

Zooplankton and epibenthic fauna in shrimp ponds: factors influencing assemblage dynamics

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Abstract

The assemblage composition, biomass and dynamics of zooplankton and epibenthos were examined in a commercial shrimp (penaeid prawn) pond in subtropical Australia. Physicochemical characteristics of the pond water were measured concurrently. Numbers and biomass of zooplankton in the surface tows (140 µm mesh) varied from 111.7 ind. L⁻¹ (324 µg L⁻¹) to 8.3 ind. L⁻¹ (44.2 µg L⁻¹). Immediately after the ponds were stocked with shrimp postlarvae there was a rapid decline in zooplankton numbers, particularly the dominant larger copepods. We attributed this to predation by the shrimp postlarvae. Subsequent peaks in zooplankton numbers were principally due to barnacle nauplii. Changes in abundance and biomass of the zooplankton assemblage were not correlated with physicochemical characteristics. Epibenthic faunal abundance in the beam trawls (1 mm mesh) peaked at 14 ind. m⁻² and the biomass at 0.8 g m⁻². Unlike zooplankton, the peaks in abundance of epibenthos did not correspond to the peaks in biomass. This was due to the large differences in the size of the dominant taxa across the season. Sergestids (*Acetes sibogae*) and amphipods were the most abundant taxa in beam trawl samples, with amphipods abundance increasing towards the end of the growout. Negative correlations were found between epibenthos abundance and pH and temperature. These relationships were strongly influenced by the high abundances of amphipods and may reflect an effect on the growth of macroalgae in the pond rather than a direct effect on the epibenthos. No correlations were found

between epibenthic fauna biomass and physicochemical parameters. Abundances of epibenthic fauna were not related to zooplankton densities, indicating that this source of food was not likely to be a limiting factor. Neither the pond water exchange regime nor moon phase could explain changes in abundances of zooplankton or epibenthos assemblages. Zooplankton clearly contribute to the nutrition of shrimp postlarvae immediately after stocking. The establishment of an abundant assemblage of zooplankton before stocking shrimp postlarvae would appear to be beneficial, if not essential. Later in the season, zooplankton and epibenthos apparently contribute little to shrimp biomass. Owing to their relatively low biomass, the consumption of shrimp feeds by epibenthos is likely to be insignificant compared with that of the shrimp.

Introduction

Shrimp aquaculture ponds generally support a diverse biota other than the cultured species. Phytoplankton growth in ponds is stimulated by the addition of fertilizers and the waste products from shrimp (Burford 1997) and provides food for assemblages of pond zooplankton and epibenthic fauna. Zooplankton can contribute to the nutrition of farmed shrimp, as demonstrated by studies of stable isotopes (Anderson, Parker & Lawrence 1987), laboratory feeding studies (Chen & Chen 1992) and analysis of gut contents (Maguire, Gibbs & Collett 1984; Allan, Moriarty & Maguire

1995; Martinez-Cordova, Villarreal-Colmenares & Porchas-Cornejo 1998a).

Epibenthic fauna may also contribute to the nutrition of farmed shrimp. Larger crustaceans, particularly *Acetes* spp., have been recorded from shrimp ponds in Australia and throughout South-East Asia (Hall 1962; Johnson 1965; Maguire *et al.* 1984; Supamattaya, Hoffmann, Boonyaratpalin & Kanchanaphum 1998). Although *Acetes* are known to be a natural prey of penaeid shrimp (Xiao & Greenwood 1993) the level of predation on *Acetes* by farmed shrimp is unknown. Likewise, the effects of *Acetes* as predators of smaller zooplankton or shrimp postlarvae have yet to be determined.

Previous studies of zooplankton in shrimp ponds have shown that these are complex assemblages with rapid temporal changes in structure (Preston, Coman & Fry 2003). However, the factors that influence the dynamics of these assemblages have not been examined in any detail and thus are poorly understood. These factors include the variations in sources of food, predation and the influences of variations in physical and chemical water quality parameters.

In this study we examined assemblages of zooplankton and epibenthic fauna in a commercial shrimp (*Penaeus japonicus* Bate) pond over the entire grow-out season. The aim was to determine the dynamics of the assemblages and examine the influence of variations in physical and chemical water quality parameters. Among the larger crustaceans we focused particularly on *Acetes*, the most abundant member of the epibenthic fauna found in shrimp ponds in the study area. The focus of this study was on accurately determining variation within a single pond to provide the basis for designing future studies with sufficient precision to evaluate differences between ponds and among sites.

Materials and methods

Study site

Samples were collected from a single pond at Moreton Bay Prawn Farm, Cleveland, Australia (27°30'S, 153°20'E). The pond was one of eight ponds used to farm *P. japonicus*. The pond we studied was 1 ha in surface area and 1.5 m deep in the centre. The farm was supplied water from a nearby tidal creek. The water was screened before the intake pump with a large mesh (2 cm), and then again with a 4-mm mesh prior to entering the

pond. Water in the ponds was changed either by draining a proportion of the water and refilling (exchanging) or by running water into the pond without draining and allowing the water to flow through the outlet (flow-through).

At the beginning of a season the water in the pond is exchanged infrequently (less than weekly), as the biomass of the shrimp increases the water is exchanged more frequently (every 1–2 days). The outlet of the pond is screened to prevent loss of shrimp during exchanges. The mesh size is increased from 1 mm to 4 mm, and finally to 10 mm throughout the season. The pond was filled in late September, and stocked with shrimp at densities of close to 25 ind.m⁻² in early November. From early April (5 months after stocking) shrimp were regularly trap harvested from the pond for marketing. The pond was drained in late July, 8.5 months after stocking. Overall yield from the pond was 4.5 tonne (range from farm was 2–6 tonne) and survival was approximately 60%. The shrimp were fed a fishmeal-based commercial pelleted diet, usually between two and five times per night. Feeding rates were determined by diving and peaked at 93 kg ha⁻¹ day⁻¹ in April, but had fallen to < 20 kg ha⁻¹ day⁻¹ by early June as a result of harvesting of shrimp for marketing and falling water temperatures. Paddlewheels were used to provide circulation in the pond and help to maintain dissolved oxygen levels in the ponds. Lime was added to the ponds to maintain pH at close to 8 throughout the season. Phytoplankton blooms were maintained by fertilization of the pond with chicken manure.

