

Effects of water exchange and abiotic factors on zooplankton and epibenthic fauna in shrimp ponds

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Abstract

Assemblages of zooplankton and epibenthic invertebrates were collected from a commercial *Penaeus monodon* (Fabricius) pond at fortnightly intervals over an entire grow-out season. The pond inlet and outlet water were also sampled intensively over three 1-week periods throughout the season. Before stocking the ponds with shrimp postlarvae, copepods dominated the zooplankton. Immediately after the ponds were stocked, there was a rapid decline in zooplankton numbers, particularly the dominant larger copepods, suggesting heavy predation by shrimp postlarvae. For the rest of the season, barnacle nauplii were the dominant zooplankton component in the pond. Pond water exchanges had little detectable influence on the composition or density of the zooplankton assemblage. Instead, the dominance of barnacle nauplii appeared to have been maintained by steady recruitment due to barnacle reproduction in the pond. While changes in the biomass of pond zooplankton were not correlated with physico-chemical characteristics, changes in density were positively correlated with temperature, and negatively correlated with pH, dissolved oxygen and secchi disc readings. Epibenthic faunal density peaked at the end of the season, while the biomass peaked during the middle part of the season. Sergestids (*Acetes sibogae* Hansen) were the most abundant epibenthic taxa. No correlations were found between physico-chemical parameters and epibenthic fauna biomass or density. Abundances of epibenthic fauna were not related to zooplankton densities, suggesting that trophic interactions between these assemblages is not important. No *Acetes* were captured in samples of outlet water, and only on a single occasion were large numbers captured in the inlet water; after this, there was a notable increase in the number of *Acetes* in the

pond. This evidence, together with the lack of an increase in the size of *Acetes* during the season, suggests that water exchange is an important but unpredictable source of recruitment of epibenthic fauna into the pond. The results emphasize the benefits of ensuring that appropriate zooplankton assemblages have been introduced into the ponds, when they are filled, to support the shrimp immediately after stocking. This will depend on the initial inoculum and may be difficult to manipulate with water exchanges once established. Assemblages of epibenthic fauna appear more likely to change with exchanges and may need to be monitored across the season, particularly if their presence reduces production through adverse impacts such as competition with postlarvae, introduction of disease or deteriorated water quality.

Keywords: zooplankton, epibenthos, shrimp ponds, assemblages, *Acetes*, water exchange

Introduction

A diverse range of animals, other than the cultured species, have been described from shrimp aquaculture ponds (Martinez-Cordova, Barraza & Pasten 1997; Martinez-Cordova, Villarreal-Colmenares & Porchas-Cornejo 1998; Coman, Connolly & Preston 2003; Preston, Coman & Fry 2003). Assemblages of these animals have been shown to change considerably in both abundance and diversity throughout a grow-out season (Martinez-Cordova *et al.* 1997, 1998; Coman *et al.* 2003; Preston *et al.* 2003). These fauna may play a beneficial role in the productivity of shrimp ponds, particularly at the beginning of the season when they contribute to the nutrition of the shrimp (Chen & Chen 1992; Martinez-Cordova *et al.* 1997, 1998; Coman *et al.* 2003), and it would be useful

for pond managers to know the conditions that can optimize the growth and survival of these animals.

Factors that may influence the dynamics of these assemblages include variations in food, predation, physical and chemical water quality parameters, and import or export during water exchanges. Coman *et al.* (2003) investigated the effects of a range of water quality parameters in ponds in subtropical Australia, but found no strong correlations. In the same study, the effect of water exchange was considered. Although no correlations were found between the volume of water exchanges and change in zooplankton density, the results warranted further investigation, using a sampling design specifically aimed at measuring the effects of exchanges on the zooplankton communities in the pond.

Most farmers still use regular water exchanges as the main method of controlling water quality (Jackson, Preston, Burford & Thompson 2003). Nutrient input to shrimp ponds results in phytoplankton blooms (Burford 1997), which in turn support much greater densities of zooplankton than in surrounding waters. Accordingly, it would be expected that the water entering the pond during exchanges would contain much fewer individuals than the water leaving the pond. As pond managers exchange up to 10% of the volume of a pond at any one time, it may be expected that there would be a measurable effect on the assemblages of zooplankton in the pond.

In this study, zooplankton and epibenthic invertebrates were sampled from a commercial *Penaeus monodon* pond over the entire grow-out season, with periods of intensive sampling of pond, inlet and outlet water over three 1-week periods throughout the season. The aim was to examine the influence of water exchanges on the dynamics of the assemblages at specific times during the season, while also determining whether the general temporal pattern in assemblage structure was comparable with that which has been previously described from the region (Coman *et al.* 2003; Preston *et al.* 2003). Among the larger crustaceans, the study focused particularly on *Acetes*, the most abundant member of the epibenthic fauna found in shrimp ponds in the south-east Queensland (R. Koenig, Rocky Point Prawn Farm, pers. comm.; Coman *et al.* 2003).

Materials and methods

Study site and pond management

Samples were collected from a pond at Moreton Bay Prawn Farm, Cleveland Australia (27°30'S, 153°20'E).

The pond was one of eight used to farm *P. monodon*, each approximately 1 ha in surface area and 1.5 m deep in the centre. Water was supplied from a nearby tidal creek, first screened before the intake pump with a large mesh (20 mm), and then again with a 4 mm mesh before entering the pond. Water in the ponds was changed by either draining a proportion of the water out and refilling (exchanging), or by running water into the pond without draining and allowing the water to flow through the outlet (flowing through).

At the beginning of a season, the water in the pond was exchanged infrequently (less than weekly) and the managers relied mainly on flowing through water each day or two. As the biomass of the shrimp increased, the water quality parameters changed more rapidly and water was exchanged more frequently (1–2 days) and flowing through was used only occasionally. The outlet of the pond was screened to prevent loss of shrimp during exchanges. Early in the season, the screen had a mesh size of approximately 1 mm, and as the season progressed the mesh size was increased to 4 mm, and finally to 10 mm by the end of the season. Increasing mesh size increases the exchange flow, which is more important towards the end of the season when exchanges are more frequent. Shrimp were stocked after the second sampling period at approximately 25 ind. m⁻² and were fed a fishmeal-based commercial pelleted diet (C.P. feeds, Bangkok, Thailand), usually between 2 and 4 times day⁻¹. Feed rates were determined by monitoring feed trays and adjusting accordingly. Paddlewheels provided circulation and helped to maintain dissolved oxygen levels. Lime was added to maintain pH at close to 8 throughout the season. Phytoplankton blooms, which help to maintain pond water quality and also provide natural food for newly stocked postlarvae, were maintained by fertilization with chicken manure.

