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Seasonal and spatial distribution of mesozooplankton in a tropical estuary, Nha Phu, South Central Viet Nam

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Abstract: This study provides a description of mesozooplankton (holo- and meroplankton) abundance, biomass and diversity patterns inside and outside a tropical estuary (Nha Phu Estuary, Khanh Hoa, Viet Nam). In total 185 zooplankton species have been recorded during the study period (2009–2010), copepods contribute with the largest share of species (more than 100), Tunicata with 20, Cnidaria with 17 and Chaetognatha with 9 species. At the most species rich site the number of zooplankton species varies between 55 and 123. The number of species and the annual variation in numbers declines towards the head of the estuary (14–37 species). In contrast, the highest numbers of individuals occur in the inner part of NPE. Calanoids that are the most abundant group of the copepods occur in densities up to 28.2 ind. L^{-1} (Aug. 9). At 'Outer NPE' and 'Outside NPE' the maximum density of calanoids is 5.8 and 10.7 ind. L^{-1}, respectively. The declining diversity of zooplankton towards the head of the estuary is also supported by various indices (Shannon's index, Margalef's index). A cluster analysis on similarity of species supports a clustering of the inner NPE sites vs the other sites. There is a general separation between the dominant copepod species in the inner (*Bestiola* sp., *Acartia pacifica*, *Pseudodiaptomus incisus*) and outer (*Paracalanus gracilis*, *Acrocalanus gibber, Subeucalanus subcrassus, Oithona rigida, Corycaeus andrewsi, Oithona plumifera)* part of the estuary though a few species are common in both areas (*Paracalanus crassirostris* and *Euterpina acutifrons*). The zooplankton community at the inner NPE is subjected to more variable hydrographic conditions (salinity in particular) than the communities at the other sites where more stable conditions prevail. A short residence time in the inner part of the estuary due to the tide is supposed to impede a strong horizontal structuring of the zooplankton community.

Key words: abundance; biomass; mesozooplankton; tropical ria; Nha Phu Estuary

Introduction

The growing need for aquatic resources to supply increasing human populations in many tropical countries have exposed near coastal ecosystems to a multitude of antropogenic factors with possible detrimental effect on their ecosystem services. Substitution of mangrove forests by shrimp and fish ponds, increased discharges of waste water and overexploitation of aquatic resources are threatening tropical ecosystems worldwide (Alongi 2002; Nagelkerken 2009).

To achieve an understanding of the functioning of such human impacted estuaries we have explored a Vietnamese system exposed to a range of antropogenic factors during the recent past. Until mid-1980's the head part of the estuary was covered by a mangrove forest, but it was deforested in the period from 1988–1999 and gradually substituted by shrimp ponds (unpublished data). The head part of the estuary is heavily exploited by local fishermen and it is also used for various aquaculture activities (Strehlow 2006).

As part of a series of ecological and hydrographic studies in our target estuary, our present issue is to report about the zooplankton and to explore if the zooplankton exhibit spatial and temporal patterns related to the major environmental factors. The basic condition in many tropical estuaries is the combination of varying freshwater discharges (wet and dry season) and high water temperatures. Salinity fluctuation is pronounced during the wet season due to the high frequency of intensive rainfall events. With freshwater discharges to the estuary there will also be supplies of nutrients that may boost primary production. As a consequence food for phytoplankton feeding zooplankters will vary seasonally related to the wet and dry seasons. Irregularities in rainfall, eutrophication, seston input from rivers and outlets from fish and shrimp cultures can all potentially impact the zooplankton community through their impact on primary producers and other food chain components. Knowing that organisms may respond in a species specific manner on environmental conditions it is difficult to predict how the zooplank-

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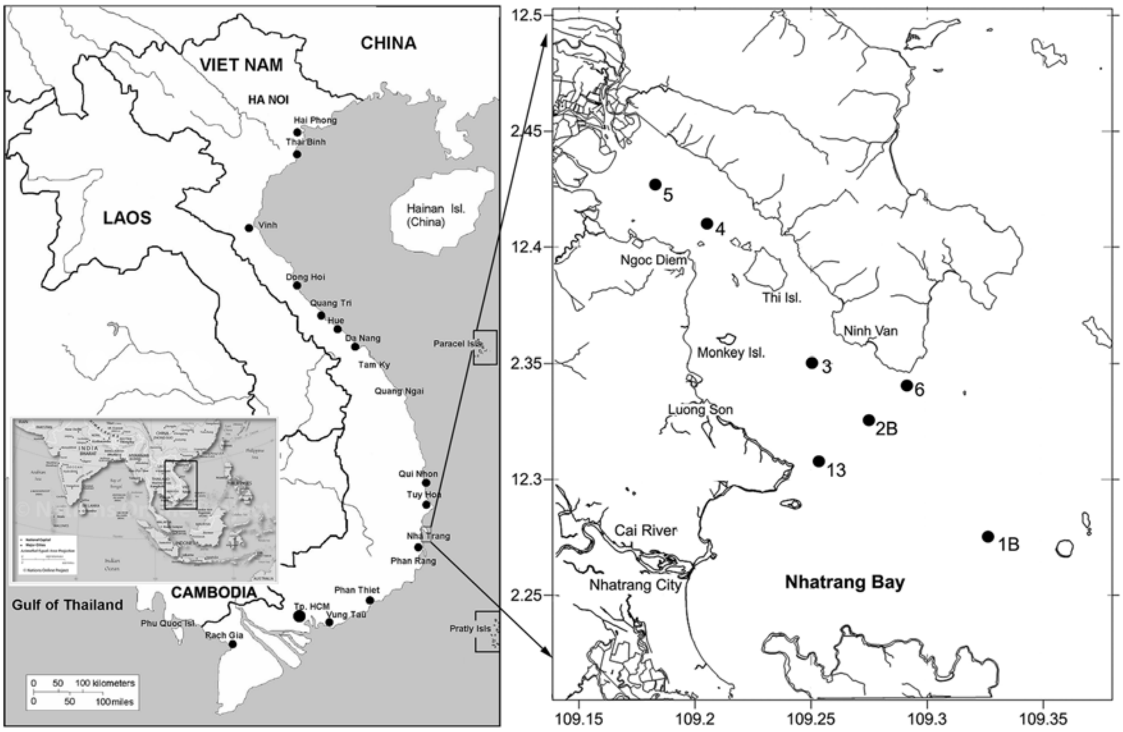

Fig. 1. Map of Nha Phu Estuary. The numbers refer to sites sampled in 2009–2010.

ton community will respond on the complex of factors present.

Our study system is a small estuary Nha Phu Estuary (NPE) in Khanh Hoa province in Viet Nam. The present report is part of the ecosystem study program ‘Climate change and estuarine ecosystem in Viet Nam’ carried out from 2009–2011 and founded by Ministry of Foreign Affairs of Denmark Danida.

Material and methods

Study site

Nha Phu Estuary is situated in the northern central part of Khanh Hoa, Viet Nam (12°22.8′ N; 109°13.7′ E). The estuary has a surface area of 105 km^2 of which about half (49 km^2) of the area is shallow water (< 2 m) (Lund-Hansen et al. 2010). The total volume is 0.66 km^3 at mean tide. The drainage area of the two rivers entering the estuary is about 1200 km^2 with a high (1300 mm) precipitation in the rainy season (September – December) and a lower (340 mm) in the dry season (Lund-Hansen et al. 2010). The tide in the Nha Phu estuary is diurnal with a tidal range of 1–2 m, depending on phase. Based on basic physical properties the residence time is 4$^1/_2$ days. By using the rate of change of Kd (PAR) after a period of heavy rain and discharge of freshwater into the estuary a residence time of 5–6 days was estimated by Lund-Hansen et al. (2010).