Sampling

Pond fauna were 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, also conducted against the flow of the water current, with flowmeters fitted to the mouth of the same net used to collect the samples. Zooplankton were sampled using a conical plankton net 350 mm in diameter at the mouth, 1000 mm in length and 140 µm mesh size. The cod end of this net was 90 mm in diameter and 240 mm long and made of PVC with 40-mm windows covered by 140-µm mesh. A float was attached to the mouth to maintain the net at the

surface to avoid the chance of hitting the pond bottom.

Epibenthic species were collected using a beam trawl, with mouth 500 mm wide and 300 mm high, 1400 mm in length, constructed of 1-mm mesh size. A small metal tickler chain (2-cm links) was suspended across the front of the net. The opening at the rear of the net was approximately 100 mm across and a canvas collar was folded and tied with cord.

Pond water temperature, pH, dissolved oxygen and salinity were all measured twice daily (dawn and dusk) using a TPS data logger (model 90 FL). Secchi disc readings were taken at the same time as the other parameters were measured.

Sampling design

Zooplankton samples were collected on three consecutive nights every fortnight throughout the growing season, within 4 days of a full or new moon, from when the pond was filled in September 1996 until it was emptied in July 1997. This period included two sampling occasions before the ponds were stocked with *P. japonicus* postlarvae. Three replicate plankton samples were collected on each night. The samples were collected from the same site along the edge of the pond, over a distance of 53 m, between two jetties.

Beam trawl samples were not collected along the same path as the plankton tows because power lines to the paddlewheels ran across that route. An alternative towing path was used, covering a distance of 44 m across the corner of the pond. The beam trawl collected large numbers of the *P. japonicus* when towed, these were returned to the water live. To minimise disturbance to the commercial crop, beam trawl samples were only undertaken on the first and last night of each sampling occasion. Samples were collected in triplicate each night. Beam trawls were only collected once prior to stocking. Because of potential damage to young postlarvae, beam trawls were not taken on the first sampling occasion after the pond was stocked.

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. One half was then divided further

into two size fractions; 90–300 μm , and $> 300 \mu\text{m}$, using nylon mesh screens. Each size fraction was rinsed with fresh water and dried at 60°C to determine biomass. Samples were treated this way so that some animals could be used later for stable isotope analysis. The remaining half of the sample, used for determining species composition, was preserved in 70% ethanol. The preserved sample was split using the Folsom plankton splitter, so that between 500 and 1500 zooplankters remained in the sub sample to be sorted under a dissecting microscope. Specimens were identified to the lowest practicable taxonomic level to allow completion of sorting the samples in a reasonable period (typically 3 h).

We examined the size structure and sex ratio of *Acetes* captured from the beam trawls only. Time did not permit us to do this for *Acetes* captured in the surface tows.

All *Acetes* from the beam trawls were counted, measured (occipital carapace length), weighed and sexed (it was not possible to sex individuals below 3 mm carapace length). Other crustaceans, including incidental shrimp species, such as *Metapenaeus bennettiae* and *P. esculentus*, were counted and measured, all other species encountered in the beam trawls were counted.

Data analysis

Relationships between biological and environmental variables were initially examined individually with linear regressions. Backward, stepwise multiple regressions were then used to study the relationships between the biological variables and environmental variables. In this process all the environmental variables were included in the initial regression. Variables that did not contribute to significant variation were removed prior to running the next regression. Variations in the abundance of *Acetes* throughout the season, and between the sexes were investigated with ANOVA.

Temporal changes in the composition of the zooplankton and epibenthic fauna assemblages were investigated using multivariate methods from the PRIMER statistical package (Carr 1996). Patterns of similarity are displayed using nonmetric multidimensional scaling (MDS), and the contribution of different taxa were analysed using the SIMPER routine. For multivariate analyses, raw counts were transformed using $x^{0.25}$ to emphasize the distribution of less

common species in the analysis, and the Bray–Curtis similarity coefficient was used throughout.

We also examined the effects of pond water exchange on the abundance of zooplankton and the effects of moon phase on the abundance of zooplankton and epibenthic fauna. The effects of water exchange were examined by comparing the volume of water exchanged between two sampling days in each fortnight and the change in numbers of zooplankton for those 2 days. Volumes were calculated from farm records of the depth of water removed from the pond at each exchange.

The sampling strategy was not designed to investigate rigorously the effect of moon phase, which would require sampling each stage of the moon at all times of the season. However, to detect if there was extreme effect of moon on the pond biota, the moon phase at each sampling fortnight was plotted as an average moon phase index, where 0 represented a new moon and 1 represented a full moon. The index did not take into account whether the moon was waning or waxing.

Results

Environmental characteristics

The weekly average water temperature rose from 22°C at the beginning of the season (October), to a peak of 29°C in February and declined to 15°C in July (Fig. 1a). Dissolved oxygen values ranged from 5.5 to 8.1 mg L⁻¹, the minimum values coincided with the warmest pond temperatures. The fortnightly averages for pH were between 7.7 and 8.6 for most of the season, with a single low of 6.6 that coincided with a period of heavy rain. Salinity ranged from 32 to 36.8 g L⁻¹.