Sampling equipment

Pond fauna was collected using two different nets hand-towed over a measured distance against the flow of the current created by paddlewheels. The volume of water sampled by each net was calculated from calibration tows fitted with flow meters. Zooplankton were sampled using a conical plankton net measuring 350 mm diameter at the mouth, 1000 mm in length with a 140 µm mesh size. A float was attached to the mouth to hold the net at the water surface. Epibenthic species were collected

using a beam trawl, with a 500 mm wide and 300 mm high mouth, constructed of 1 mm mesh. A small metal tickle chain (20 mm links) was suspended across the front of the net.

Pond water temperature, pH, dissolved oxygen and salinity were all measured twice daily (dawn and dusk) using a data logger (T. P. S). Secchi disc readings were taken at the same time.

Sampling strategy

Samples to determine the dynamics of the assemblages of zooplankton and epibenthic fauna within the pond were collected fortnightly across the whole season, within 4 days of a full or a new moon, from when the pond was filled in October 1997 until it was emptied in May 1998. This period included two occasions before stocking of postlarval stage 15 *P. monodon*. Three replicate samples were collected on each occasion. Zooplankton net tows were taken from the same site along the edge of the pond, over a distance of 53.0 m, between two jetties.

Beam trawl samples could not be collected along exactly the same path as the plankton tows due to the presence of paddlewheel power cables. The towing distance was, therefore, shorter than that used for plankton samples (39.5 m). The beam trawl also collected stocked shrimp when towed, and these were returned to the water live. Owing to potential damage to young postlarvae, beam trawls were not taken until the first week of exchange water sampling.

The samples for determining the effect of water exchanges were collected over three separate 1-week periods in December, January and March. The first samples were collected 8 weeks after the postlarvae were stocked; before this time, water exchanges from the pond were infrequent. The timing of the second and the third sampling periods was determined by the dates that the farm managers increased the mesh size on the outlet screen. On each of the three sampling periods, samples were taken from within the pond each day. During the second and third sampling periods, samples were also taken after each exchange event (either drain or fill). Samples were also taken of the water draining from the pond (outlet) and filling the pond (inlet); two replicate samples were collected on each occasion using the zooplankton net.

Sample processing

Samples were rinsed into plastic bags and frozen immediately after collection. Plankton samples were

split initially into two equal parts using a Folsom plankton splitter (Van Guelpen, Markle & Duggan 1982). One half was then divided further into two size fractions: 90–300, and > 300 μm . Each size fraction was rinsed with freshwater and dried at 60 °C to determine biomass. The remaining half of the sample used to determine species composition was preserved in 70% ethanol. The preserved sample was split to an appropriate level for sorting using the Folsom plankton splitter before sorting under a dissecting microscope. Specimens were identified to the lowest practical taxonomic level to allow completion of sorting the samples in a reasonable period (typically 3 h).

The size structure and sex ratio of *Acetes* captured in the beam trawls were examined. All *Acetes* from the beam trawls were counted, measured (occipital carapace length), weighed and sexed if > 3 mm carapace length. Other crustaceans, including incidental shrimp species such as *Metapenaeus bennettiae* (Race & Dall) and *P. merguensis* (De Man), were counted and measured. All other species encountered in the beam trawls were counted, but not measured and the sex ratio was not determined.

Data analysis

Pairwise comparisons of environmental variables were performed to examine the strength of the relationships between these independent variables. Where collinearity existed, the variable of least importance was excluded from further analyses. Backward stepwise multiple regressions were then used to study the relationships between the biological variables and environmental variables. In this process, all the non-collinear environmental variables were included in the initial regression. Variables that did not contribute to significant variation were removed before running the next regression. Variations in the abundance of *Acetes* throughout the season, and between the sexes, were investigated with ANOVA.

Results

Environmental characteristics

The fortnightly average of the dawn and dusk water temperature increased from 20.0 °C at the beginning of the season, to a peak of 27.9 °C in January and declined to 19.5 °C in May (Fig. 1a). Dissolved oxygen values ranged from 4.4 to 6.4 mg L⁻¹, the minimum values coinciding with the warmest pond temperatures. The fortnightly averages for pH were between 7.1 and 8.4, the lowest values being recorded during

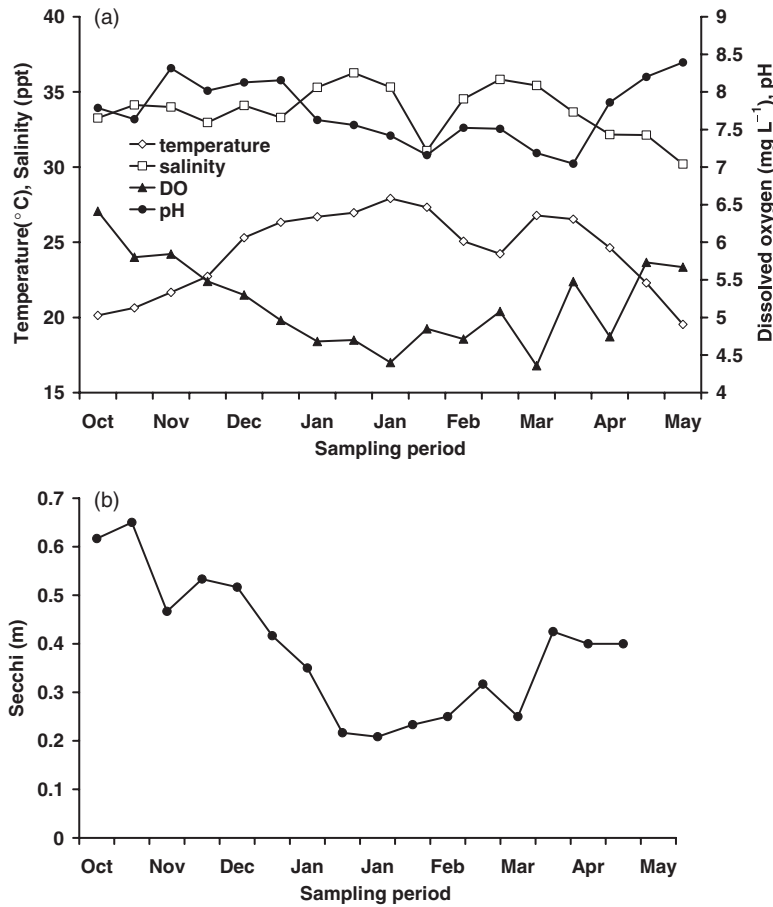


Figure 1 Variation in physical parameters over time across the grow-out season. (a) Fortnightly averages of physical parameters measured at dawn and dusk: dissolved oxygen (mg L^{-1}), pH, temperature ($^{\circ}\text{C}$) and salinity (ppt); (b) fortnightly average of secchi disc reading (m).

the middle part of the season. Salinity ranged from 31.1 to 36.3 mg L^{-1} , with a mid-season low linked to a period of heavy rain. Secchi disc values ranged from 0.21 to 0.43 m from the sixth fortnight after the pond was filled until the end of the grow-out. Before this time, values were higher, with the maximum reading of 0.65 m being recorded the week before shrimp postlarvae were stocked (Fig. 1b).