Sampling methods

Mesozooplankton samples were collected from 7 stations (Fig. 1) inside and outside Nha Phu Estuary in April 2009, monthly from August 2009 until May 2010 and in July 2010. All samples were collected during day time by a conical plankton net (mesh size: 200 µm; mouth diameter: 37 cm; length: 100 cm) that was towed vertical by hand. The water depth was less than 10 m at all stations except 1B. At the latter site three samples were collected: 1) from 1 m above the bottom to the surface (25 m); 2) from the bottom to 10 m and 3) from 10 m depth to the surface. At the other sites we took a sample from 1 m above the bottom to the surface. All samples were preserved in 5% formalin (pH-neutralized). We used SBE 19 Plus Seabird CTD to measure salinity and temperature profiles during each sampling occasion. To measure chlorophyll-*a* content 1000 ml of sea water was collected by using the Niskin bottle. It was stored in a dark box with temperature of ca. 18 °C during transport to the laboratory. The water samples were filtered through 47 mm GF/F filters. Filters were folded and wrapped in aluminum foil, labeled, and stored in deep freezer for 12 to 24 h. Afterwards the filters were placed in glass vials with 5–10 ml of 90% acetone for pigment extraction. Samples were then centrifuged and absorbance of the supernatant was measured at wavelengths of 630, 647, 664 and 750 nm with a spectrophotometer UV-Vis Double Beam UVD 3500 (Labomed, Inc). Chlorophyll-*a* content was calculated using the formula of Jeffrey & Humphrey (1975) and pheophytin by using the formula of Lorenzen (1967).

Laboratory work

To count zooplankton individuals retained in the plankton net, we used a 500 µm sieve to separate each sample into two size groups: > 500 µm and < 500 µm (retained on a 25 µm sieve). The organisms retained on the 500 µm sieve were counted directly, whereas the individuals collected on the 25 µm mesh were brought into a suspension of filtered seawater added up to a final volume of 50 ml. After careful mixing, a 1 ml aliquot was used for counting zooplankters under a MPC-1 binocular microscope. Species were identified mainly according to Chen & Zhang (1965), Owre (1967), Chen et al. (1974), Nishida (1985), Nguyen (1995) and Boltovskoy (1999).

The density of zooplankton species at each station was standardized to number per cubic meter based on an estimate of the amount of water filtered by the plankton net (pulled distance times the mouth area and assuming 100%

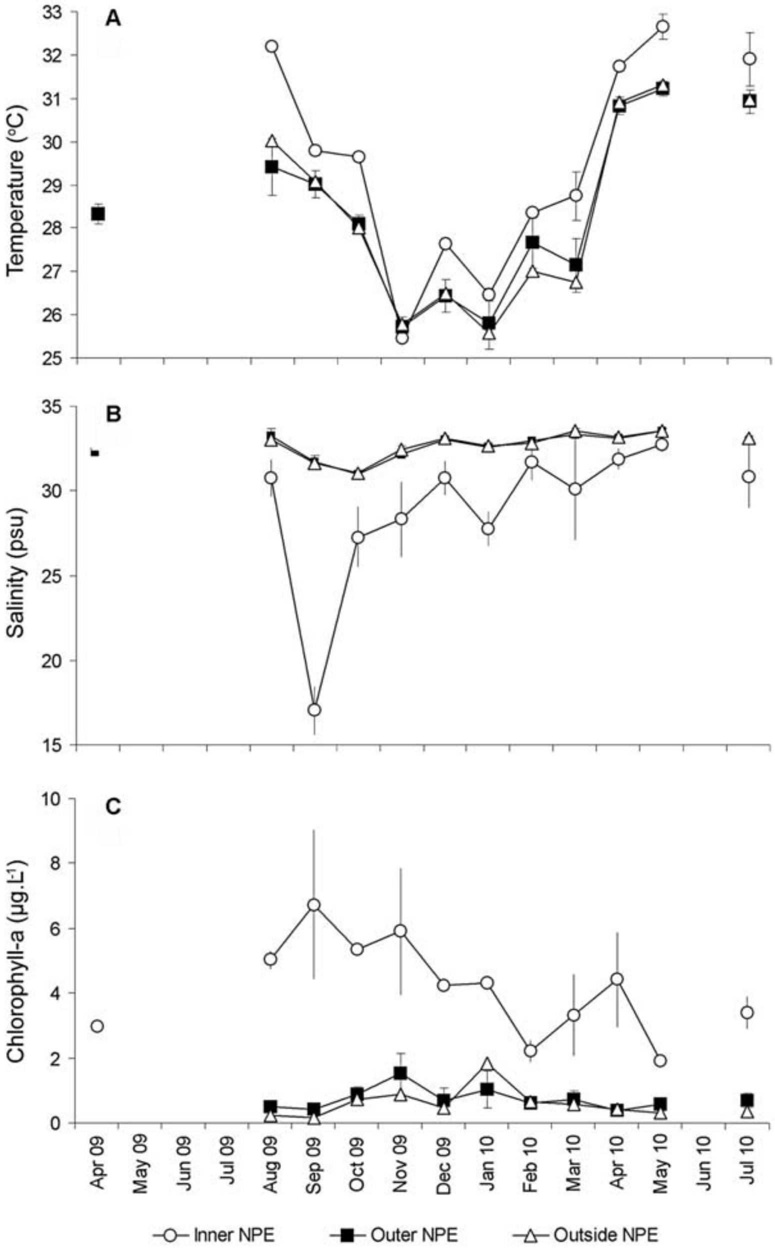

Fig. 2. Hydrographic data from the upper water layer at inner Nha Phu Estuary (NPE) (station 4 & 5), from outer NPE (station 3) and from outside NPE (station 1, 2, 6 &13) at each sampling date in the study period (2009–2010). A: temperature (℃ ± SD); B: salinity (psu ± SD); C: chlorophyll-a (µg L^{-1} ± SD).

efficiency). Specimens of Cnidaria and Ctenophora were not counted but just recorded as present or absent as many specimens were seriously damaged. Because of insufficient descriptions, invertebrate larvae were not identified to species level but to a lower taxonomic level. Body size of at least 3 individuals of each species was measured under a binocular microscope and used for calculating the biomass of zooplankton by using Plankton-sys (Bioconsult, DK).

As a measure of biodiversity patterns, similarities in the species composition between stations were estimated by the Bray-Curtis index and stations were clustered based on this index. The species richness was calculated by the Margalef's index (d) (Margalef 1958): $d = (S-1)/\log_e N$; S: Number of species, N: the total number of individuals.

The species diversity was estimated by Shannon-Wiener index (H') (Shannon 1948):

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

S: Number of species, p_i is the frequency of the ith species.