Secchi disc values ranged from 0.33 to 0.77 m during most of the grow-out period but increased rapidly to 1.5 m at the end of the season, when large amounts of water were being exchanged for drain harvests, as a result of the incoming water containing fewer algae than were present in the pond (Fig. 1b).

Zooplankton densities

Zooplankton were most abundant prior to stocking the ponds with postlarvae (Fig. 2a). Following the introduction of postlarvae, zooplankton numbers declined from 111.7 ind. L⁻¹ to 8.3 ind. L⁻¹ (Fig. 2a).

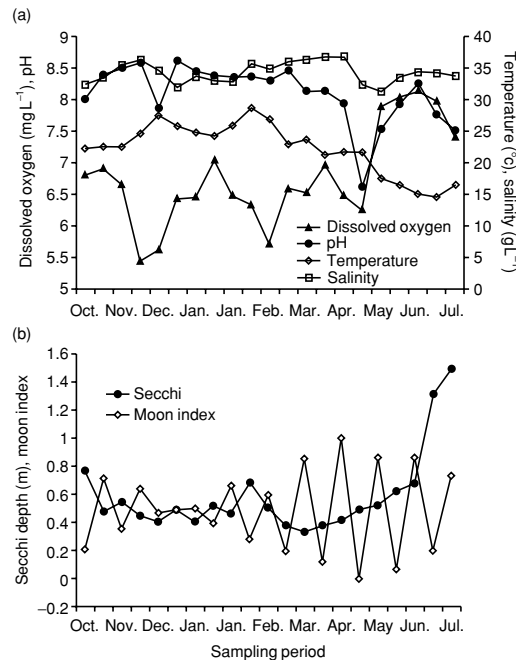


Figure 1 Plots of variation in physical and biological parameters over time across the grow-out season. (a) Fortnightly averages of physical parameters measured at dawn and dusk: [dissolved oxygen (mg L⁻¹), pH, temperature (°C) and salinity (g L⁻¹)]. (b) Fortnightly average of Secchi disc reading (m) and moon index. Note that owing to timing of sampling over January there were three sampling occasions in this month.

From then until the end of the season numbers varied between 9.7 and 61.3 ind. L⁻¹ (Fig. 2a). Analysis of each of the abiotic variables revealed that none of these, either alone or in combination, were significantly related to zooplankton density (Table 1).

Zooplankton biomass

The biomass of the zooplankton generally matched the pattern of abundance. The maximum biomass (324 µg L⁻¹) was prior to stocking. Following the introduction of postlarvae the biomass declined 44.2 µg L⁻¹. From then, until the end of the season, biomass varied between 30.1 and 154.3 µg L⁻¹.

The large fraction of zooplankton (> 300 µm) dominated the biomass in the first two sampling periods (Fig. 2b). From then on relative contributions of the 90–300 µm and the > 300 µm fractions varied, although in the period from March to May the smaller fraction (90–300 µm) contributed more to the overall biomass. As was found for

Table 1 Proportion of variation explained by regressions (i.e. r^2 values) between biological parameters and physicochemical properties of the pond water

Variable	Single factor regressions					Multiple backward stepwise regressions
	Temp.	Salinity	DO	pH	Secchi	Overall
Zooplankton abundance	0.03	-0.13	-0.02	0.01	-0.01	0.20
Zooplankton biomass	-0.01	-0.02	0.01	-0.01	-0.01	0.08
Epibenthos abundance	<i>-0.64***</i>	-0.10	0.46***	<i>-0.45***</i>	0.44***	0.81***
Epibenthos abundance without amphipods	0.04	0.00	-0.01	0.01	0.00	0.12
Amphipod only abundance	<i>-0.68***</i>	-0.10	0.48***	<i>-0.47***</i>	<i>0.45***</i>	0.85***
Epibenthos biomass	0.02	0.02	-0.02	0.00	0.00	0.07
<i>Acetes</i> beam trawl sample abundance	0.02	0.00	0.00	0.00	-0.00	0.25
<i>Acetes</i> surface tow sample abundance	0.16*	<i>0.02</i>	<i>0.16*</i>	-0.13	-0.03	0.67***

Significance of regressions: * $0.05 < P \leq 0.10$; *** $P = 0.001$. *Italics* indicates physicochemical properties retained after multiple backward stepwise regression.

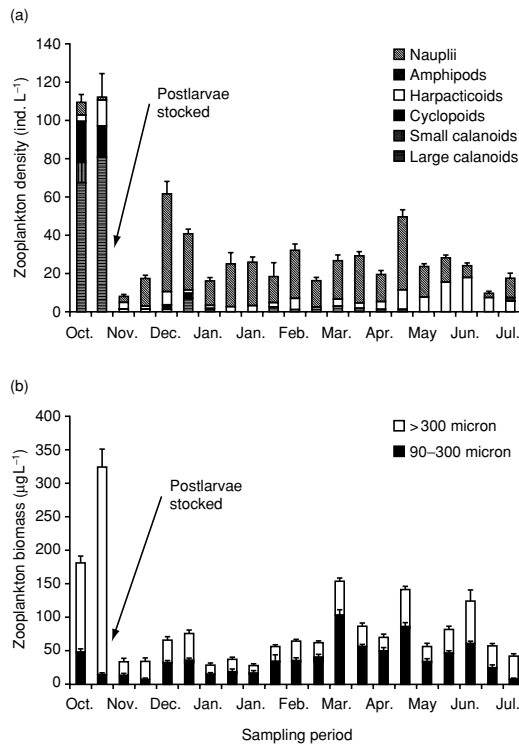


Figure 2 Characteristics of the zooplankton assemblage across the season. (a) Total zooplankton density (zooplankters L^{-1} + SE). Note that only most common taxa are presented; SE for total abundance of all taxa combined. (b) Zooplankton biomass for $> 300 \mu m$ and $90-300 \mu m$ size fractions (μg dry weight L^{-1} + SE).

zooplankton abundance, none of the abiotic variables, either alone or in combination, were significantly related to zooplankton biomass (Table 1).