Dissolved oxygen, temperature and secchi disc values were found to be collinear (Table 1a); dissolved oxygen was therefore the only of these three variables retained in further regression analyses.

Zooplankton densities

A peak in zooplankton density of 130 ind. L^{-1} was recorded before stocking the pond with postlarvae (Fig. 2a). Following the introduction of postlarvae between the second and third sampling periods, zooplankton numbers declined to below 12 ind. L^{-1} . Zooplankton were most abundant through the middle of the season (mid January to late March) when

Table 1a Collinearity matrix (regression r^2 values) of physico-chemical parameters

| | DO | pH | Salinity | Secchi |
|-------------|---------|--------|----------|---------|
| Temperature | 0.72*** | 0.39** | 0.20 | 0.64*** |
| DO | | 0.24* | 0.17 | 0.70*** |
| pH | | | 0.17 | 0.26* |
| Salinity | | | | 0.10 |

Significance of regressions.
* $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

the density varied from 220 to 590 ind. L^{-1} . Stepwise regression showed that pH and dissolved oxygen (and therefore temperature and secchi disc readings) were the best combination of predictors of zooplankton density (Table 1b).

Zooplankton biomass

The biomass of the zooplankton generally matched the pattern of density, apart from the pre-stocking samples, which were very large relative to the abun-

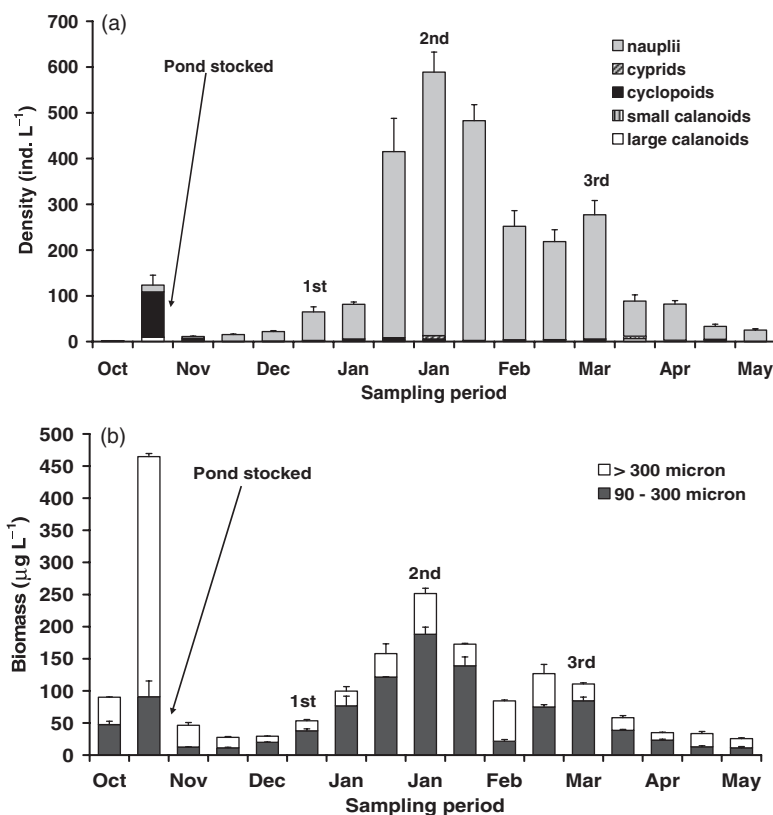


Figure 2 Variation in (a) total zooplankton density (ind. L⁻¹ + SE); (b) zooplankton biomass for > 300 and 90–300 µm size fractions (µg dry weight L⁻¹ + SE). First, second and third indicate the times when exchanges were intensively sampled.

Table 1b Proportion of variation explained by multiple backward stepwise regressions (i.e. r² values) between biological parameters and physico-chemical properties of the pond water

| Variable | Multiple regression r ² values | Abiotic variables retained |
|------------------------------------|---|----------------------------|
| Zooplankton abundance | 0.59** | DO, pH |
| Zooplankton biomass | 0.17 | – |
| Epibenthos abundance | 0.21 | – |
| Epibenthos biomass | 0.00 | – |
| Acetes beam trawl sample abundance | 0.24 | – |

Significance of regressions.
**P ≤ 0.01.

dances recorded at those times (Fig. 2b). The maximum biomass (> 450 µg L⁻¹) was before stocking. Following the introduction of postlarvae, the biomass declined to < 50 µg L⁻¹. From then until the end of the season, biomass varied between 25 and 250 µg L⁻¹, with peaks matching those in abundance.

The large fraction of zooplankton (> 300 µm) dominated the biomass from the second to the fourth sampling period (Fig. 2b). From then on, the relative

contributions of the 90–300 µm and the > 300 µm fractions varied. However, with the exception of the late February sample, the smaller fraction (90–300 µm) contributed more to the overall biomass. Analysis of the abiotic variables revealed that no combination of these was significantly related to zooplankton biomass (Table 1b).

Zooplankton taxa

Thirty taxa were identified during the season, most of which were rare (Table 2). Barnacle nauplii became numerically dominant in the zooplankton assemblage in late November, and remained the dominant zooplankton until the end of the season (Fig. 2a). Cyclopoids were very abundant in the second sampling period, but throughout the rest of the season were present in much smaller numbers. Other taxa accounting for greater than 0.3% of zooplankton numbers were large calanoids (*Acartia* spp.), small calanoids (*Acartia* spp. and unidentified), harpacticoids and barnacle cyprids. However, these taxa were all present in small numbers across the whole season, rather than becoming abundant at any particular time.

