRP) concentrations in inlets (bold lines) and production ponds (fine lines) of both (a) the less intensive farm and (b) the higher-intensity farm. The timing of the monsoon with respect to the two production cycles is indicated.

in the dry season. Seasonal effects on water quality are direct in some parameters and indirect in others. Direct influences were detected in salinity, temperature, DRP and NO_3–N, which showed externally determined trends in the wet season. Both DRP and NO_3–N levels can be expected to have an impact on the dynamics of phytoplankton, which is considered to be the key determinant of water quality in ponds (Piedrahita 1990; Lorenzen *et al.* 1997).

The impact of seasons on water quality has been described for the culture of catfish in temperate climates: the most important differences between seasons (winter and summer) were considered to be day length, temperature and the increased level of feed added to ponds during the summer months (Tucker & van der Ploeg 1993). In contrast, the difference between seasons in tropical systems is related more to increased precipitation, winds and reduced irradiance associated with the monsoon. During the monsoon, the sea is more turbulent, which re-suspends the sediments, and rainfall increases the degree of runoff. Although excessive precipitation has been recognized as a problem linked to the monsoon in tropical brackish water aquaculture (e.g. Hopkins, Sandifer & Browdy 1995), the extent of seasonal influences on water quality parameters in such systems has not been fully appreciated.

The findings of the present study have two key management implications. Firstly, seasonality has a major impact on water quality in dynamics in tropical (as well as temperate) systems. This impact may have to be accounted for in the management of intensive culture systems, particularly those operating near the carrying capacity of the pond for

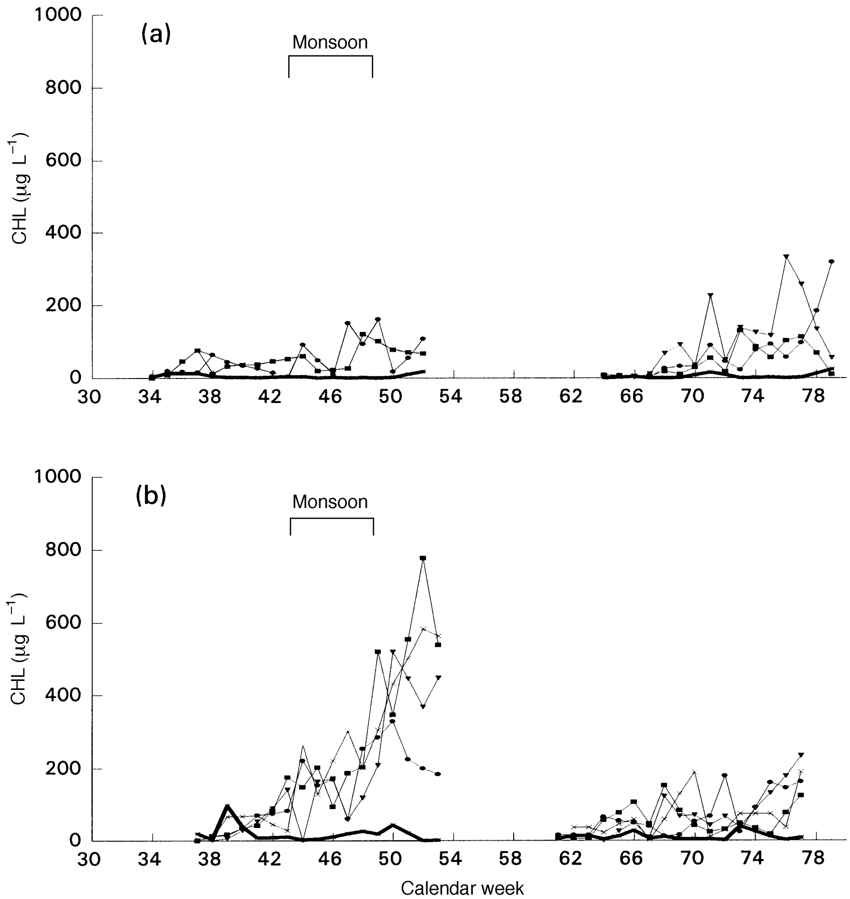


Figure 6 Chlorophyll *a* (CHL) concentrations in inlets (bold lines) and production ponds (fine lines) of both (a) the less intensive farm and (b) the higher intensity farm. The timing of the monsoon with respect to the two production cycles is indicated.

assimilation of wastes. Secondly, a better understanding of the mechanisms involved in these seasonal effects may lead to the identification of management measures which may increase the pond carrying capacity. For example, there is some indication that ammonia transformations were more efficient in the monsoon than in the dry season and identification of the mechanisms involved may allow these to be utilized in a controlled way.