Zooplankton taxa

Thirty-five taxa were identified through the season, most of which were rare (Table 2). The dominant taxa were copepods and barnacle nauplii. Large calanoid copepods, including *Acartia* spp. and *Pseudodiaptomus* spp., were very abundant in the first two sampling periods, but throughout the rest of the season were present in much smaller numbers. Barnacle nauplii were common from late November onwards. From early December until late May barnacle nauplii were the dominant zooplankton. From May until the end of the season harpacticoid copepods were dominant. On the last sampling occasion, amphipods, which had been rare throughout the rest of the season, were common (Fig. 2a).

Temporal variation in the structure of the zooplankton assemblages

Pattern analysis revealed that the zooplankton assemblages captured during the first two sampling periods were distinctly different from those collected on all other sampling occasions (Fig. 3a). The samples collected during the third sampling period were distinct from all other sampling occasions. From

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

Taxa	% by numbers	% frequency of occurrence
Crustacea		
Cirripedia		
Barnacle nauplii	50.3	100
Barnacle cyprid (sp. 1)	< 0.1	30.7
Barnacle cyprid (sp. 2)	< 0.1	20.1
Barnacle eggs	< 0.1	3.7
Copepoda		
Harpacticoids	17.0	100
<i>Acartia</i> spp. (large)	11.6	93.1
<i>Pseudodiaptomus</i> spp.	7.8	92.6
Calanoids (small unid.)	4.5	85.7
Cyclopoids	6.2	76.7
<i>Acartia</i> spp. (small)	1.9	64.6
calanoids (large unid.)	< 0.1	23.8
Decapoda		
Crab zoea	0.1	57.1
Penaeid zoea	< 0.1	14.3
<i>Acetes sibogae</i>	< 0.1	8.5
<i>Lucifer hansenii</i>	< 0.1	6.4
Carid larvae	< 0.1	4.2
Crab megalopa	< 0.1	3.7
<i>Acetes</i> zoea	< 0.1	1.6
Penaeid postlarvae	< 0.1	1.1
<i>Metapenaeus</i> spp. juvenile	< 0.1	0.5
<i>Acetes</i> postlarvae	< 0.1	0.5
Pericardia		
Amphipods	0.5	56.6
Isopods	< 0.1	1.1
Cumaceans	< 0.1	0.5
Branchiopoda		
<i>Artemia salina</i>	< 0.1	3.2
Ostracoda		
Ostracods	< 0.1	2.7
Gastropoda		
Gastropod (sp.1)	< 0.1	30.7
Gastropod (sp.2)	< 0.1	0.5
Chaetognatha		
Chaetognaths	< 0.1	10.1
Insecta		
Chironomid larvae	< 0.1	9.5
Fishes		
Fish larvae (unid.)	< 0.1	3.7
Annelida		
Polychaete adults	< 0.1	1.6
Polychaete larvae	< 0.1	1.1
Chelicerates		
Terrestrial mite	< 0.1	1.1
Aschelminthes		
Nematodes	< 0.1	0.5

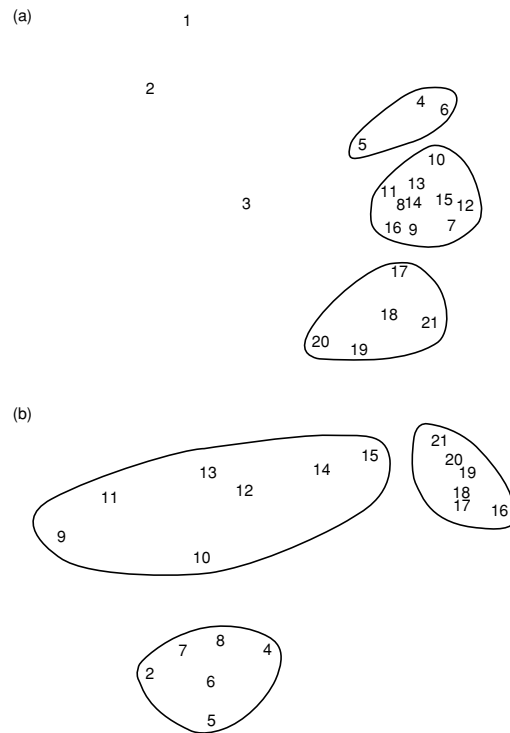


Figure 3 Two-dimensional MDS plot of species composition of samples, labelled to show fortnight in which samples were collected. (a) Zooplankton samples (stress=0.11). (b) Beam trawl samples (stress=0.09). Note that no beam trawl samples were collected in fortnights 1 and 3.

then on there was a distinguishable temporal pattern in the groupings of the zooplankton assemblages.

The zooplankton assemblages collected from the 4th, 5th and 6th sampling periods formed a distinguishable group. Likewise, the zooplankton assemblages captured from the pond during the 7th to the 16th sampling were distinguishable from those captured on earlier or later occasions. The remaining five sampling occasions contained zooplankton assemblages that formed their own distinct group. SIMPER analysis of the relative contributions of different taxa revealed large *Acartia*, cyclopoids and *Pseudodiaptomus* contributed the highest percentage to the pairwise differences between groups of samples. These taxa were most abundant early in the season. Among the other taxa, barnacle nauplii, gastropods and harpacticoid copepods were also important contributors to the differences between groups. The nauplii were most abundant mid season, and harpacticoids at the end of the season. Gastropods were never common, but were more abundant after the early season samples.