The species evenness was estimated by Pielous's index (Pielou 1966)

$$J' = \frac{H'}{H'_{\max}}$$

where is H' is the number derived from the Shannon diversity index and $H'_{\max}$ is the maximum value of H', equal to:

$$H'_{\max} = -\sum_{i=1}^{S} \frac{1}{S} \ln \frac{1}{S} = \ln S$$

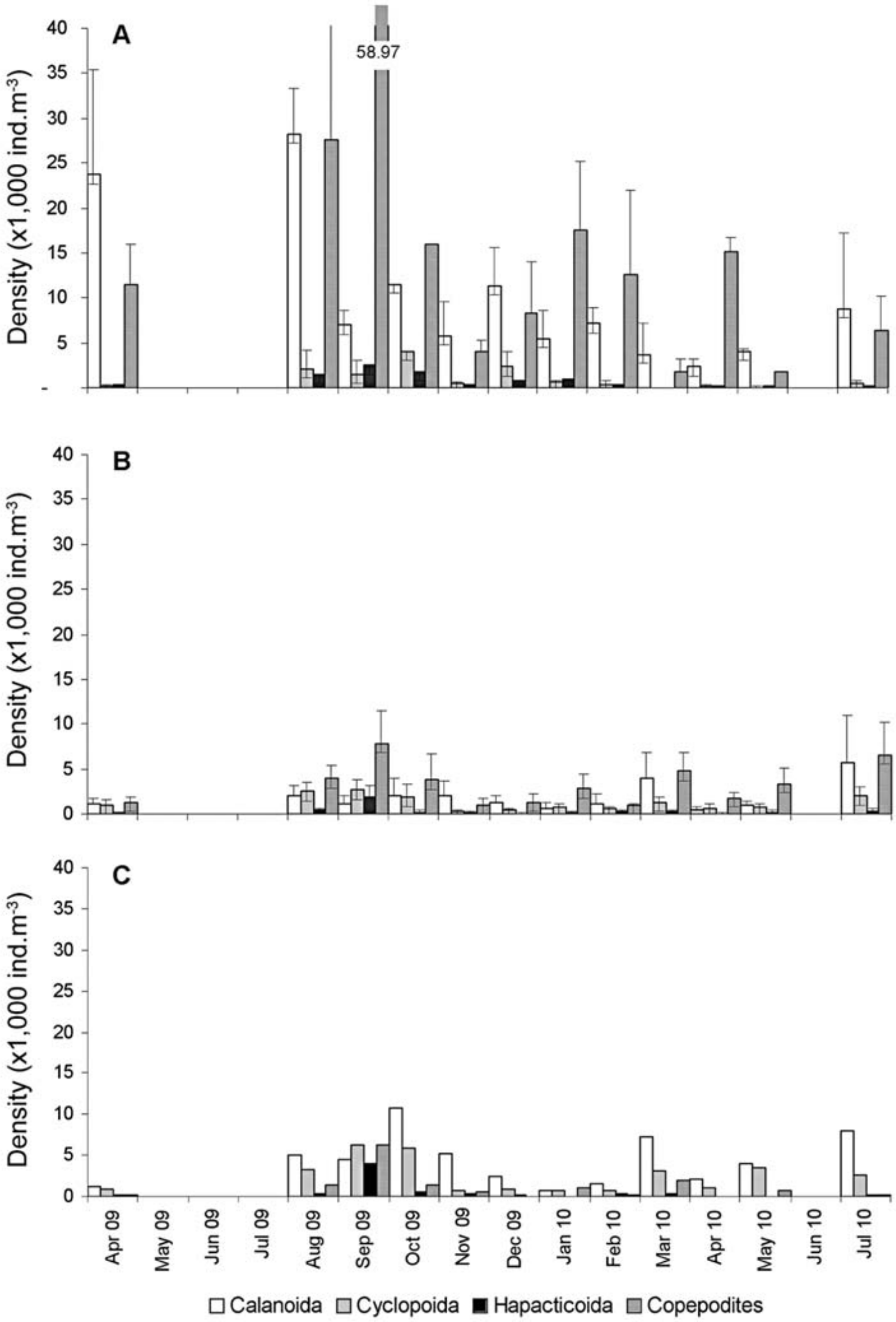

Fig. 3. Temporal patterns of density (ind. m^{-3}) of Calanoida, Cyclopoida, Harpacticoida, copepodites at (A) 'Inner NPE', (B) 'Outer NPE' and (C) 'Outside NPE'.

Results

Hydrography

There was a seasonal variation in surface water temperature between 25.5 ℃ (wet season) and 32.7 ℃ (dry season) (Fig. 2A). In the inner part of NPE the surface salinity varied between 17 and 30 psu, whereas the salinity of the water at the other sites was more stable (31–34 psu) (Fig. 2B). The salinity at the inner sites can episodically reach lower levels than observed during our sampling dates following incidences of heavy rain. We have snapshots of such events indicating that significant drops in salinity at the surface water can be detected along the whole NPE and even at the outside positions until next tide. The average concentration of chlorophyll *a* in the surface water varied between 2 and 7 μg L^{-1} near the head of the estuary (Fig. 2C). At the other sites the chlorophyll-*a* content was always below 2 μg L^{-1} (mostly below 1 μg L^{-1}).

Mesozooplankton

In total 184 mesozooplankton species were observed in the period from April 2009 to May 2010. Among these calanoids, cyclopoids, tunicates and cnidarians were the most species rich groups, with 61, 35, 20 and 17 species, respectively (Table 1).

