Marine Pollution Bulletin 60 (2010) 2154–2160

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Maintenance of estuarine water quality by mangroves occurs during flood periods: A case study of a subtropical mangrove wetland

Mao Wang [a], Jinhan Zhang [a], Zhigang Tu [a], Xueqin Gao [a], Wenqing Wang [a,b,*]

[a] Key Laboratory of Ministry of Education for Coastal and Wetland Ecosystems and School of Life Sciences, Xiamen University, Xiamen 361005, China
[b] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 361005, China

ARTICLE INFO

Keywords:
Mangrove
Purification
Water quality
Carbon
Nitrogen
Phosphorus

ABSTRACT

Seasonal changes in water quality were measured in samples taken at various distances from shallow water across mudflat to mangroves during flood period and from mangroves across mudflat to shallow water during ebb period in a subtropical mangrove estuary (Zhangjiang Estuary, Fujian, China). The TN (total dissolved nitrogen), TP (total dissolved phosphorus), COD (chemical oxygen demand), and DOC (dissolved organic carbon) contents during the flood period were significantly higher than those during the ebb period. In contrast, the opposite was true for the POC (particulate organic carbon) content and transparency. The mangroves at Zhangjiang Estuary may trap nutrients at rates of 90.5 g N/m^2/yr, 2.2 g TP/m^2/yr, and 13.7 g C/m^2/yr in the form of DOC, and export POC at a rate of 81.8 g/m^2/yr. Our results support the hypothesis that the maintenance of estuarine water quality by mangroves occurs during flood periods.

Since mangrove ecosystems are suitable for brackish water shrimp culture, many shrimp ponds have been constructed in or adjacent to mangrove wetlands (Twilley et al., 1993; Csavas, 1994; Robertson and Phillips, 1995; Rivera-Monroy et al., 1999; Wang and Wang, 2007). This is the case of the Zhangjiang Estuary, Fujian, China (Fig. 1). Intensive shrimp aquaculture is an inefficient production system because only approximately 20% of the nitrogen of the feed input is incorporated into the shrimp harvest (Briggs and Funge-Smith, 1994; Jackson et al., 2003). Remaining nitrogen acts to fuel plankton and microbial production within ponds, often resulting in negative effects on pond water and sediment (Moriarty, 1997; Burford and Glibert, 1999). The exchange of coastal waters in shrimp aquaculture ponds is important to ensure optimal survival and high yields (Rivera-Monroy et al., 1999; Jackson et al., 2003). This exchange is also the primary means of pollutant discharge (Paez-Osuna et al., 1997; Funge-Smith and Briggs, 1998; Preston et al., 2000; Jackson et al., 2003; Shimoda et al., 2007), potentially leading to deleterious effects in receiving waters such as eutrophication if not planned and managed appropriately (Lin, 1989; Sansanayuth et al., 1996; Naylor et al., 1998). This concern has led to an increase in research on systems receiving shrimp pond effluents (McKinnon et al., 2002; and other references cited in this paper).

Mangrove ecosystems create a suitable environment for removing and transforming pollutants in waste water (Wu et al., 2008). This function is fulfilled through the processes of sedimentation, filtration, microbial activity, plant absorption, etc., when waste water passes through mangroves (Nedwell, 1975; Tam and Wong, 1993; Corredor and Morell, 1994; Wong et al., 1995; Alongi, 1996; Rivery-Monroy et al., 1999). Many studies have demonstrated that mangroves make a significant contribution to the removal of nutrients and organic matter from waste water (Sansanayuth et al., 1996; Wong et al., 1997; Chu et al., 1998; Tilley et al., 2002) and to the maintenance of estuarine water quality (Saenger, 2002). Nevertheless, most of our knowledge regarding the purification process comes from simulation experiments. In these studies, shrimp pond effluents were discharged directly into the semi-enclosed or wholly enclosed vegetated areas of mangroves (Gautier et al., 2001; Tilley et al., 2002; Huang et al., 2004; Wu et al., 2008), pond-cultured mangrove saplings (Shimoda et al., 2005a), or pot-cultivated mangrove seedlings (Chen et al., 2000), and retained for certain periods of time. On most occasions, there was no tidal flushing or cycle (Wu et al., 2008). Most shrimp ponds have been constructed in places originally occupied by mangroves (Wang and Wang, 2007). To save energy, the discharge of shrimp pond effluents is generally processed during ebb periods by gravity. These effluents ultimately find their way into the coastal areas through creeks (McKinnon et al., 2002; Costanzo et al., 2004; Mishra et al., 2008). They merge with estuarine waters before returning to the vegetated areas during flood periods (Zhang et al., 1999). Thus, the proposed method to use mangrove wetlands

* Corresponding author at: School of Life Sciences, Xiamen University, Xiamen 361005, Fujian, China. Tel.: +86 592 2181431; fax: +86 592 2181430.
E-mail address: mangroves@xmu.edu.cn (W. Wang).