Epibenthic fauna density

The abundance of epibenthic fauna increased from early season lows of less than 0.5 ind. m⁻² to highs of 14 ind. m⁻² by the end of the season (Fig. 4a). Density remained below 4.5 ind. m⁻² until May, then increased rapidly as a result of appearance of large numbers of amphipods (see below). Regression analysis revealed positive relationships between epibenthos density and dissolved oxygen and Secchi disc readings, but negative relationships with temperature and pH (Table 1). Stepwise regression

showed that temperature and pH were the best combination of predictors of benthic faunal density. Secchi disc reading was significant, but only at the 0.057 level.

Because of the potential of the high abundance of amphipods to mask patterns among the other taxa, we re-examined the data for amphipods alone. Regression analysis demonstrated the same relationship between the abiotic variables and amphipod density as for total epibenthic fauna density (Table 1). However, when amphipods were removed from the data, no significant effects on the density of

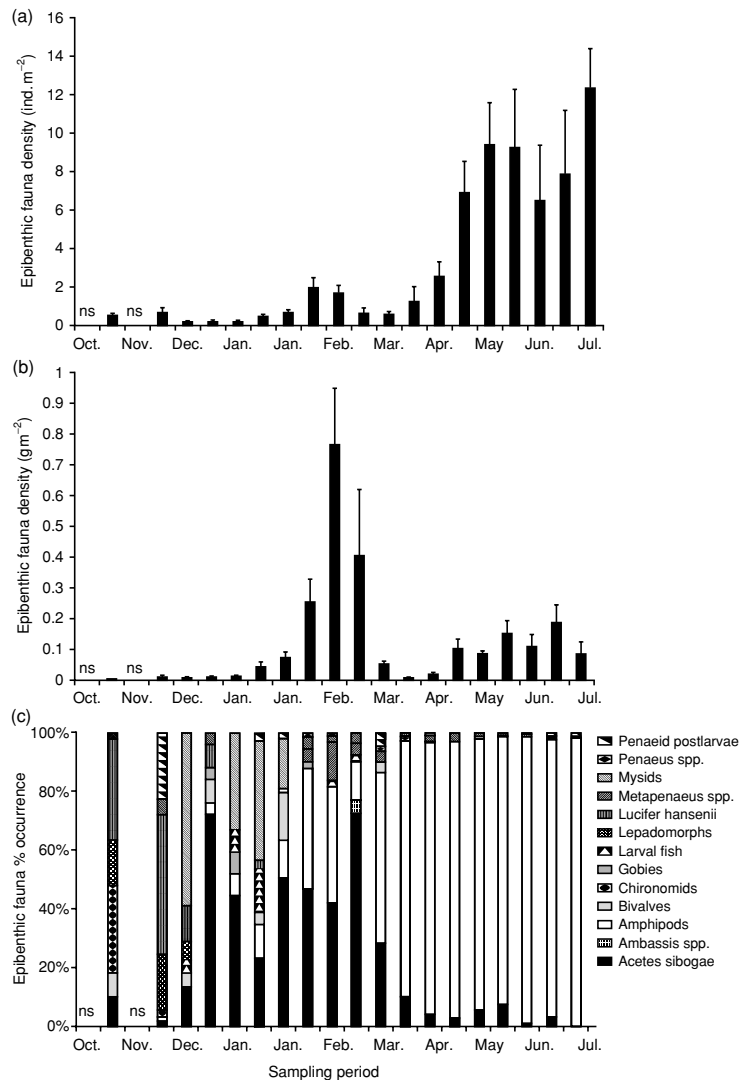


Figure 4 Characteristics of the epibenthic fauna assemblage across the season. (a) Total epibenthic fauna density (ind. m⁻² + SE). (b) Epibenthic fauna biomass (g dry weight m⁻² + SE). (c) Per cent occurrence of most common epibenthic taxa. ns = no samples taken.

the other epibenthic fauna were attributable to any of the abiotic variables, singularly or in combination (Table 1).

Epibenthic fauna biomass

The dominant peak in the biomass of epibenthic fauna ($> 0.8 \text{ g m}^{-2}$) occurred mid-season, in February and March (Fig. 4b). This was due to the presence of low numbers of large animals, especially adult shrimp (*Metapenaeus* spp.) and small fish, principally perchlets (ambassidae) and silver bellies (*Gerres* spp.) The appearance of large numbers of amphipods in the beam trawl catch from May onwards was reflected in a small peak in biomass ($< 0.2 \text{ g m}^{-2}$). None of the abiotic variables were significantly related to epibenthic faunal biomass (Table 1), nor were any combination of these variables able to explain a significant amount of variation in epibenthic faunal biomass (Table 1).

Epibenthic taxa

Thirty-two taxa were caught in the beam trawls (Table 3). Amphipods and *Acetes sibogae australis* were the dominant taxa, none of the other taxa contributed more than 2% of the overall abundance. At the beginning of the season several taxa were equally represented in beam trawls; however, by the end of the season amphipods dominated the assemblage (Fig. 4c). Amphipods were generally associated with algal clumps collected from the pond by the beam trawl. In individual trawls, when the algae was collected, amphipod densities were as high as 22 ind. m^{-2} (average for sampling period 1.2 ind. m^{-2}).