Table 2 Taxa recorded from zooplankton surface tows ordered by % occurrence within taxonomic group

| Taxa | % by numbers | % frequency of occurrence |
|-----------------------------|--------------|---------------------------|
| Crustacea | | |
| Cirripedia | | |
| Barnacle nauplii | 96.1 | 100 |
| Barnacle cyprid (sp. 1) | 0.8 | 85.5 |
| Barnacle cyprid (sp. 2) | <0.1 | 8.2 |
| Barnacle eggs | <0.1 | 0.9 |
| Copepoda | | |
| Calanoids (small unid.) | 0.4 | 99.1 |
| Harpacticoids | 0.3 | 99.1 |
| <i>Acartia</i> spp. (large) | 0.4 | 98.2 |
| <i>Acartia</i> spp. (small) | 0.7 | 90.9 |
| Cyclopoids | 1.1 | 70.9 |
| <i>Pseudodiaptomus</i> spp. | <0.1 | 59.1 |
| Calanoids (large unid.) | <0.1 | 11.8 |
| Decapoda | | |
| Crab zoea | <0.1 | 60.0 |
| Penaeoid zoea | <0.1 | 21.8 |
| <i>Acetes sibogae</i> | <0.1 | 3.6 |
| Carid larvae | <0.1 | 3.6 |
| <i>Lucifer</i> postlarvae | <0.1 | 1.8 |
| <i>Lucifer hansenii</i> | <0.1 | 0.9 |
| Crab megalopa | <0.1 | 0.9 |
| Branchiopoda | | |
| <i>Artemia salina</i> | <0.1 | 5.5 |
| Peracarida | | |
| Isopods | <0.1 | 3.6 |
| Stomatopoda | | |
| Stomatopod larvae | <0.1 | 2.7 |
| Gastropoda | | |
| Gastropod (sp.1) | <0.1 | 23.6 |
| Gastropod (sp.2) | <0.1 | 0.9 |
| Chaetognatha | | |
| Chaetognaths | <0.1 | 10.0 |
| Chelicerates | | |
| Terrestrial mite | <0.1 | 5.5 |
| Insecta | | |
| Chironomid larvae | <0.1 | 3.6 |
| Mosquito larvae | <0.1 | 1.8 |
| Aschelminths | | |
| Nematodes | <0.1 | 0.9 |
| Fish | | |
| Fish larvae (unid.) | <0.1 | 7.3 |
| Syngnathid juvenile | <0.1 | 0.9 |

% by numbers, contribution of taxon to the total number of zooplankters recorded throughout the season; % frequency of occurrence, percentage of plankton tows in which taxon was recorded.

Epibenthic fauna density

The maximum abundance of epibenthic fauna of $>7 \text{ ind. m}^{-2}$ was recorded from the final sampling occasion in May (Fig. 3a). For the remainder of the season, density varied between 0.25 and

2.4 ind. m^{-2} , with densities of $<2 \text{ ind. m}^{-2}$ recorded from early and mid-January and late March. Stepwise regression revealed that no combination of abiotic variables explained the variation in epibenthos density across the season (Table 1b).

Epibenthic fauna biomass

The maximum biomass of epibenthic fauna ($>0.6 \text{ g m}^{-2}$) occurred as a single peak in mid-January (Fig. 3b). This was due to the presence of low numbers of large shrimp (*Metapenaeus* spp.). Apart from the magnitude of this peak, the pattern of biomass across the remainder of the season was similar to abundance due to the dominance of a single taxon, *Acetes*, in the samples. No combination of abiotic variables was able to explain a significant amount of variation in epibenthic faunal biomass (Table 1b).

Epibenthic taxa

Nineteen taxa were caught in the beam trawls (Table 3). *Acetes* and *P. merguensis* (juveniles) were the dominant taxa, and none of the other taxa contributed more than 2% of the overall abundance. *Acetes* was the most abundant taxon across the whole season, apart from early April when *P. merguensis* dominated the samples (Fig. 3a). Several taxa, including Ambassidae, Gobiidae, silver bellies (*Gerres* sp.), mysids and *Metapenaeus* spp., were caught in small numbers over the whole season. *Lucifer hansenii* (Nobili) specimens were caught in the first beam trawl samples only.

Acetes population dynamics

Over the season, a total of 2749 *Acetes* were collected in the beam trawls, and a further 48 were captured in the surface net tows. Owing to the dominance of *Acetes* in the beam trawl samples, their pattern of abundance was very similar to the overall epibenthic fauna density apart from the samples in early April. The maximum abundance of *Acetes* in the beam trawl was recorded in the final sampling week when density reached 7 ind. m^{-2} . The minimum number of *Acetes* were captured in early April, when the density was less than 0.2 ind. m^{-2} . Regression analysis demonstrated the same relationship between the abiotic variables and *Acetes* density in beam trawls as for total epibenthic fauna density (Table 1b). There was no significant relationship between variation in the numbers of *Acetes* captured in the beam trawl

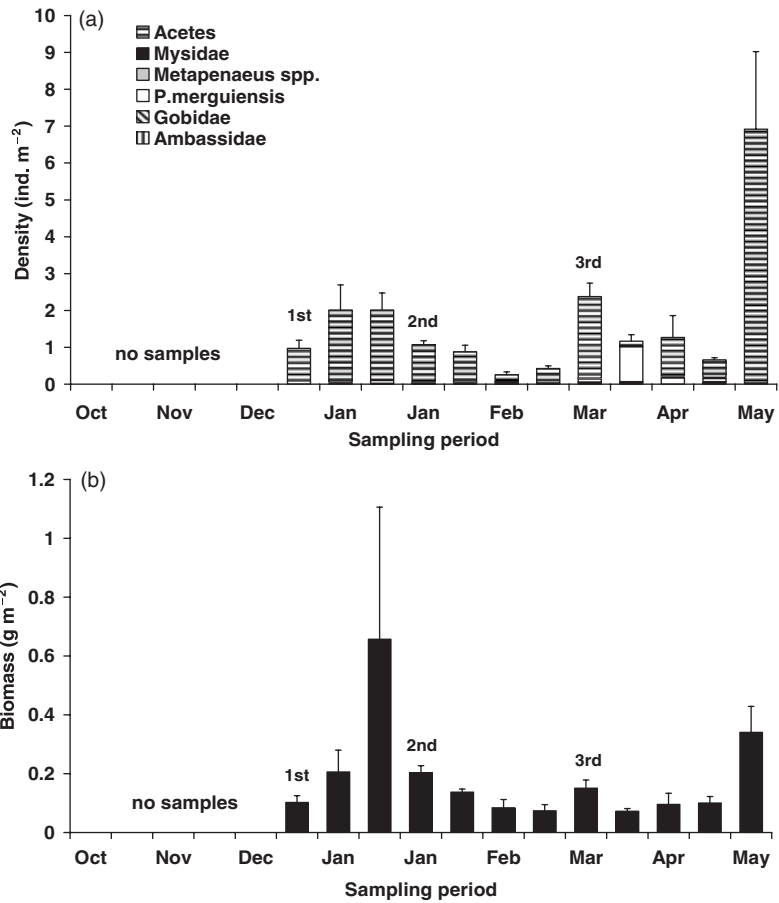


Figure 3 Variation in epibenthic fauna (a) density (ind. m⁻² + SE); (b) biomass (g dry weight m⁻² + SE). First, second and third indicate the times when exchanges were intensively sampled.

and variation in zooplankton densities or biomass ($r^2 < 0.09$ in both cases).