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References

Boyd C.E. (1995) Soil and water quality management in aquaculture ponds. *INFOFISH International* **5,** 29–36.

Boyd C.E. & Fast A.W. (1992) Pond monitoring and management. In: *Marine Shrimp Culture: Principles and Practices* (ed. by A.W. Fast & L.J. Lester), pp. 497–513. Elsevier Science Publishers, Amsterdam.

Briggs M.R.P. & Funge-Smith S.J. (1994) A nutrient budget of some intensive marine shrimp ponds in Thailand. *Aquaculture and Fisheries Management* **25,** 789–811.

Chen S. (1992) Coping with diseases in shrimp farming. In: *Shrimp 1992, Hong Kong: Proceedings of the 3rd Global Conference on the Shrimp Industry* (ed. by H. de Saram &

T. Singh), pp. 113–117. INFOFISH, Kuala Lumpur, Malaysia.

Giovannini P. & Piedrahita R.H. (1994) Modelling photosynthetic production optimization for aquaculture ponds. *Aquacultural Engineering* **13,** 83–100.

Hopkins S.J., Sandifer P.A. & Browdy C.L. (1995) A review of water management regimes which abate the environmental impacts of shrimp farming. In: *Swimming Through Troubled Water: Proceedings of the Special Session on Shrimp Farming, Aquaculture '95* (ed. by C.L. Browdy & J.S. Hopkins), pp. 157–166. World Aquaculture Society, Baton Rouge, LA.

Kongkeo H. (1997) Comparison of intensive shrimp farming systems in Indonesia, Philippines, Taiwan and Thailand. *Aquaculture Research* **28,** 789–796.

Lorenzen K., Struve J. & Cowan V.J. (1997) Impact of farming intensity and water management on nitrogen dynamics in intensive pond culture: a mathematical model applied to Thai commercial shrimp farms. *Aquaculture Research* **28,** 493–507.

Macintosh D.J. & Phillips M.J. (1992) Environmental issues in shrimp farming. In: *Shrimp 1992, Hong Kong: Proceedings of the 3rd Global Conference on the Shrimp Industry* (ed. by H. de Saram & T. Singh), pp. 118–145. INFOFISH, Kuala Lumpur, Malaysia.

Madenjian C.M., Rogers G.L. & Fast A.W. (1988) Predicting nighttime dissolved oxygen loss in aquaculture ponds. *Canadian Journal of Fisheries and Aquatic Sciences* **45,** 1842–1847.

Piedrahita R.H. (1990) Modelling water quality in aquaculture ecosystems. In: *Aquaculture and Water Quality: Advances in World Aquaculture,* Vol. 3 (ed. by D.E. Brune & J.R. Tomasso), pp. 322–362. World Aquaculture Society, Baton Rouge, LA.

Piedrahita R.H. (1991) Simulation of short-term management actions to prevent oxygen depletion in ponds. *Journal of the World Aquaculture Society* **22,** 157–166.

Primavera J.H. (1997) Socioeconomic impacts of shrimp culture. *Aquaculture Research* **28,** 815–827.

Seok K., Leonard S., Boyd C.F. & Schwartz M.F. (1995) Water quality in annually drained and undrained channel catfish ponds over a three-year period. *Progressive Fish-Culturist* **57,** 52–58.

Tucker C.S. & van der Ploeg M. (1993) Seasonal changes in water quality in commercial channel catfish ponds in Mississippi. *Journal of the World Aquaculture Society* **24,** 473–481.

Wang J.K. & Fast A.W. (1992) Shrimp pond engineering considerations. In: *Marine Shrimp Culture: Principles and Practices* (ed. by A.W. Fast & L.J. Lester), pp. 415–429. Elsevier Science Publishers, Amsterdam.