Temporal variation in the structure of the epibenthic faunal assemblages

Pattern analysis revealed a temporal progression of assemblages, with three discernible grouping corresponding to early, middle and late samples. The samples from the second and fourth to the eighth sampling periods formed the first distinguishable group (Fig. 3b). The second group corresponded to the middle group of samples, collected during the ninth to 15th sampling periods. The remaining samples formed the third, distinguishable group. SIMPER analysis showed that amphipods and *Metapenaeus* were the main contributors to differences

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

Taxa	% by numbers	% frequency of occurrence
Crustaceans		
Pericardia		
Amphipods	85.1	25.8
Mysids	2.0	25.8
Decapoda		
<i>Acetes sibogae</i>	7.7	31.5
<i>Metapenaeus</i> spp. (juv.)	0.8	13.7
Penaeid postlarvae	0.7	11.3
<i>Lucifer hansenii</i>	0.8	8.1
Penaeid juveniles	0.2	6.5
<i>Penaeus plebejus</i>	0.1	3.2
Carids	< 0.1	1.6
Crab megalopa	< 0.1	1.6
<i>Penaeus esculentus</i>	< 0.1	0.8
Carid larvae	< 0.1	0.8
<i>Portunus pelagicus</i>	< 0.1	0.8
Crab sp. 1	< 0.1	0.8
Cirripedia		
Lepadomorph barnacles	0.3	4.0
Balanomorph barnacles	< 0.1	0.8
Fish		
Fish larvae	0.4	13.7
Ambassidae	0.1	4.0
Fish (unid.)*	0.1	4.0
<i>Gerres</i> sp.	0.2	2.4
Gobiidae (sp. 1)	< 0.1	2.4
Gobiidae (sp. 2)	< 0.1	1.6
<i>Therapon jarbua</i>	< 0.1	0.8
<i>Platycephalus</i> sp.	< 0.1	0.8
Bivalves		
Bivalves	0.4	1.7
Insects		
Chironomid larvae	0.4	4.9
Mosquito larvae	< 0.1	1.6
Gastropoda		
Gastropod (sp. 3)	0.1	3.2
Annelida		
Polychaetes	< 0.1	2.4
Aschelminthes		
Nematodes	< 0.1	1.6
Chaetognatha		
Chaetognaths	< 0.1	0.8

*Not identified due to damage.

between groups of samples. Among the other taxa, *Lucifer hansenii*, *Acetes sibogae* and bivalves were also important contributors to differences between samples. *Lucifer* were only present in early samples.

Bivalves and *Metapenaeus* were most common in middle samples, however, bivalves were also present in early season samples, whereas *Metapenaeus* were present in late samples. *Acetes* were present throughout the season, but were most common in middle and late samples. The late-season samples were dominated by amphipods, but these were also present in mid-season samples.

Acetes sibogae population dynamics

Over the season, a total of 681 *A. sibogae* were collected in the beam trawls and a further 457 were captured in the surface net tows (Fig. 5). The pattern of the density of *A. sibogae* caught in the beam trawls and surface tows was different, with peaks in the beam trawl samples occurring earlier in the season than the surface tows. Beam trawl catches peaked between late January and early March, when densities were as high as 0.92 m⁻², and again in late May and early June, when density reached 0.64 m⁻². Throughout the remainder of the season, numbers of *A. sibogae* were less than 0.4 m⁻². Surface tow catch rates were highest from March to early June, with numbers ranging from 0.9 to 2.6 m⁻³. The numbers of *A. sibogae* captured in beam trawls or in surface tows were not significantly related to any of the single abiotic variables in the pond (Table 1). However, stepwise regression revealed positive relationships between the number of *A. sibogae* captured in surface tows and salinity and dissolved oxygen, and negative relationships with pH and secchi readings. In contrast to this, there were no significant results for *A. sibogae* captured in the beam trawls (Table 1).

There was no significant relationship between variation in the numbers of *A. sibogae* captured in

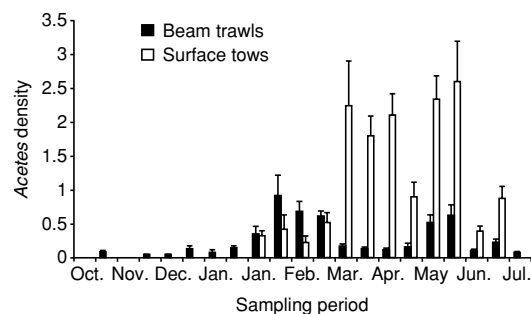


Figure 5 Average number of *Acetes* captured in beam trawls (ind. m⁻²) and surface zooplankton tows (ind. m⁻³) each fortnight.

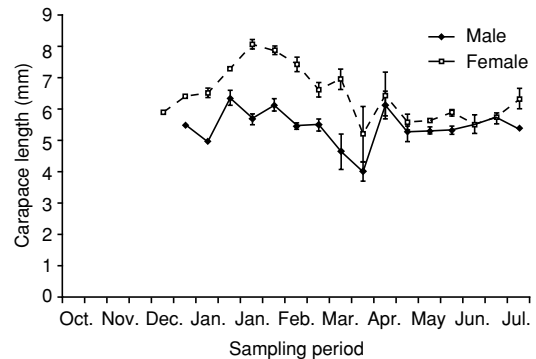


Figure 6 Average carapace length (mm + SE) of male and female *Acetes* from beam trawl tows for each fortnight. Animals too small to be sexed were not included in this plot.

either beam trawl or surface net tows and variation in zooplankton densities or biomass (all r² values < 0.08).

The *A. sibogae* captured with the beam trawl varied in carapace length from 1.8 mm to 10.5 mm. There was significant variation in average carapace length between sampling occasions (ANOVA: d.f. 16 546, P < 0.0001), but there were no consistent trends of increasing or decreasing size throughout the sampling period (Fig. 6). Among the individuals that could be sexed, there was no significant difference in sex ratio (1:1, χ² = 1.0558, P > 0.25). Females were on average larger than males (ANOVA: d.f. 1546, P < 0.0001). Only three females with ovary development were encountered and very few larvae (< 150) were captured in the zooplankton samples.

Water exchange and moon phase

There was no significant relationship between the volume of water exchanged and the change in zooplankton density prior to and after the exchange (r² = 0.02). Likewise moon phase was not significantly related to the catchability of zooplankton, epibenthic fauna or *A. sibogae* (all r² values < 0.04).