0025-326X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2010.07.025

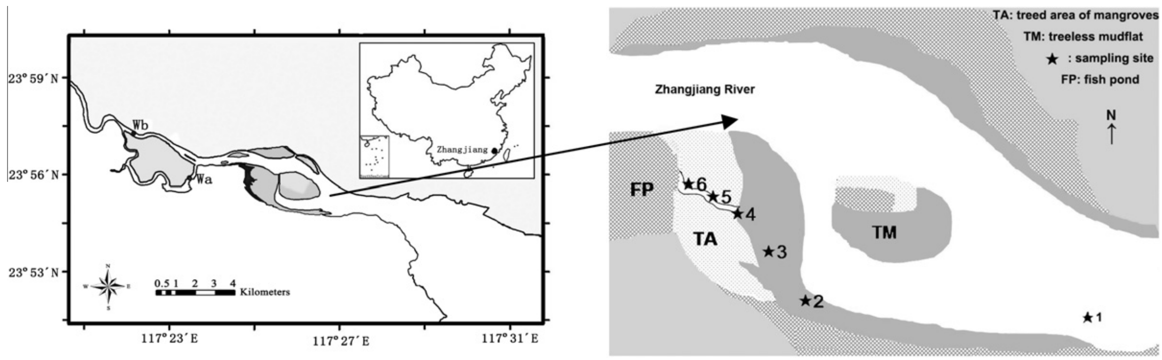

Fig. 1. Map of the coastal region of the Zhangjiang Estuary indicating the location of the sampling sites see Fig. 1.

as filters of pond discharge prior to the release of effluents to estuarine waters has not yet been tested in the field under natural conditions (Twilley et al., 1993; Csavas, 1994; Robertson and Phillips, 1995). Till now, much less is known about the fate of pond pollutants after they are discharged into estuarine water through mangroves (Grant et al., 1995; Jones et al., 2001).

Most attentions were focused on the changes in water quality in receiving creeks (Trott and Alongi, 2000; Costanzo et al., 2004). It was proven that the symptoms of aquaculture effluent (e.g. elevated nutrient and chlorophyll concentration) were only measurable in close proximity to the discharge points (Samocha and Lawrence, 1997; McKinnon et al., 2002; Costanzo et al., 2004). Costanzo et al. (2004) found that the water quality at the month of effluent creeks was equivalent to control values (no discharge creeks), indicating that pond effluent was contained within the effluent-receiving creeks. However, there are also evidences showing that the influence of shrimp pond effluent can extend further (Jones et al., 2001; Costanzo et al., 2004).

Much effort has been invested in measuring flux of organic matter and nutrients from mangroves (Twilley, 1988). However, we still know little about mangrove-near shore exchange patterns (Werry and Lee, 2005; Sánchez-Carrillo et al., 2009). Most available reports have studied the flux of organic matter and nutrients through a small mangrove creek (Boto and Wellington, 1988; Ayukai et al., 1998; Trott et al., 2004; Rezende et al., 2007; Sánchez-Carrillo et al., 2009). Very few studies have measured the nutrient flux between creeks/mangroves and estuaries (Moran et al., 1991; Tilley et al., 2002). Thus, it is difficult to assess the potential use of mangroves in extracting nutrients from pond effluents (Rivera-Monroy et al., 1999). This lack of understanding also complicates the control of shrimp pond development in mangrove estuaries. Robertson and Phillips (1995) estimated that 2–22 ha of mangrove forest is required for complete clearance of the nitrogen load in the effluent from a 1 ha intensive shrimp pond. However, Rivera-Monroy et al. (1999) argued that the required area was 0.04–0.12 ha. Shimoda et al. (2005b) estimated that 6.2 or 8.9 ha of mangrove forest was required by 1 ha shrimp ponds to fully process the phosphorus.