The *Acetes* captured in the beam trawl varied in carapace length from 1.8 to 9.5 mm. There was significant variation in average carapace length between sampling occasions [ANOVA: df (16, 2420); $P < 0.001$], but there were no consistent trends of increasing or decreasing size throughout the sampling period. However, Tukey's tests indicated that the average size of *Acetes* captured in the beam trawl did decline significantly between the samples taken in early and late March and remained smaller until the end of the season.

Water exchanges

Zooplankton density in the water drained from the pond during exchanges was 2.4–58.8% of the density in the pond before the exchange. Zooplankton density in the incoming water was 9.1–50.0% of the drained water and consequently also always lower than in the pond (Fig. 4).

Barnacle nauplii were always the numerically dominant zooplankton taxon in both pond and outlet samples during water exchanges ($\geq 83\%$, Fig. 5). Apart from 1 day in the first sampling period, no other taxon accounted for $> 3\%$ of total zooplankton numbers. Although there is some indication that the proportion of other taxa in outlet samples may be slightly higher than in the pond, their very low abundance makes it difficult to be confident that these differences are important. However, in the inlet samples, calanoid copepods were the dominant taxa caught in December. In the second and third sampling periods, barnacle nauplii accounted for $> 90\%$ of the zooplankton in the inlet waters, but the relative abundance of other taxa was higher than in either the pond or outlet samples.

Exchange-related changes in pond zooplankton density can be predicted from the water volume exchanged, pond water volume, starting pond zooplankton density and zooplankton density in incoming or outgoing water. This calculation assumes perfect mixing within the pond, and no selec-

tivity (e.g., filtering effect) at intake or discharge points. Other factors affecting the predictions could include decreases in zooplankton due to sudden deterioration of pond conditions or very high predation

Table 3 Taxa recorded from beam trawls ordered by % occurrence within taxonomic group.

| Taxa | % by numbers | % frequency of occurrence |
|---------------------------|--------------|---------------------------|
| Crustaceans | | |
| Decapoda | | |
| <i>Acetes sibogae</i> | 91.3 | 97.9 |
| <i>Penaeus merguensis</i> | 4.1 | 32.3 |
| <i>Metapenaeus</i> spp. | 0.5 | 11.5 |
| <i>Lucifer hansenii</i> | 0.2 | 4.2 |
| <i>Penaeus plebejus</i> | <0.1 | 1.0 |
| Carids | <0.1 | 1.0 |
| Peracarida | | |
| Mysids | 0.5 | 12.5 |
| Isopods | 0.3 | 3.1 |
| Cirripedia | | |
| Balanomorph barnacles | 0.2 | 2.1 |
| Insects | | |
| Mosquito larvae | <0.1 | 1.0 |
| Fishes | | |
| Ambassidae | 1.3 | 19.8 |
| Gobiidae sp. 1 | 0.7 | 19.8 |
| <i>Gerres</i> sp. | 0.6 | 14.6 |
| Fish larvae | 0.1 | 2.1 |
| Gobiidae sp. 2 | <0.1 | 1.0 |
| Hemirhamphidae | <0.1 | 1.0 |
| Tetraodontidae | <0.1 | 1.0 |
| Chirocentridae | <0.1 | 1.0 |
| Syngnathidae | <0.1 | 1.0 |

% by numbers = contribution of taxon to the total number of epibenthos recorded throughout the season; % frequency of occurrence = percentage of beam trawls in which taxon was recorded.

pressure or a rapid increase in populations due to reproduction.

However, pond zooplankton density did not follow these predictions. For example, the density was much higher than predicted on day 2 of the January intensive sampling period, when no water exchange had occurred the previous day (Fig. 6). On day 3 of the same sampling period, the number of zooplankton captured in the pond was much lower than expected, after taking into account the net loss of animals due to an exchange. In contrast, on day 4 of sampling, the number of zooplankton in the pond increased dramatically after water was drained from the pond, when only a very slight increase would be expected (Fig. 6).

No *Acetes* were ever captured in the outlet samples; however, small numbers of other large taxa (maximum 2 per sample), including stocked shrimps, were captured in January and March outlet samples. Only zooplankton were captured in the outlet water in December, when the finest mesh screen was still over the outlet. Few *Acetes* (maximum of 2 per sample) were captured in the inflow samples taken in December and January; however, on one particular occasion in the March sampling period, an average of > 30 *Acetes* were captured from each sample replicate. If this density of *Acetes* continued to enter the pond for the entire exchange, approximately 10 000 individuals could have entered the pond in this single exchange.

As with the zooplankton, it might be expected that changes in the density of *Acetes*, in the pond over the weeks when the water exchanges were sampled, could be predicted. As no *Acetes* were captured in the outlet and, on most occasions, only a few in the

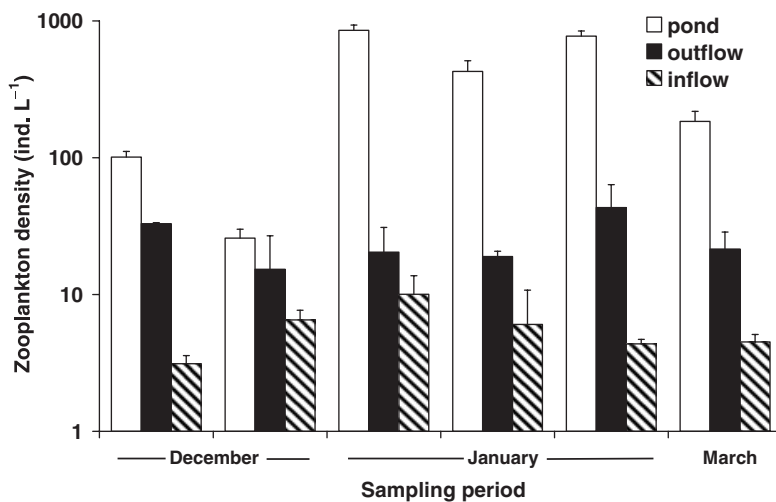


Figure 4 Zooplankton density in pond, outlet and inlet water at times of intensive sampling (ind. L⁻¹+SE); note that this graph has a logarithmic scale, and data are only presented when both outlet and inlet water was sampled.