Discussion

Zooplankton density and diversity

Prior to stocking with postlarvae, the shrimp farm pond supported a high abundance and biomass of zooplankton. In the *P. japonicus* pond that we

examined, the prestocking zooplankton abundance was $>110 \text{ org. L}^{-1}$. Similar values have been recorded for the prestocking biomass of zooplankton in *P. monodon* ponds in Australia (Preston *et al.* 2003). Zooplankton abundance in *P. monodon* ponds in Taiwan varied from 1–15 org. L^{-1} at the beginning of a season to 0.2–3.4 org. L^{-1} 4 weeks later (Chen & Chen 1992). In this study, 300- μm mesh was used, which would allow some of the smaller zooplankton species to escape, thus accounting for the slightly lower numbers recorded. In *P. vannamei* ponds the abundance of zooplankton collected using a 100- μm mesh was always greater than 100 org. L^{-1} , reaching a maximum abundance of over 5000 org. L^{-1} (Martinez-Cordova *et al.* 1998a). Zooplankton numbers in *P. californiensis* ponds varied from 250 org. L^{-1} –380 org. L^{-1} depending on aeration treatment; 60- μm mesh was used in this study and may account for the slightly elevated numbers (Martinez-Cordova, Porchas-Cornejo, Villarreal-Colmenares & Calderon-Perez 1998b).

The results of our study support previous observations that pond zooplankton are suitable prey for shrimp postlarvae. There was a rapid decline in zooplankton numbers and biomass immediately after *P. japonicus* postlarvae were stocked, and zooplankton abundance remained relatively low for the rest of the season. This pattern is consistent with the results obtained in *P. monodon* ponds in Taiwan (Chen & Chen 1992) and Australia (Preston *et al.* 2003) and in *P. vannamei* ponds in Mexico (Martinez-Cordova *et al.* 1998a).

Little is known about changes in pond zooplankton assemblages due to predation by shrimp postlarvae. Laboratory studies have shown that juvenile *P. monodon* held in small containers (1-L and 500-mL beakers) are capable of capturing and ingesting copepods, including *Oithona*, *Acartia* and *Pseudodiaptomus* (Chen & Chen 1992). These authors also suggested that that juvenile *P. monodon* preferred larger copepods. In the *P. japonicus* pond that we examined, the prestocking assemblage was dominated by large calanoid including *Acartia* and *Pseudodiaptomus*. When *P. japonicus* postlarvae were introduced there was a rapid decline in these relatively large copepod species ($>300 \mu\text{m}$), indicating their suitability as prey. For the rest of the season the zooplankton assemblage was dominated by smaller species (90–300 μm), principally barnacle nauplii. Whether size preferences or the relative ability of postlarvae, juvenile and adult shrimp to capture

different-sized zooplankton are important determinants of the composition of these zooplankton assemblages is yet to be established. Several benthic taxa such as chironomid larvae, isopods and adult gastropods and polychaetes were captured in the surface plankton tows. This is probably a reflection of the shallowness of the pond, but may also be an indication of predation avoidance by these animals.

Previous studies of shrimp pond zooplankton have shown that the composition of prestocking assemblages is unpredictable (Preston *et al.* 2003). During the production season farm managers regularly exchange water. However, we found no significant relationship between the volume of water exchanged and the change in zooplankton density. Likewise, there was no evidence of pronounced changes in species composition in relation to water exchange. After the first two sampling periods, the total zooplankton abundance was mainly influenced by the abundance of barnacle nauplii. Barnacle nauplii are generally short lived, metamorphosing to cyprids between 1 and 2 weeks after spawning (e.g. Lang & Marcy 1982). The continuously high relative abundance of nauplii must have been maintained by steady recruitment. There are two likely sources of recruitment, ingress during water during exchanges or reproduction by adult barnacles that have settled on structures within the pond. Early in the season, prior to any settlement of barnacles in the pond, recruitment must have been via the inlet water. Later in the season recruitment from within the pond may also have occurred. We have yet to determine the relative contributions of these sources of recruitment.

Variation in the abundance and composition of pond zooplankton assemblages is likely to be influenced by variations in the abundance and type of food items. Martinez-Cordova *et al.* (1998a) considered that zooplankton abundance in *P. vannamei* ponds was partially related to chlorophyll *a* concentration. However, zooplankton numbers in *P. monodon* ponds in Australia (Preston *et al.* 2003) could not be linked to chlorophyll *a* concentrations. Chlorophyll *a* concentrations were highly variable, with no observable seasonal trend (Burford 1997). Although we did not measure chlorophyll *a* in the *P. japonicus* pond we did measure Secchi depth. Secchi depth gives some indication of algal biomass, but we found no correlation between Secchi depth and zooplankton abundance. In addition to phytoplankton, detritus, including that derived from shrimp feeds, may provide a source of nutrients

for zooplankton. Among the zooplankton in the *P. japonicus* ponds, harpacticoids increased in abundance towards the end of the grow-out season, influencing the zooplankton community structure. Although yet to be determined, these detritivores may be capable of exploiting pelleted feeds.

Declines in abundances of zooplankton towards the end of the season may also be linked to deteriorating pond water quality. Although water nutrients were not measured in this study, it has been established that ammonia levels in shrimp ponds increase to $>0.4 \text{ mg L}^{-1}$ at the end of a grow-out season (Burford 1997). Ammonia levels of $<0.2 \text{ mg L}^{-1}$ have been shown to have negative impacts on several *Acartia* species (Sullivan & Ritacco 1985; Buttino 1994). The impact of ammonia and other water quality parameters on zooplankton in shrimp ponds has not been established and could be investigated further.