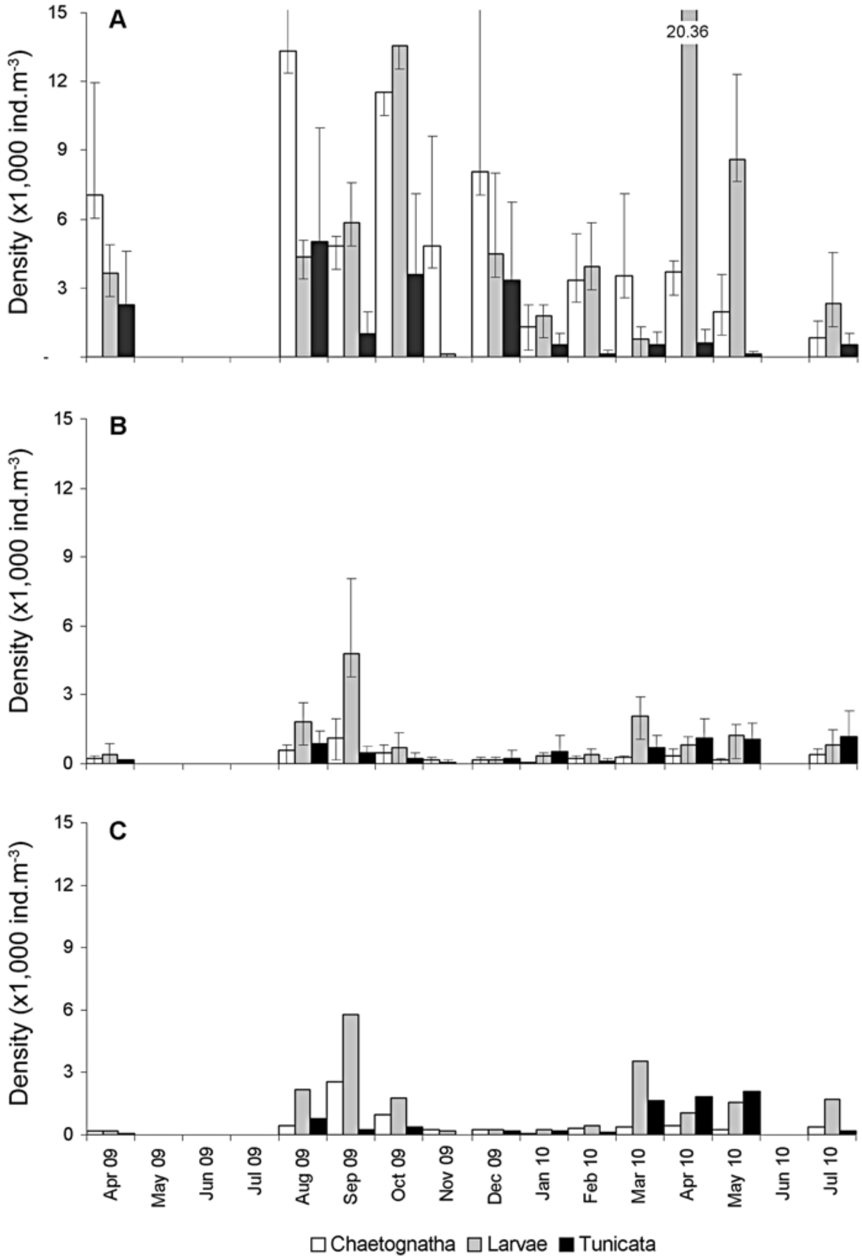

Fig. 4. Temporal patterns of density (ind. m^{-3}) of Chateognatha, Larvae, Tunicata and salinity at (A) 'Inner NPE', (B) 'Outer NPE' and (C) 'Outside NPE'.

Calanoids are dominant at all sites and sampling dates (Figs 3A–C). They occur in numbers from less than 2.4 ind. L^{-1} (Apr. 10) up to 28.2 ind. L^{-1} (Aug. 9) at 'Inner NPE' (Fig. 3A). At 'Outer NPE' and 'Outside NPE' the maximum density of calanoids is 5.8 ind. L^{-1} and 10.7 ind. L^{-1}, respectively (Figs 3B, C). Cyclopoids occur in a maximum density of 6.3 ind. L^{-1} (Sept. 9 'Outside NPE') and harpacticoids show a maximum density of 4.0 ind. L^{-1} (Sept. 9 'Outside NPE'). Copepodites are present at all sampling dates at 'Inner NPE' and the density varies from 1.7 (May 10) to 59.0 (Sept. 9) ind. L^{-1}. At the other sites they show much lower densities but they do also peak in Sept. 9 with 7.8 and 6.2 ind. L^{-1} at 'Outer NPE' and 'Outside NPE', respectively. Except at 'Inner NPL' the densities of all groups were at a minimum from Dec. 9 to Mar. 10, suggesting some monsoon related seasonality.

Among the other mesoplanktonic organisms Chaetognatha, Tunicata and larvae of benthic organisms are particularly important (Figs 4A–C). Like for the calanoids these groups are more abundant at the 'Inner NPE' than at the other sites. A maximum of 13.4 (Aug. 9), 3.4 (Aug. 9) and 20.4 ind. L^{-1} (Apr. 10) for Chaetognatha, Tunicata and larvae, respectively. At the other sites all groups occurred with less than 6 ind. L^{-1}.

The biomass data reflect these patterns except that copepodites are less dominant in biomass than in numbers. Thus biomass patterns differ slightly from abundance patterns (Fig. 5). The maximum biomass of copepods was 51.5 (Oct. 09), 15.6 (Sept. 9) and 37.8 µg C m^{-3} (Aug. 9) at 'Inner NPE', 'Outer NPE' and 'Outside NPE', respectively. Except that cope-

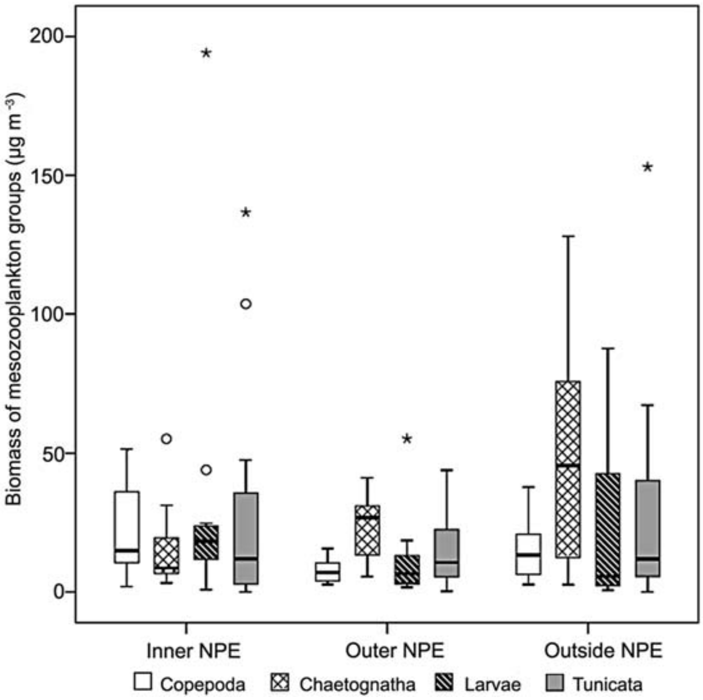

Fig. 5. Box plot of biomass of copepods, chaetognaths, bivalve larvae, tunicates at the three sites. Medians, 25 – and 75% percentiles of biomass values at each station throughout 2009–2010 are indicated.

Table 1. The number of zooplankton species within the different taxonomic groups observed in the zooplankton samples collected in Nha Phu Estuary in in 2009 and 2010.

Zooplankton group	S	%
Amphipoda	5	2.7
Chaetognatha	9	4.9
Cladocera	3	1.6
Cnidaria	17	9.2
Calanoida	61	33.2
Cyclopoida	35	19.0
Hapacticoida	8	4.3
Ctenophora	3	1.6
Cumacea	1	0.5
Gastropoda	8	4.3
Mysidacea	2	1.1
Ostracoda	3	1.6
Polychaeta	7	3.8
Sergestidae	2	1.1
Tunicata	20	10.9
Total	184	

podites exhibit peak abundance in Aug and Sep marks of monsoon related seasonality is weak. Generally the biomass of other mesozooplankton groups (Chaetognatha, larvae and Tunicata) had median values below 25 µg C m^{-3}. Larvae of benthos peaked in Apr. 10 with 194 µg C m^{-3} and tunicates in Dec. 9 with 137 µg C m^{-3} at inner NPE. Biomasses of the different groups were similar at inner and outer NPE. Outside the estuary chaetognaths had the highest frequency of biomasses above 50 µg C m^{-3} (Fig. 5).

Among the variables potentially impacting the abundance of copepods in NPE the availability of food organisms and numbers of predators in particular could be important. Many copepods are known to be herbivores and there is also a significant though weak correlation between the numbers of copepods in NPE and chlorophyll-*a* (Fig. 6, $r^2 = 0.23$, $P < 0.001$). Chaetognaths are predators on a variety of food items and they do also show a positive correlation with copepods (Fig. 7, $r^2 = 0.50$, $P < 0.001$).

Mesozooplankton community

There is an increase in the maximum number of copepod species from the inner part of NPE to outside NPE (Fig. 8). However, there is considerable intra-annual variation in species richness at the various sites examined. In the inner NPE we have identified between 14 and 38 species and outside the number of species vary between 55 and 124 copepod species (Fig. 8, Table 2). From the diversity indices it is obvious that the community at inner NPE has the lowest diversity and species richness and the opposite for the community outside NPE. There is obviously a negative relationship between diversity and density. We cannot recognize any seasonal trends in the number of species (Fig. 9) though the highest number was recorded in August at all sites. It is also remarkable that the number of copepod species at the inner NPE is lowest in between monsoon seasons (September and October, March and April) though we do not presently have explanations for this.