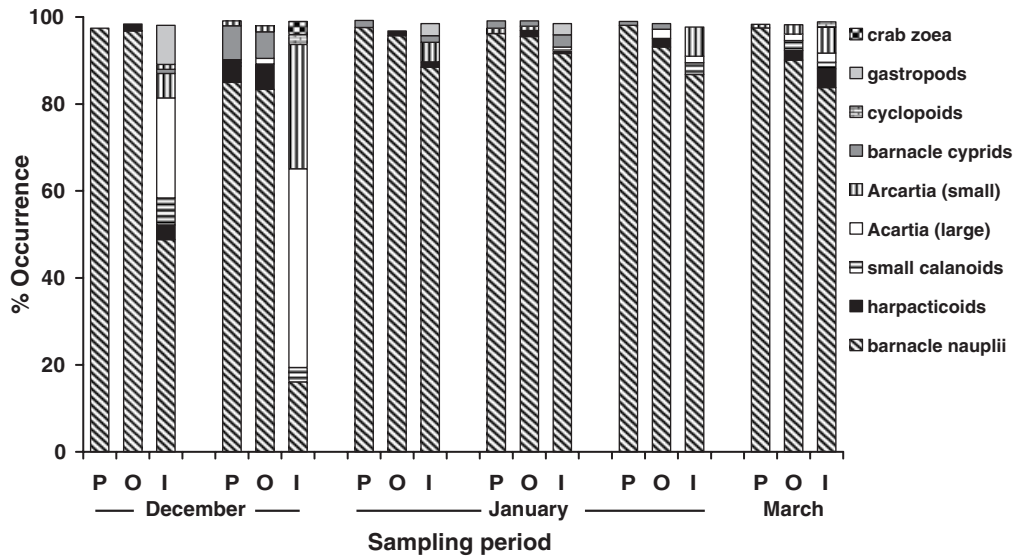


Figure 5 Percent occurrence of zooplankton taxa in pond, outlet and inlet water at times of intensive sampling; P, pond; O, outlet; I, inlet; note totals not always 100% because very rare taxa are not presented.

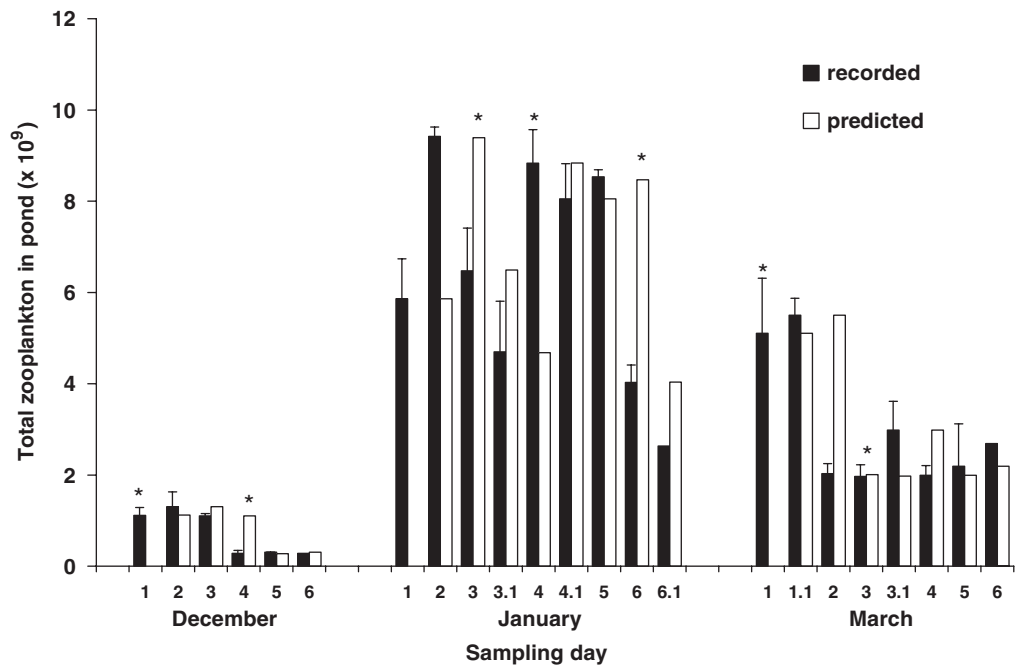


Figure 6 Daily variations in recorded (+SE) and predicted number of zooplankton in pond during intensive sampling periods. Predicted densities were calculated from the previous day numbers ± inputs calculated from zooplankton densities in the exchange water. * indicates days when exchanges were performed; note that day 1.1 represents second samples taken on day 1 after exchange.

inlet, we would expect only minimal changes in numbers between each day of sampling. This was not the case, with changes in numbers of *Acetes* captured in the pond always being greater than was predicted (Fig. 7).

Discussion

The rapid decline in zooplankton numbers and biomass immediately after postlarvae were stocked is consistent with the results obtained from ponds used

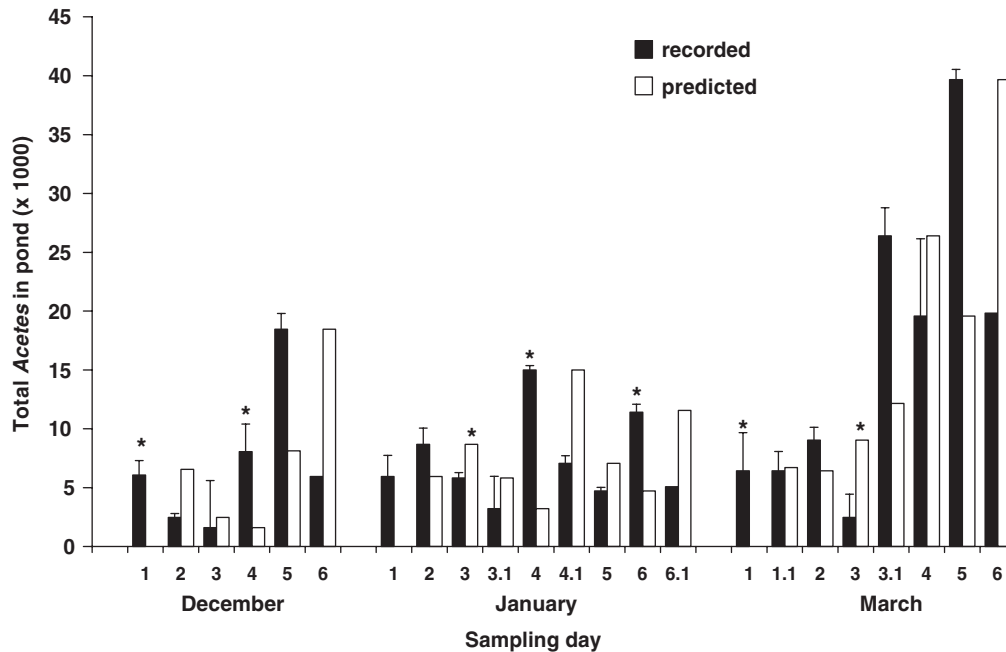


Figure 7 Daily variations in recorded (+SE) and predicted number of *Acetes* in pond during intensive sampling periods. Predicted densities were calculated from the previous day numbers \pm inputs calculated from *Acetes* densities in the exchange water. *Days when exchanges were performed; note that day 1.1 represents second samples taken on day 1 after exchange.

to rear *P. monodon* (Chen & Chen 1992; Preston *et al.* 2003), *P. vannamei* (Boone) (Martinez-Cordova *et al.* 1997, 1998) and *P. japonicus* (Bate) (Coman *et al.* 2003). Furthermore, early in the season, it is difficult to evenly distribute the small biomass of artificial feed around the whole of a 1 ha pond and it would be more efficient for the postlarvae to feed on zooplankton that are distributed throughout the pond. It appears therefore that predation by shrimp postlarvae is the probable cause of the decline in zooplankton abundance directly after stocking.