In this study, we hypothesized that the maintenance of estuarine water quality by mangroves occurs during flood periods. A before-and-after sampling design was used to measure changes in water quality during a tide cycle in a subtropical mangrove estuary. We sought to provide some insight into the changes in water quality during a regular tide cycle, and to further quantify the influence of mangroves on the aquatic environment.

The study was conducted in a subtropical mangrove wetland, the Zhangjiangkou Mangrove Reserve, located on the southeast coast of China (117°24′07″–117°30′00″ E, 23°53′45″–23°56′00″ N). The estuary is semi-enclosed and opens into the Taiwan Strait. It occupies ca. 2360 ha and is fringed by 117.9 ha of mangroves. The dominant species are *Avicennia marina*, *Kandelia obovata*, and *Aegiceras corniculatum*. The average tree height is about 2.3 m, and the canopy coverage is greater than 90%. Tides are semi-diurnal, and the average tide amplitude is 2.32 m. The flood period lasts around 6–7 h and the ebb period lasts about 5 h. Annual rainfall is 1714 mm, average temperature is 21.2 °C, and average water salinity is 19‰. The depth of the water column at high tide was about 0.4 m.

There were two water locks at the uppermost distribution point of the mangroves (Wa and Wb, Fig. 1). They were closed except on rainy days. To minimize the influence of river water on our surveys, all of the samples were taken on days with no rain. Thus, the estuary received no river influx or pond effluents, but rather was influenced only by tidal action and was virtually free of any terrestrial or freshwater influences.

Before the 1990s, most mangroves of the Zhangjiang Estuary were cleared for shrimp farming. Now, nearly the whole estuary is surrounded by semi-intensive ponds (Fig. 1). This pattern is representative of mangroves in China in general (Wang and Wang, 2007). These ponds are connected to seawater by waterspouts. The spouts were only opened during water exchange (discharge of pond water or influx of fresh seawater). The discharge of pond effluent was caused by gravity during the ebb period and the effluent was discharged into the estuary through creeks in mangroves or treeless mudflats. In contrast, fresh seawater was pumped into ponds during the flood period. Effluent is periodic. The frequency and extent of water exchange from ponds varied according to the stage of the growth cycle and the water salinity, ranging from 0% in the first month after stocking to 30% volume per week in the final growth and harvesting stages.

Based on the direction of tide flow, topographic conditions, and mangrove distribution, six sites were selected for sampling (Fig. 1). These sites were distributed along the tide path at different distances from the shoreline. Site 1 was at the mouth of the estuary and farthest from the mangroves. Site 2 was closer to the mangroves and located on a treeless mudflat. Site 3 was at the edge of the mangroves. Sites 4, 5, and 6 were within the treed areas.

From June 2005 to March 2006 (June 2005, September 2005, November 2005 and March 2006), surface water samples were collected from the 6 sites. The samples were taken 10–20 cm below the water surface. All samples were taken on spring tide days due to the fact that creeks are inaccessible by boat on neap tide days. Sampling was carried out with the tide, beginning at Site 1. The same actions were carried out at Sites 2–6, and were finished before the tide started to ebb. We then waited at Site 6 until the tide turned (i.e., water refluxing), and proceeded to take samples again in the opposite direction. Salinity, pH, and DO were measured *in situ* during the sampling process at a depth of 20 cm using portable meters (Star 3, Thermo Orion, USA). Transparency (light attenuation) was determined using a 25 cm diameter Secchi disk. All *in situ* measurements had three replicates. We collected three 500 mL water samples at each site and stored them on ice for chemical analysis within 1–2 d of collection.

The alkaline potassium supersulfate digestion-UV spectrophotometric method was used to measure total dissolved nitrogen (TN). The phosphomolybdenum-blue spectrophotometric method was used to measure the inorganic and total dissolved phosphorus (TP). The potassium dichromate spectrophotometric method was used to measure particulate organic carbon (POC). The H_2SO_4–$K_2Cr_2O_7$ oxidation spectrophotometric method was used to measure dissolved organic carbon (DOC). The alkaline $KMnO_4$ method was used to measure chemical oxygen demand (COD). All measurements followed Standard GB17387.4-1997 (National Marine Monitoring Standard of China, Part 4: Seawater Analysis) (State Bureau of Oceanic Administration, 1991).

The flux of materials was calculated using the 'Eulerian' method (Ayukai et al., 1998), whereby water flow (v) and material concentration (c) are measured at a fixed station (Site 3) and the net flux is calculated by adding up flux increments ($F = v, c$) over a the tidal cycle. The mean water depth during high tide in the vegetated areas of mangroves was 0.4 m. The current velocity was nearly zero during the highest tide.