In the inner part a few species dominate the total density of mesozooplankton. Five species (Fig. 10, Table 3) contribute with roughly 50% of the total adult density at station 5. Outside NPE there is a more equal density pattern across species as 10 species account for 50% of the total abundance (Fig. 10). Based on the number of individuals of each species observed during

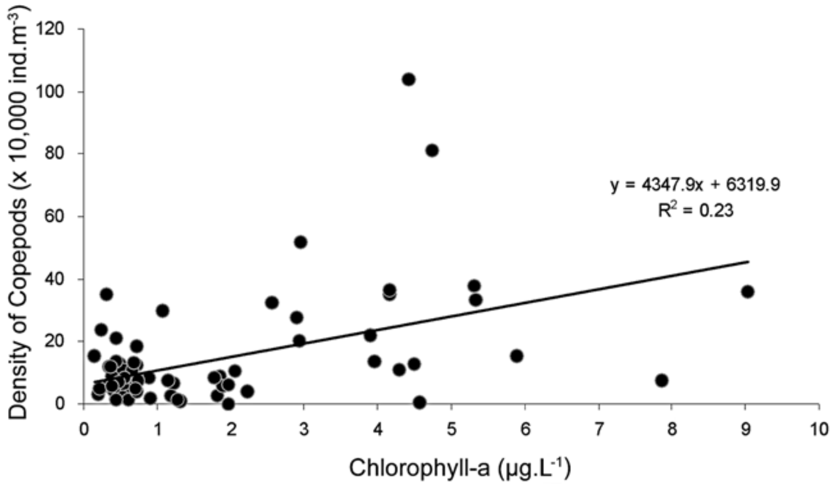

Fig. 6. Correlation between the density of copepods and chlorophyll-*a* ($r^2 = 0.23$, $P < 0.001$).

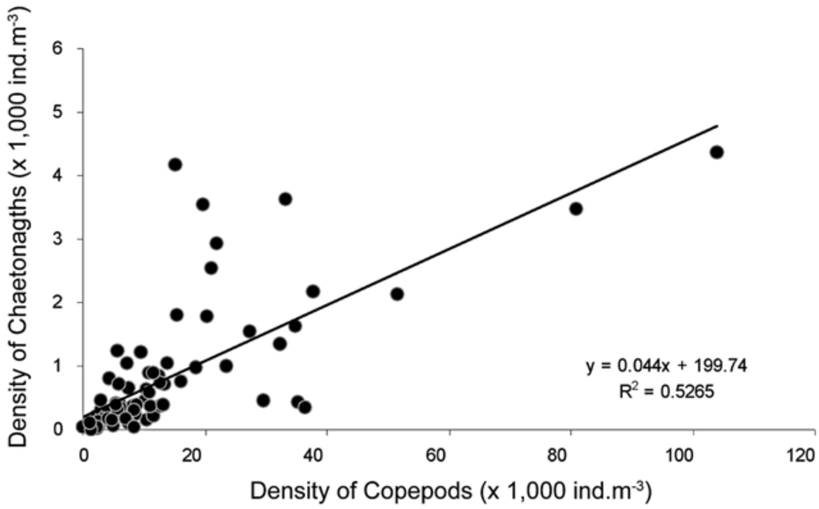

Fig. 7. Correlation between the abundance of chaetognaths and copepods ($r^2 = 0.50$, $P < 0.001$). One outlier has been removed (x, y = 35 880, 13 520).

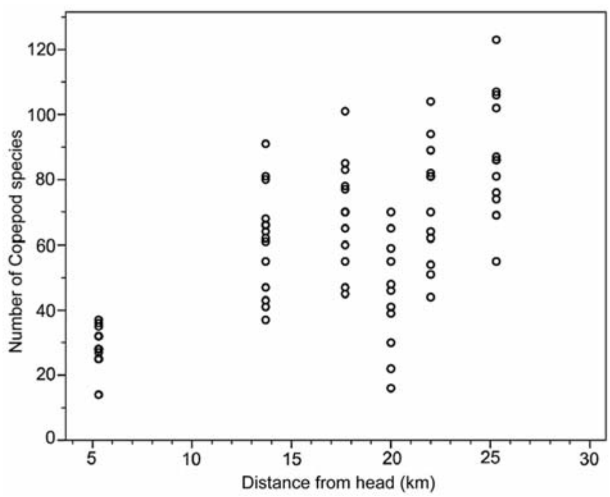

Fig. 8. Number of copepod species at stations in Nha Phu Estuary ranked after their distance in km from the head of the estuary. Each circle represents the number of copepods observed on one sampling date in the study period (April 2009 until July 2010). At 20 km from the head (station 13) we have observed salinity fluctuations due to input of water from Cai River (see Fig. 1).

the whole study period at each station, the five top ranked species have been identified (Table 3). It appears that most of these species are euryhaline although with different salinity ranges. Some of the species such as *Paracalanus crassirostris*, and *Euterpina acutifrons* are high ranked in all three sectors of NPE, whereas *Bestiola sp.* and *Paracalanus parvus* are restricted to the inner and outer part of the estuary, respectively. Analyzing for similarity (Bray-Curtis) between stations, two major groups each showing an intergroup similarity of 80% can be distinguished: inner stations (4 and 5) versus outer and outside NPE stations. In the latter group there is a further split at about 90% similarity separating station 3 and 13 from station 1B, 2B and 6 (Fig. 11).

Discussion

Zooplankton and copepods in particular play a key role as a link between autotrophic pelagic producers and heterotrophic pelagic and benthic consumers in many

Table 2. Diversity indices of the copepod community at various sites in Nha Phu Estuary. The data are based on zooplankton samples collected 12 times (11 times for site 5) during the study period 2009–2010.

NPE area	Site	S_{range}	S_{median}	Shannon (H')	Pielou's evenness (J')	Species richness (d)
Inner NPE	5	16–37	30	2.09 (± 0.27)	0.64 (± 0.08)	2.58 (± 0.64)
	4	14–38	29	2.37 (± 0.33)	0.71 (± 0.08)	2.81 (± 0.62)
Outer NPE	3	37–81	53	2.87 (± 0.23)	0.72 (± 0.04)	6.41 (± 1.34)
	13	16–90	47	2.68 (± 0.50)	0.71 (± 0.08)	5.67 (± 2.06)
	6	45–104	76	2.95 (± 0.45)	0.69 (± 0.08)	7.87 (± 1.96)
	2B	55–124	70	3.11 (± 0.33)	0.74 (± 0.06)	7.54 (± 1.65)
Outside NPE	1B	45–101	86	3.20 (± 0.24)	0.72 (± 0.05)	9.40 (± 1.64)

Explanations: S_{range}: minimum and maximum numbers of copepod species registered; S_{median}: median number of copepod species (nearest whole number); H', J' and d: mean (± SE).