The pattern of zooplankton abundance across the remainder of the season was, however, different in this study from previous reports (Martinez-Cordova *et al.* 1997, 1998; Coman *et al.* 2003; Preston *et al.* 2003). Previously, zooplankton abundance has been observed to remain relatively low for the remainder of the season, after the post-stocking decline. The dominance of barnacle nauplii in the middle of the season resulted in the relatively smaller biomass compared with the beginning of the season when larger cyclopoids and calanoids dominated, even though copepods were much less numerous.

The pattern of abundance of zooplankton assemblages in shrimp ponds has been linked to their suitability as prey for shrimp postlarvae in a number of

studies (Chen & Chen 1992; Martinez-Cordova *et al.* 1997, 1998; Coman *et al.* 2003), and this is a likely cause of the decrease in abundance of cyclopoids soon after the postlarvae were stocked into the pond. However, other factors may have a greater influence on the assemblage later in the season, particularly as the shrimp are less likely to feed on zooplankton as they grow towards harvest size. Coman *et al.* (2003) found no link between pond physical parameters and zooplankton abundance in a *P. japonicus* pond. In the present study, however, relationships were found to exist between zooplankton abundance and some physico-chemical parameters. These relationships were most strongly influenced by the abundance of barnacle nauplii because of their dominance over most of the season. Barnacle nauplii are generally short-lived, metamorphosing to cyprids between 1 and 2 weeks after spawning (e.g. Lang & Marcy 1982). Therefore, the continuously high abundance of nauplii must have been maintained by steady recruitment either from within or from outside the pond. These relationships may therefore represent conditions that are favourable for barnacle spawning. Zooplankton density was positively correlated with temperature and negatively correlated with dissolved oxygen and pH. The lower dissolved oxygen and

pH values recorded through the middle of the season may be in part a result of the elevated temperatures at that time. Temperature may be the most important factor as it seems unlikely that lower oxygen levels or pH would be favourable conditions to stimulate spawning. Secchi disc readings were negatively correlated with zooplankton abundance; therefore, zooplankton were more abundant when the algal biomass was higher. This higher algal biomass could have potentially stimulated the spawning of barnacles.

Zooplankton density in the inlet water was substantially lower than in the pond. Although the zooplankton composition in the inlet water was sometimes quite different from the pond, the much lower density probably meant that any influence on pond assemblage composition was insignificant and could not be detected.

After the post-stocking decline in zooplankton abundance, barnacle nauplii were the dominant taxa in the ponds for the rest of the season. Barnacle nauplii were always more abundant in pond water than in the inlet water, indicating that recruitment through the inlet water was not a major determinant of their abundance in the pond. Furthermore, the density of barnacle nauplii was always higher in the outlet water than in the inlet water so more nauplii were lost, at each exchange, than were gained. Also, because nauplii are short-lived (e.g. Lang & Marcy 1982), they would probably metamorphose to cyprids and settle out rather than accumulate in the zooplankton population. The major source of recruitment for barnacle nauplii must be from the reproduction of adult barnacles within the pond.

The decrease in zooplankton numbers in the pond from one day to the next will also be strongly influenced by barnacle nauplii. The decreases could not be explained by water exchanges, but may be linked to metamorphosis of nauplii to cyprids and consequent settling.

The lower density of zooplankton in the outlet compared with within the pond indicates that zooplankton were somehow able to avoid being discharged, despite the outlet being positioned near the pond edge where the current created by the paddlewheels was strong. The structure of the drainage outlet may alter the flow of the water and screen away some of the zooplankton, particularly likely early in the season when the finest mesh screen is on the outlet, creating greater resistance and reducing the discharge rate. It has been shown that zooplankton densities are higher in waters near the edge of the

pond due to currents created by paddlewheels (Preston *et al.* 2003), so an estimate of the entire pond based on these samples from the pond edge may be slightly high. However, these overestimates would be negated to a degree because the drainage outlet was situated at the edge of the pond, within the path of higher velocity water from which pond samples were also collected.

Apart from *Acetes* and *P. merguensis*, epibenthic fauna was scarce in the present study. Amphipods, which had been the dominant epibenthic fauna in the previous grow-out season (Coman *et al.* 2003), were not present this season, possibly due to the absence of the macroalgae with which they had previously been associated (Coman *et al.* 2003). The pattern of abundance of epibenthic fauna in the pond did not reflect the changes observed in zooplankton abundances, suggesting that although zooplankton may be a part of the diet, their role as prey is not a major determining factor for the epibenthic fauna assemblage.

The larger fauna captured in the beam trawl, such as non-crop penaeids and fish, will be introduced to the ponds as larvae or juveniles and are not likely to reach reproductive age within a grow-out season. Recruitment of these species is therefore limited to introduction via water exchanges, and their occurrence within the pond will be strongly affected by occurrence in the supply water. The abundance of species such as *P. merguensis* will be influenced by seasonally restricted reproduction in the surrounding natural systems (Courtney, Masel & Die 1995; Courtney & Masel 1997).

If recruitment occurred over a very short period of time, it would be expected that from that point, a steady increase in the mean size of individuals in the population would be observed over the remainder of the season. In contrast to this expected increase in average size, the average size of the *Acetes* in the pond declined between early and late March. Furthermore, there were large numbers of *Acetes* captured in the final sampling period and also *P. merguensis* juveniles captured in the early April samples, after relatively small catch rates for both species in the previous fortnights. This suggests that significant recruitment of the species into the pond had occurred between collecting the two samples and that recruitment may occur in pulses over the whole season.