A three-way ANOVA was performed, with sites (6 levels), seasons (4 levels) and tides (2 levels) were entered as fixed factors and used to compare change in water quality parameters. We used a paired samples test to compare the differences of water quality parameters between flood and ebb periods. For all tests a criterion of $p \leqslant 0.05$ was used to determine statistical significance.

The TN, TP and COD and transparency were all significantly affected by site, season and tide. The DOC and POC only showed significantly tidal and seasonal differences. There were no significant differences between flood and ebb tides in DO, pH and salinity, while these parameters showed significant site and season differences (Table 1).

Although the mean TN, TP, COD, and POC contents showed seasonal (Figs. 2A–6A) and spatial (Figs. 2B–6B) variation, there were no significant differences ($p > 0.05$). Based on the results of the paired samples test, the seasonal and spatial mean TN, TP, COD, and DOC contents were significantly higher during the flood period than during the ebb period. During a tide cycle, the average TN level declined by 14.1% (from 1.73 mg/L to 1.48 mg/L), the TP declined by 17.8% (from 58.43μg/L to 48.12 μg/L), COD level declined by 12.7% (from 1.14 mg/L to 0.99 mg/L), and the DOC level declined by 14.8% (from 0.15 mg/L to 0.13 mg/L) (Table 2).

For the POC, the seasonal and spatial mean contents were significantly higher during the ebb period than during the flood period. During a tide cycle, the average POC level increased by 3.4% (from 6.81 mg/L to 7.05 mg/L) (Table 2). At Site 3 (the edge of the mangroves), the mean POC content increased from 6.79 mg/L during the flood period to 7.07 mg/L during the ebb period. If we assume that all the increased POC originated from the mangrove and that the mean water depth in the mangrove was 0.4 m, the net output of organic carbon by means of POC in Zhangjiang mangrove estuary was 0.25 g $C/m^2/d$, or 81.8 g $C/m^2/yr$.

No consistent changes in DO, pH, and salinity were observed during a tide cycle (Fig. 7). However, water transparency increased by 16.3% (from 23.4 cm to 27.2 cm) (Table 2).

The paired samples test showed that strong contrasts in most water quality parameters (TN, TP, COD, DOC, POC, and transparency) were evident between the flood and ebb periods. As summarized above, the mangroves purify water by stripping N, P, and other deoxidizing matters from effluent and exporting organic carbon. These results also support our hypothesis that mangroves maintain estuarine water quality during flood tides.

From the flood period to the ebb period, the TN and TP contents in the water at the edge of the mangroves (Site 3) decreased from 1.65 mg/L to 1.34 mg/L and from 40.66μg/L to 32.99 μg/L, respectively. These results support the general view that mangroves conserve nitrogen and phosphorus. Using the Eulerian method, it was estimated that the mangroves of the Zhangjiang Estuary could trap nutrients at rates of 90.5 g $N/m^2/yr$ and 2.2 g $P/m^2/yr$, respectively.

Other researchers have estimated the amounts of N and P required to support total net mangrove growth were 21.9 $g/m^2/yr$ and 0.2 $g/m^2/yr$, respectively (Spain and Holt, 1980; Clough et al., 1983; Gong and Ong, 1990). Thus, the amount of nitrogen and phosphorus that enters mangroves is much higher than that needed for plant growth. Other mechanisms such as accumulation in sediments and microbial transformation play a role (Alongi, 1988, 1994; Corredor and Morell, 1994; Tam and Wong, 1999; Ye et al., 2001; Tam et al., 2009). In terms of wastewater-borne nitrogen, the relative importance of these processes varies and affects by many factors such as plant species, types of wastewater, and salinity (Ye et al., 2001). Pot cultivation experiments showed that most N and P were removed by soil. Under saline water condition, N nutrient removal efficiencies by *Kandelia candel* pot-cultivation systems were 92.7% (80.7% by soil and 12.0% by plant), and P

Table 1
Three-way ANOVA table on the effects of site, season and tide on the water quality parameters in the Zhangjiang Estuary, Fujian, China.