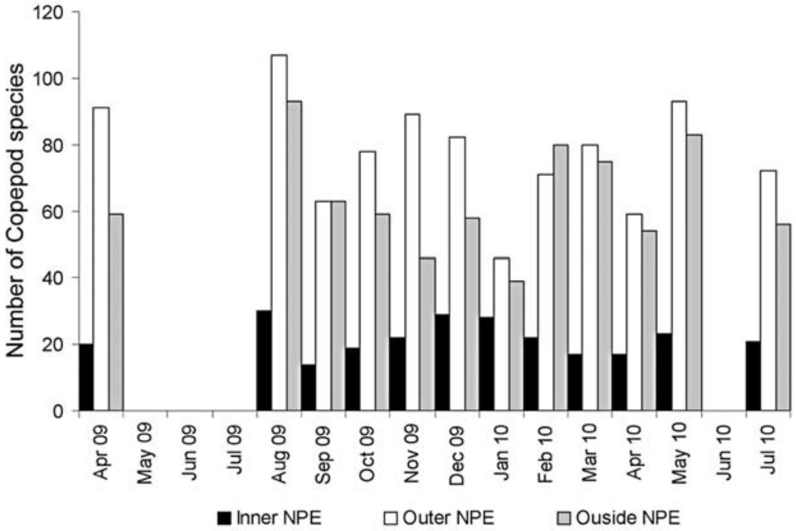

Fig. 9. Seasonal variation in the number of copepod species at the three sites in NPE.

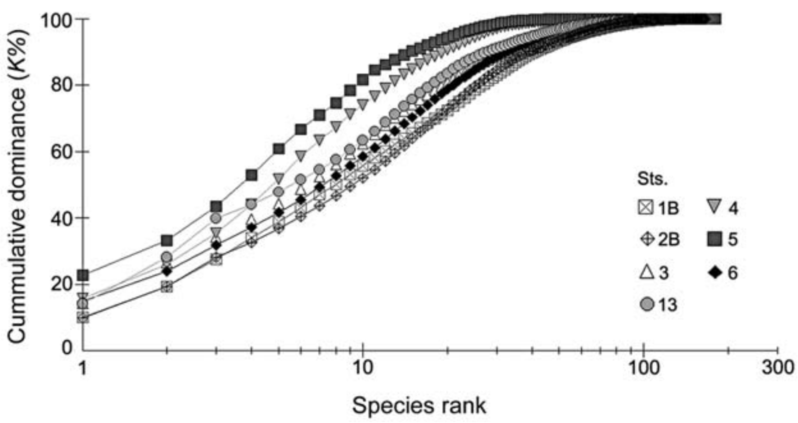

Fig. 10. Cumulative dominance of species at all examined sites in NPE.

marine ecosystems. However, the importance of copepods and other zooplankton groups in shallow water tropical systems such as estuaries have not been fully explored. As the species richness, composition and dynamics of the copepod community may have consequences for the functioning of the ecosystem (mainly by modifying particulate organic matter and energy fluxes), identification of factors controlling diversity patterns and dynamics of dominant species is an important issue.

The here observed patterns of copepod diversity and density from the head towards the open coastal area is similar to what has been observed in other studies from tropical estuaries (Nguyen & Truong-Si 2006; Duggan et al. 2008; Chew & Chong 2011).

The high number of copepod species in the open coastal area reflects the high species pool in the South Chinese Sea and should be explained within a more global framework of diversity drivers. According to Rombouts (2010) the mean ocean temperature is the

Table 3. The five most common copepod species at the various sites in NPE and their trophic group (TG), reproductive mode (RM) and observed salinity spectrum (SS).

Top ranked species	TG	RM	SS	Sites						
				Inner		Outer				Outside
				5	4	3	6	13	2B	1B
Bestiola sp[3]	H	FS	5–15	1	1					
Paracalanus crassirostris F. Dahl, 1894[1]	O	FS	15–30	2	2		2		3	2
Euterpina acutifrons (Dana, 1847)[4]	H	EGG	5–33	3	5	3		4	4	5
Acartia pacifica Steuer, 1915[1]	O	FS	15–28	4						
Pseudodiaptomus incisus Shen & Lee, 1963[1]	H	EGG	5–15	5						
Paracalanus parvus Claus, 1863[1]	O	FS	15–30		3		5			
Acartia erythraea Giesbrecht, 1889[1]	O	FS	15–30		4					
Paracalanus gracilis Chen & Zhang, 1965[1]	O	FS	15–30			1	1	1	1	1
Acrocalanus gibber Giesbrecht, 1888[1]	H	FS	15–30			2		3		4
Subeucalanus subcrassus Giesbrecht, 1888[1]	O	FS	15–30			4				
Oithona rigida Giesbrecht, 1896[2]	H	EGG	28–34			5		2		
Corycaeus andrewsi Farran, 1911[5]	H	EGG	15–30				3	5	2	
Oithona plumifera Baird, 1843[2]	H	EGG	15–30				4		5	3

Explanations: [1]Mauchline (1998); [2]Hopcroft & Roff (1996); [3]Camus et al. (2009); [4]Zurlini et al. (1978); [5]Wiggert et al. (2005); [6]Johan et al. (2013). H: herbivore; C: carnivore; O: omnivore. BS: free spawner; EGG: egg carrying.

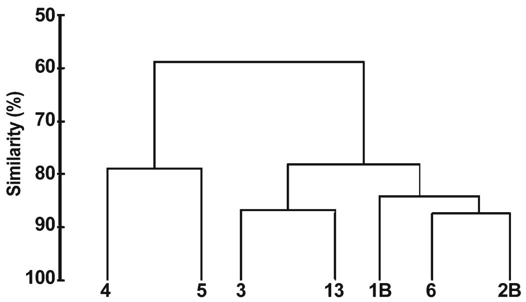

Fig. 11. Similarity of stations with respect to species composition calculated by Bray-Curtis similarity index.

most important correlate of large-scale variations in copepod diversity. The decline in diversity inside NPE, in contrast, is a result of local factors. Several environmental factors might influence species richness but in estuaries the variation in salinity is a key factor (Duggan et al. 2008; Johnson et al. 2011) and it is probably the most important factor limiting the number of zooplanktonic species in the inner part of NPE. So, our data clearly indicate considerable fluctuations in salinity in the upper water layer at the inner sites, whereas salinity in the outer part of NPE is much more stable. Supplies of freshwater from the rivers leading to NPE during the rainy season in particular are responsible for salinity variation in the mouth region (Lund-Hansen et al. 2010). The lowest number of species was registered in Sept. 9 at the inner sites of NPE while the salinity was at a minimum. Apart from salinity variation discharges of various inorganic and organic pollutants through the rivers passing the densely populated coastal area surrounding NPE might also reduce species richness. At present we do not have any specific information to support this.

In contrast to the pattern of species richness, the density of zooplanktonic organisms is generally higher in the mouth region than in the outer parts of NPE. A higher fraction of mesozooplanktonic organisms in the inner part of NPE consists of juvenile specimens (copepodites) as also reflcected in the biomass data, where we see a relative high biomass outside NPE despite the general lower numbers.

Generally, the observed abundance pattern of copepods can be expected to be a result of a dynamic interplay between food concentrations influencing growth and reproduction of copepods and zooplanktivorous consumers such as chaetognaths, comb jellies and various fish under different temperature and salinity settings.

Phytoplankton is an important food resource to many copepod species, to other pelagic microzooplankton (heterotrophic flagellates, dinoflagellates and ciliates) is the main food item (Calliari et al. 2009). Whether phytoplankton or microzooplankton is the food base for copepods, the abundance of these organisms can be expected to decline with increasing distance from the mouth.

The biomass of microphytoplankton as evidenced by chlorophyll-a measurements is generally highest in the mouth region of NPE (Doan Nhu Hai, personal communication). Satellite images do also show elevated concentrations of chlorophyll-a at the inner sites relatively to the outer sites (unpublished data). Dense human populations and limited waste water treatment, fertilized rice fields and shrimp ponds in the surroundings of NPE are all expected to contribute with nutrients to the head of the estuary as also supported by the patterns of nutrient concentrations in the estuary. Generally, nutrients will be used rapidly or transported out of the system due to the short retention time.