Epibenthic fauna density and diversity

Apart from amphipods and *A. sibogae*, epibenthic fauna was rare in the *P. japonicus* pond, beam trawl samples. Small taxa such as *Lucifer hansenii* and chironomids were present only at the beginning of the season, and it is likely that these were suitable prey for juvenile *P. japonicus* (e.g. Round 1999). Likewise, many of the other biota that were occasionally caught, including mysids, gastropods, fish and polychaetes, are known to be preyed upon by farmed shrimp (e.g. Maguire *et al.* 1984; Nunes & Parsons 2000). *Metapenaeus* species were most abundant in the middle sampling period, but numbers declined towards the end of the season. These were the largest of the taxa caught by the beam trawls, apart from the *P. japonicus*, and their decline in abundance may be linked to predation on them by larger *P. japonicus* towards the end of the season.

The amphipods did not appear until late in the grow-out season and were associated with the appearance clumps of unidentified macroalgae. Although adult penaeids are known to predate on amphipods (e.g. Wassenberg & Hill 1993), their numbers continued to increase until the end of the season. Regression showed that temperature, dissolved oxygen, pH and Secchi disc readings were correlated with amphipod abundance. This may have reflected the suitability of water quality conditions for the growth of macroalgae, thus providing food and shelter for the amphipods.

The fauna captured by the beam trawl are larger than those caught by plankton net and are not likely to complete life cycles within a grow-out season. Recruitment of these species is therefore likely to be limited to introduction via water exchanges, and occurrence within the pond will be strongly affected by occurrence in the water supply for the ponds. The diets of the taxa caught by the beam trawls has not been described, but it is possible many of these taxa may be able to utilise the formulated feeds fed to the shrimp. Although it has not been established, food availability may not strongly influence abundance of epibenthic fauna.

Populations of *Acetes*

The pattern of abundance for adult *A. sibogae* collected in the benthic samples was not reflected in the surface samples. The *A. sibogae* were more prevalent in the surface samples towards the end of the season. It is possible that this is caused by the *A. sibogae* moving into the water column to avoid predation as the shrimp grow larger. Earlier in the season the shrimp are probably not large enough to predate on the adult *A. sibogae*.

The variation in the abundance of *A. sibogae* from beam trawl samples did not appear to be correlated to any of the physical factors measured. Although their abundance in surface tows was linked to some physical parameters, it is possible that biological interactions mentioned above may be more important in influencing their distribution within the water column. Adult *Acetes* are found in estuaries, and are able to survive in a range of salinities and turbidities (Xiao 1991). Dissolved oxygen and pH are linked to these physical characteristics, as well as water temperature. The temperature in the shrimp ponds over most of the grow-out season probably does not fall outside the critical range for *A. sibogae*, so that the physical conditions over the sampling period were probably favourable most of the time and did not directly affect the abundance of *Acetes*.

Changes in zooplankton abundance did not appear to significantly affect the abundance of *A. sibogae*. Although zooplankton, such as copepods and crustacean and molluscan larvae, are known to be a significant part of the diet for many species of *Acetes*, they also consume phytoplankton and organic debris (Xiao & Greenwood 1993). It has not yet been observed that *Acetes* will directly take shrimp pellets, but it seems likely that they would

feed on the debris if little else was available. *Acetes* are non-selective omnivores (Xiao & Greenwood 1993), and are likely to survive well in an environment providing that at least one of these food supplies is available.

Adult and juvenile *A. sibogae* were captured from the pond throughout the entire season. This suggests either continual recruitment into the pond throughout the season or reproduction within the pond. If the animals originated from a single introduction it might be expected that the mean size of individuals in the population would increase steadily across the season. There was no evidence of this, although it is possible smaller animals present throughout the season were the result of reproduction within the pond. Very few larval stages of *A. sibogae* were captured from the pond, and throughout the sampling period only three ovigerous females were captured. Together this would suggest that there was only minimal reproduction occurring within the pond and it appears probable that *A. sibogae* were recruited into the pond over the whole season.

Water exchange and moon phase

There was no correlation detected between water exchange and change in abundance of zooplankton or epibenthos in the pond. However, the sampling strategy was not designed to specifically investigate this, and it is possible that, although a relationship was not detected, exchanges may play an important role in determining the abundance of some taxa in shrimp ponds. This warrants further investigation. The phase of the moon does not appear to influence greatly abundance of shrimp pond fauna. This is possibly a result of the shallowness of the pond, and also the inability of larger taxa, such as *Acetes*, to move to other environments, as might happen in an open water environment.

Overall, changes in zooplankton assemblages were most notably affected by the stocking of post-larvae and abundance of barnacle nauplii, whereas epibenthos assemblages were most affected by amphipod abundance. Zooplankton appear to play an important role in the nutrition of shrimp post-larvae immediately after stocking. The establishment of an abundant bloom of zooplankton prior to stocking shrimp postlarvae would appear to be beneficial, if not essential. The results of our study indicate that *P. japonicus* postlarvae consumed a

wide variety of zooplankton, including both large and small copepod species. Later in the season, the relatively low dry weight biomass of zooplankton (1.5 kg ha^{-1}) compared with the dry weight biomass of shrimp (up to 1000 kg ha^{-1}) suggests that zooplankton contributed little to shrimp biomass. Zooplankton may have other nutritional roles, such as providing shrimp growth factors (Moss, Pruder, Leber & Wyban 1992), but this has yet to be determined. Our estimate of late-season biomass of epibenthic species (2.0 kg ha^{-1}) also indicates a minor contribution to shrimp biomass. Likewise, their consumption of pelleted shrimp feeds would appear to be insignificant compared with that of the shrimp. More detailed studies are needed to further elucidate the precise trophic roles of zooplankton and epibenthos in shrimp ponds.

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