Factors	TN		TP		COD		DOC		POC	
	T	p	T	p	T	p	T	p	T	p
Si	19.229	<0.01	4.398	⩽0.05	16.482	<0.01	1.472	0.260	0.365	0.865
Ti	28.918	<0.01	5.508	⩽0.05	5.588	⩽0.05	4.429	⩽0.05	8.318	⩽0.05
Se	207.319	<0.01	49.913	<0.01	179.576	<0.01	22.434	<0.01	116.339	<0.01
Si × Se	11.064	<0.01	1.730	0.150	4.753	<0.01	1.120	0.418	2.355	0.054
Si × Ti	4.727	<0.01	0.214	0.951	1.243	0.338	0.669	0.654	0.376	0.858
Ti × Se	1.732	0.203	0.873	0.477	0.533	0.667	1.239	0.333	1.597	0.232
	Transparency		DO		pH		Salinity			
	T	p	T	p	T	p	T	p		
Si	19.111	<0.01	7.320	<0.01	22.832	<0.01	93.177	<0.01		
Ti	7.849	⩽0.05	0.133	0.721	3.805	0.070	0.033	0.858		
Se	7.961	<0.01	26.186	<0.01	160.433	<0.01	299.275	<0.01		
Si × Se	4.631	<0.01	4.928	<0.01	1.119	0.415	3.150	⩽0.05		
Si × Ti	1.050	0.428	0.941	0.487	1.802	0.173	4.563	⩽0.05		
Ti × Se	4.216	⩽0.05	3.346	0.053	0.345	0.793	1.754	0.202		

Si: Site; Ti: tide; Se: Season.

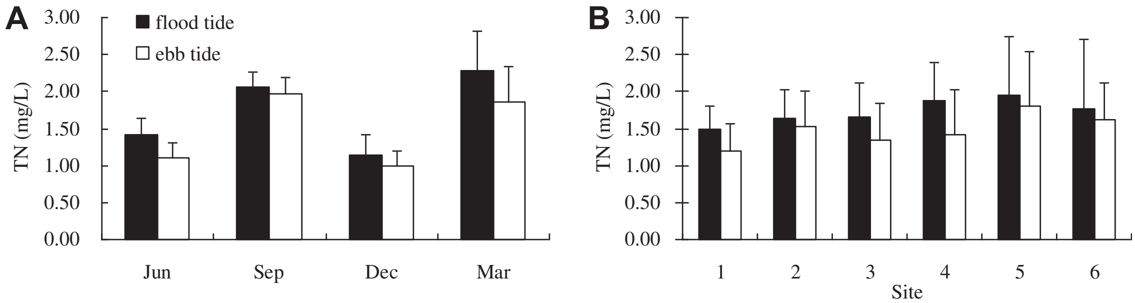

Fig. 2. Comparison of seasonal (A) and spatial (B) variation of the total dissolved nitrogen (TN) content during flood and ebb periods in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

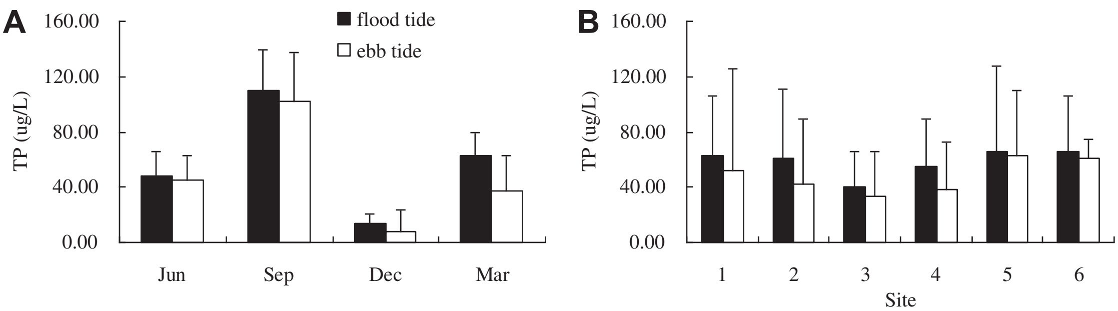

Fig. 3. Comparison of the seasonal (A) and spatial (B) variation in the total dissolved phosphorus (TP) content between flood and ebb periods in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