During seasonal or episodic rainfall events, nutrients supplied to NPE by rivers may boost primary production. Based on reported benthic metabolism rates in NPE it seems that the benthic metabolic rate is very low (Nguyen et al. 2012), indicating that mineralization of organic matter at the bottom only contributes with a small fraction of nutrients. In other words, burst of phytoplankton depends very much on episodically supplies of nutrients from rivers.

Suspended particulate matter (SPM) that may fuel bacteria based food chains do also show a peak at the mouth region as a result of riverine supplies (Lund-Hansen et al. 2010). Because of tidal currents the concentration of SPM will be diluted with distance from the mouth.

Altogether the potential for copepod production (growth and reproduction) and recruitment are expected to decline from the mouth region and seawards. However, varying environmental conditions such as salinity variation may impact the possibility for copepods to respond when food is available. Although we found that the dominant copepod species at the inner part of NPE are adapted to estuarine conditions, varying salinities may still have an impact on their performance and this may vary with water temperature.

Despite a relatively high phytoplankton stock and a resulting high secondary production by zooplankton, the standing stock of zooplankton could still be relatively low, if it is either permanently or temporarily controlled by fish larvae, zooplanktontivorous fish, chaetognaths, comb jellies or others. Fluctuating primary production as well as fluctuating consumer impact may actually be the causative agents for the observed temporal patterns of primary consumers (zooplankton). As shown there is a correlation between the abundance of chaetognaths and copepods. Preliminary studies of fish stocks in NPE show that the fraction of small and zooplanktivorous fish are higher in the inner part of NPE than in the outer part (Westergaard 2011). Analyses based on stable isotopes and stomach content have verified the importance of copepods to the fish caught in the inner part of NPE. Assessed from the presence of fish nets and traps in the inner part of NPE we presume that there is considerable fishery impact as also claimed by Strehlow (2006). Despite the strong fishery impact a number of small zooplanktivorous fish seems to escape from being caught. To what extent these fish temporally exhibit top down control on copepods remains an unanswered question until more detailed fish studies have been conducted.

The peak density of copepodites in Sept. 2009 could be a result of a combination of temperature and salinity that may be beneficial to some of the estuarine calanoids at the inner sites. Generally only a minor subset of marine species are adapted to estuarine conditions and can cope with fluctuating salinities. Among the top-ranked estuarine copepods we have observed in NPE *Bestiola* sp. *Euterpina acutifrons* and *Pseudodiaptomus incisus* generally do occur in the mesohaline section of estuaries. *Pseudodiaptomus annandalei,* a relative to *P. incises,* exemplifyes an estuarine species that can survive and reproduce under low salinity high temperature combinations (Beyrend-Dur et al. 2011). According to Beyrend-Dur et al. (2011) *P. annandalei* shows a peak in fecundity at 30–32 °C and a salinity around 15 psu (experimental population originally from southern Taiwan). As such salinity-temperature conditions occur in inner NPE in Sept. 2009, this may be a period of peak production of offspring in some of the dominant copepods in this part of NPE, explaining the temporal peak in copepodite abundance. Unfortunately we do not have continuous recordings of salinity from NPE and neither do we know how offspring production of the dominant copepods varies with fluctuating salinities at different temperatures. Furthermore, the short lifespan of copepods in tropical waters (for *P. annandalei* 15 days at 30 °C; Beyrend-Dur et al. 2011) necessitates more detailed temporal resolution of abundance data to address possible factors controlling the population dynamics of dominant copepod species.

There is no strong evidence of seasonal trends in our data despite heavy rainfalls are considered as the driver for phytoplankton growth when nutrients are supplied. Seasonally trends may be blurred by the frequent occurrence of rain in the dry season. A short retention time of the water in the inner part of NPE caused by the tide may also prevent any long-lasting horizontal structuring of pelagic communities.

Considering the whole ecosystem, the water mass at the shallow water depth in the inner part of NPE contribute with a small fraction of the whole water body. Though, it has to be recognized that this part covers a high share of the surface area of NPE. The high biomass of copepods (adults and copepodites) at the inner part may attract second level consumers such as fish larvae, small fish and chaetognaths preying on zooplankton. The positive but weak correlation between copepod densities and chaetognath densities supports this contention. Stable isotope and stomach analyses have also revealed that a majority of fish in this area are zooplanktivorous species (Westergaard 2011).

To explain the temporal patterns in major copepod groups is not possible with the information available. As there is no obvious seasonal pattern, a more detailed temporal resolution of key environmental parameters will be required as well as a more detailed knowledge of response pattern of involved copepod species on environmental characteristics.

This is the first study reporting on mesozooplankton from NPE. Consequently, we do not have any direct possibility to assess how deforestation of the mangrove has impacted our system. Neither do we know how other food chain components may have responded to the anthropogenic disturbances in this system. In itself the mangrove system is an important nursery area to many zooplanktivorous juvenile fish (Robertson et al. 1988). Studies in other mangrove estuaries indicate that mangrove streams temporarily support higher mean annual densities of copepods than areas outside, except if this includes seagrass beds (Robertson et al. 1988). As the whole mangrove forest in NPE has been eliminated, less habitats supporting a nursery function are available to fish. Beside this, a mangrove forest is also known to impact supplies of nutrients and SPM to areas outside the mangrove. We expect that more discharges from rivers will enter the estuary after the deforestation but detritus from mangrove leaves otherwise thought to be an important C-source in mangrove estuaries will be missing. More nutrients should enhance pelagic primary production and thus stimulate the production of zooplankton. On the other hand, less detritus may have the opposite effect. Possible effluents from shrimp ponds that are established in the former mangrove forest may further complicate the situation (Páez-Osuna 2001; Costanzo et al. 2004). Too many factors are potentially impacting the zooplankton community in the inner part of NPE estuary to clarify whether it has changed with the deforestation of the mangrove. Furthermore, the strong temporal variation in both diversity and density require monitoring data from more years before a baseline can be extracted. Ideally such data should also be available from comparable areas with mangrove forests before it is possible to demonstrate to what extent mangrove cutting influences pelagic processes outside. Unfortunately, it seems that mangrove forests have been eliminated without considerations for structure and function of the connected ecosystems.