While the timing of recruitment of *P. merguensis* may be related to reproductive peaks, the occasional large number of *Acetes* brought in through the inlet may be due to swarming behaviour (Xiao 1991; Xiao & Greenwood 1993; Omundsen, Sheaves & Molony

2000). If *Acetes* were swarming near the inlet when the pond was being refilled, a large number of animals could be brought in very quickly. Although the numbers of *Acetes* in exchange water may not accurately predict changes in pond populations over short periods, they may provide clues to changes observed in the density of *Acetes* across the whole season. The large increase in *Acetes* density between the last sampling in April and the May samples is equivalent to an increase in >45 000 individuals. Continuous recruitment into the pond at densities recorded from the inlet water during the final sampling period could potentially account for this increase. Swarming behaviour within the pond may also explain the variation in the number of *Acetes* captured in the trawls even when no exchanges occurred between samples. The precision of the predicted effects of water exchanges on pond epibenthos is limited not only by low densities, compared with zooplankton, but also by a lack of knowledge of the factors that influence density within the pond such as the ability of these species to avoid the drains, or predation by shrimp.

Overall, the changes in zooplankton assemblages were similar to those previously described in shrimp grow-out ponds, the notable exception being the high abundance of barnacle nauplii in the middle of the season. Zooplankton assemblages were most notably affected by the stocking of postlarvae and spawning of barnacles within the pond, while epibenthos assemblages were most affected by the introduction of *Acetes* from outside the pond. The decline in zooplankton abundance after the stocking of shrimp suggests that they may be an important part of the diet of postlarvae early in the season. In pond systems where barnacle nauplii are the major component of the assemblage, reproduction by settled adults may contribute more to the zooplankton assemblage than exchanges. The assemblage of zooplankton that was brought in with the inlet water may be very different from what was in the pond or the outlet water, but because the density is very low compared with in the pond, it has little influence on the composition of the pond population. An interesting comparison would be between ponds that exchange water regularly and ponds in which recirculation is used. In the case of recirculating ponds, the initial zooplankton inoculum would play a major role in determining the assemblage for the whole season.

For the larger epibenthic species, which do not reproduce in the pond, exchanges are likely to have a major influence on the pond populations, and beha-

viours such as swarming of *Acetes* may be particularly important. So although it is difficult to predict the effect of exchanges, it would appear that they can at times have an important effect on the pond fauna, particularly the larger epibenthic species. The establishment of a suitable zooplankton assemblage to support the shrimp immediately after stocking will be dependent on the initial inoculum and may be difficult to manipulate with water exchanges once it has become established. It may therefore be in the interest of the pond managers to ensure that appropriate zooplankton have been introduced into the ponds when they are filled. However, there may be opportunity for pond managers to influence zooplankton populations further into the season if species such as barnacles are able to settle and reproduce within a season, as observed in this study. The provision of suitable settlement structures may be a method to ensure that zooplankton, in the form of larval stages, are present in ponds across the whole season and may be worth investigating further if this is desirable for specific aquaculture systems. Assemblages of epibenthic fauna appear more likely to change with exchanges and may need to be monitored across the season, particularly if their presence reduces production through adverse impacts such as introduction of disease (e.g. Flegel, Sriurairatana, Wongteerasupaya, Boonsaeng, Panyim & Withyachumnarnkul 1995) or deteriorated water quality (e.g. Nates & Felder 1998).

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References

- Burford M. (1997) Phytoplankton dynamics in shrimp ponds. *Aquaculture Research* **28**, 351–360.
- Chen Y.L. & Chen H. (1992) Juvenile *Penaeus monodon* as effective zooplankton predators. *Aquaculture* **103**, 35–44.
- Coman F.E., Connolly R.M. & Preston N.P. (2003) Zooplankton and epibenthic fauna in shrimp ponds: factors influencing assemblage dynamics. *Aquaculture Research* **34**, 359–371.
- Courtney A.J. & Masel J.M. (1997) Spawning stock dynamics of two penaeid prawns, *Metapenaeus bennettiae* and *Penaeus esculentus*, in Moreton Bay, Queensland, Australia. *Marine Ecology Progress Series* **148**, 37–47.

- Courtney A.J., Masel J.M. & Die D.J. (1995) Temporal and spatial patterns in recruitment of three penaeid prawns in Moreton Bay, Queensland, Australia. *Estuarine, Coastal and Shelf Science* **41**, 377–392.
- Flegel T.W., Sriurairatana S., Wongteerasupaya C., Boonsaeng V., Panyim S. & Withyachumnarnkul B. (1995) Progress in characterization and control of yellow-head virus of *Penaeus monodon*. In: *Swimming through Troubled Water. Proceedings of the Social Session on Shrimp Farming* (ed. by C.L. Browdy & J.S. Hopkins), pp. 76–85. USA World Aquaculture Society, Baton-Rouge, LA, USA.
- Jackson C.J., Preston N., Burford M.A. & Thompson P.J. (2003) Managing the development of sustainable shrimp farming in Australia: the role of sedimentation ponds in treatment of farm discharge water. *Aquaculture* **226**, 23–34.
- Lang W.H. & Marcy M. (1982) Some effects of early starvation on the survival and development of barnacle nauplii *Balanus improvisus* (Darwin). *Journal of Experimental Marine Biology and Ecology* **60**, 63–70.
- Martinez-Cordova L.R., Barraza R. & Pasten N. (1997) Abundance, composition and nutritional contribution of zooplankton in fertilized and unfertilized shrimp aquaculture ponds with different feeding rates. *Journal of Aquaculture in the Tropics* **12**, 23–34.
- Martinez-Cordova L.R., Villarreal-Colmenares H. & Porchas-Cornejo M.A. (1998) Response of biota to aeration rate in low water exchange ponds farming white shrimp, *Penaeus vannamei* Boone. *Aquaculture Research* **29**, 587–593.
- Nates S.F. & Felder D.L. (1998) Impacts of burrowing ghost shrimp, genus *Lepidophthalmus* Crustacea: Decapoda: Thalassinidea, on penaeid shrimp culture. *Journal of the World Aquaculture Society* **29**, 188–210.
- Omundsen S.L., Sheaves M.J. & Molony B.W. (2000) Temporal population dynamics of the swarming shrimp, *Acetes sibogae*, in a tropical near-shore system. *Marine and Freshwater Research* **51**, 249–254.
- Preston N.P., Coman F.E. & Fry V.M. (2003) Shrimp pond zooplankton dynamics and the efficiency of sampling effort. *Aquaculture Research* **34**, 373–381.
- Van Guelpen L., Markle D.F. & Duggan D.J. (1982) An evaluation of accuracy, precision, and speed of several zooplankton subsampling techniques. *Journal du Conseil, Conseil International pour l'Exploration de la Mer* **40**, 226–236.
- Xiao Y. (1991) *Behavioural ecology of the sergestid shrimp Acetes sibogae Hansen (Sergestidae, Natantia, Decapoda, Crustacea, Arthropoda) from Eastern Australian estuaries*. PhD thesis University of Queensland, 168pp.
- Xiao Y. & Greenwood J.G. (1993) The biology of *Acetes* (Crustacea; Sergestidae). *Oceanography and Marine Biology. An Annual Review* **31**, 259–444.