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References

Alongi D.M. 2002. Present state and future of the world's mangrove forests. Environ. Cons. **29 (3):** 331–349. DOI: 10.1017/S0376892902000231

Beyrend-Dur D., Kumar R., Rao T.R., Souissi S., Cheng S.H. & Hwang J.S. 2011. Demographic parameters of adults of *Psedodiaptomus annandalei* (Copepoda: Calanoida): Temperature-salinity and generation effects. J. Exp. Mar. Biol. Ecol. **404 (1-2)**: 1–14. DOI: http://dx.doi.org/10.1016/j.jembe.2011.04.012

Boltovskoy D. (ed.) 1999. South Atlantic Zooplankton. Backhuys Publishers, Leiden, 1706 pp. ISBN: 90-5782-035-8

Bray J.R. & Curtis J.T. 1957. An ordination of the upland forest communities of Southern Wisconsin. Ecol. Monogr. **27 (4):** 325–349. DOI: http://dx.doi.org/10.2307/1942268 http://www.geobotany.org/teaching/biol474/journals/Bray 1957v27n4.pdf

Calliari D., Britos A. & Conde D. 2009. Testing the relationship between primary production and *Acartia tonsa* grazing pressure in an estuarine lagoon. J. Plankton Res. **31 (9):** 1045–1058. DOI: 10.1093/plankt/fbp049

Camus T., Zeng C. & McKinnon D. 2009. Egg production, egg hatching success and population increase of the tropical paracalanid copepod, *Bestiolina similis* (Calanoida: Paracalanidae) fed different microalgal diets. Aquaculture **297 (1-4):** 169–175. DOI: 10.1016/j.aquaculture.2009.09.018

Chen Q.C. & Zhang S.Z. 1965. The planktonic copepods of the Yellow Sea and the East China Sea, I. Calanoida. Stud. Mar. Sin. **7:** 20–131, plates: 1–52. [in Chinese with English summary]

Chen Q.C., Zhang S.Z. & Zhu C.S. 1974. On planktonic copepods of the Yellow Sea and the East China Sea, II. Cyclopoida and Harpacticoida. Stud. Mar. Sin. **9:** 27–76, plates: 1–24. [in Chinese with English summary]

Chew L.L. & Chong V.C. 2011. Copepod community structure and abundance in a tropical mangrove estuary, with comparisons to coastal waters. Hydrobiologia **666 (1)**: 127–143. DOI: 10.1007/s10750-010-0092-3

Constanzo S.D., O'Donohue M.J. & Dennison W.C. 2004. Assessing the influence and distribution of shrimp pond effluent in a tidal mangrove creek in north-east Australia. Mar. Poll. Bull. **48 (5-6):** 514–525. DOI: 10.1016/j.marpolbul.2003.09.006

Duggan S, McKinnon A.D. & Carleton J.H. 2008. Zooplankton in an Australian tropical estuary. Estuaries and Coasts: J. Cerf. **31 (2):** 455–467. DOI: 10.1007/s12237-007-9011-x

Hopcroft R.R. & Roff J.C. 1996. Zooplankton growth rates: diel egg production in the copepods *Oithona, Euterpina* and *Corycaeus* from tropical waters. J. Plankton Res. **18 (5):** 789–803. DOI: 10.1093/plankt/18.5.789

Jeffrey S.W. & Humphrey G.R. 1975. New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. Biochem. Physiol. Pflanzen **167:** 191–194.

Johan I., Abu Hena M.K., Idris M.H. & Arshad A. 2013. Taxonomic composition and abundance of zooplankton Copepoda in the coastal waters of Bintulu, Sarawak, Malaysia. J. Fish. Aquat. Sci. **8 (3):** 472–479. DOI**:** 10.3923/jfas.2013.472.479

Johnson C.L., Runge J.A., Curtis K.A., Durbin E.G., Hare J.A., Incze L.S., Link J.S., Melvin G.D., O'Brien T.D. & Guelpen L.V. 2011. Biodiversity and ecosystem function in the Gulf of Maine: Pattern and role of zooplankton and pelagic nekton. PLoS ONE **6 (1):** e16491 DOI: 10.1371/journal.pone.0016491

Lorenzen C.J. 1967. Determination of chlorophyll and pheopigments: spectrophtometric equations. Limnol. Oceanogr. **12 (2):** 343–346. DOI: 10.4319/lo.1967.12.2.0343

Lund-Hansen L.C., Hai D.N., Lam N.N. & Nielsen M.H. 2010. Optical properties of a tropical estuary during wet and dry conditions in the Nha Phu estuary, Khanh Hoa Province, south-east Vietnam. Hydrobiologia **644 (1):** 207–216. DOI: 10.1007/s10750-010-0114-1

Mauchline J. (ed.)1998. The Biology of Calanoid Copepods. Advances in Marine Biology. Vol. 33. Elsevier Academic Press, New York, 710 pp. ISBN: 978-0-12-026133-8

Margalef D.R. 1958. Information theory in ecology. General Systems Yearbook **3:** 36–71.

Nagelkerken I. (ed.) 2009 Ecological Connectivity Among Tropical Coastal Ecosystems. Springer Science and Business Media, Dordrecht, the Netherlands, 615 pp. ISBN: 978-90-481-2405-3

Nguyen C. & Truong-Si H.T. 2006. Zooplankton abundance and species diversity in Qui Nhon coastal waters, South Central Vietnam in June 2004. Coastal Marine Science **30 (1):** 328–335.

Nguyen K.H., Kristensen E. & Lund-Hansen L.C. 2012. Benthic metabolism and nitrogen transformations affected by fish cage farming in the tropical Nha Phu estuary (Vietnam). Mar. Freshwater Res. **63 (10):** 887–897. DOI: 10.1071/MF12136

Nguyen V.K. 1995. Copepods of the Tonkin Gulf. Science & Technical Publishing. House, Hanoi, Vietnam, 200 pp. [in Vietnamese]

Nishida S. 1985. Taxonomy and distribution of the family Oithoinidae (Copepoda, Cyclopoda) in the Pacific and Indian Oceans. Bull. Ocean Res. Inst. Univ. Tokyo **20:** 1–167.

Owre H.B. & Foyo M. 1967. Copepods of the Florida Current, with Illustrated Keys to Genera and Species. Fauna Caribaea 1. Crustacea, Part 1, Copepoda. Institute of Marine Science, University of Miami, Miami, Florida, 137 pp.

Páez-Osuna F. 2001 The environmental impact of shrimp aquaculture: causes, effects and mitigating alternatives. Environ. Manage. **28 (1):** 131–140. DOI: 10.1007/s002670010212

Pielou E.C. 1966. The measurement of diversity in different types of biological collections. J. Theor. Biol. **13:** 131–144. DOI: 10.1016/0022-5193(66)90013-0

Robertson A.I, Dixon P. & Daniel P.A. 1988. Zooplankton dynamics in mangrove and othernearshore habitats in tropical Australia. Mar. Ecol. Prog. Ser. **43:** 139–150.

Rombouts I.B. 2010. A multivariate approach to large-scale variation in marine planktonic copepoddiversity and its environmental correlates. Limnol. Oceanogr. **55 (5):** 2219–2229. DOI: 10.4319/lo.2010.55.5.2219

Shannon C.E. 1948. A mathematical theory of communication. The Bell System Technical Journal, **27 (4):** 379–423 DOI: 10.1002/j.1538-7305.1948.tb00917.x

Strehlow H.V. 2006. Integrated natural resources management of coastal fisheries. -The case of Nha Phu Lagoon, Vietnam-. Dissertation zur Erlangung des akademischen Grades doctor rerum agriculturarum (Dr. rer. agr.), 302 pp.

Westergaard C. 2011. Fish community structure within a tropical estuary: stable isotopes and stomach content analyses (case: Nha Phu estuaary – South East Vietnam). Master Thesis, Aarhus University, 45 pp.

Wiggert J.D. Haskell A.G.E., Paffenhöffer G.-A., Hofmann E.E. & Klinck J.M. 2005. The role of feeding behavior in sustaining copepod populations in the tropical ocean. J. Plankton Res. **27 (10):** 1013–1031. DOI: 10.1093/plankt/fbi090

Zurlini G., Ferrari I. & Nassogne A. 1978. Reproduction and growth of *Euterpina acutifrons* (Copepoda: Harpacticoida) under experimental Conditions. Mar. Biol. **46 (1):** 59–64. DOI: 10.1007/BF00393821

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