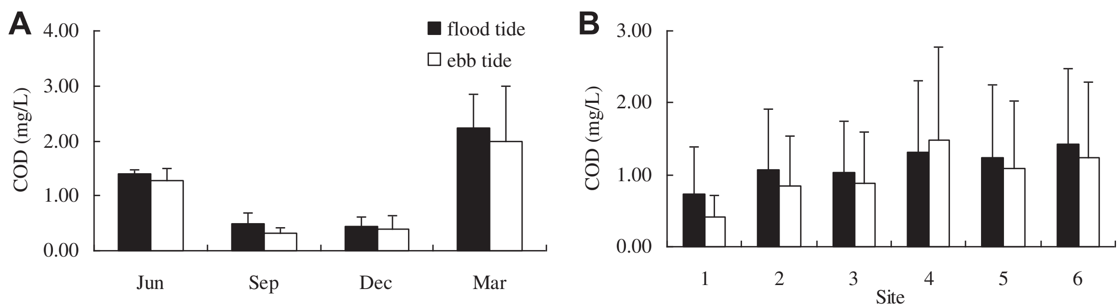

Fig. 4. Comparison of the seasonal (A) and spatial (B) variation in the chemical oxygen demand (COD) content between flood and ebb periods in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

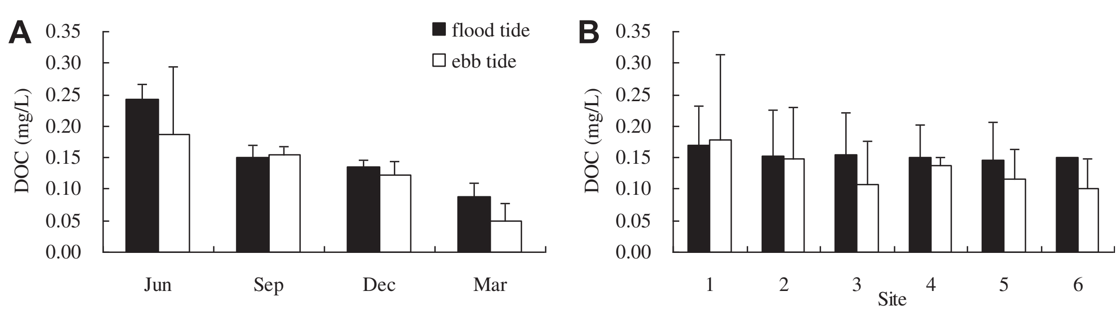

Fig. 5. Comparison of the seasonal (A) and spatial (B) variation in the dissolved organic carbon (DOC) content between flood and ebb periods in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

nutrient removal were 88.0% (84.2% by soil and 3.8% by plant) (Ye et al., 2001). Most pollutants were accumulated in the top layer (0–1.5 cm) of the soil tray, with little downward migration (Tam and Wong, 1996, 1999). In a recent greenhouse tide tank study, the plant uptake was less than 10% but 15–30% of the total nitrogen inputs were returned to atmosphere via nitrification–denitrification, and the rate was dependent on the tidal regime and the availability of oxygen in sediment (Tam et al., 2009). On average, about 15% (range: 3–47%) of total nitrogen input into mangrove soils is denitrified (Alongi, 2009). There is little evidence to reply

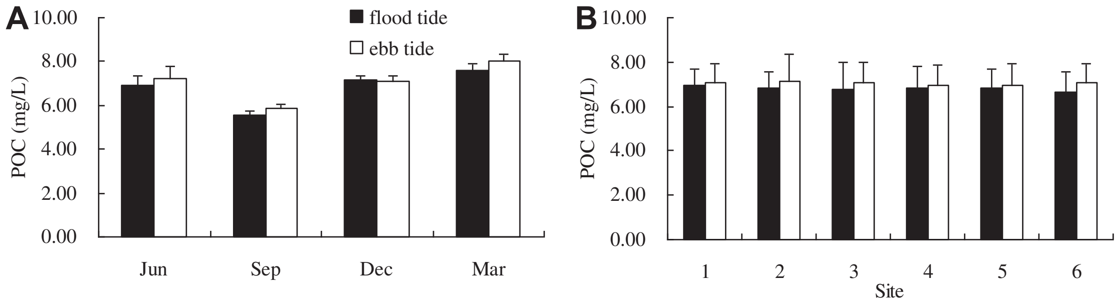

Fig. 6. Comparison of the seasonal (A) and spatial (B) variation in the particulate organic carbon (POC) content between flood and ebb periods in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

Table 2
Mean values and results of the paired samples test (between flood and ebb periods) of water quality parameters in the Zhangjiang Estuary, Fujian, China.

Index	Flood period	Ebb period	Change (%)	*T* value	*p* value
TN (mg/L)	1.73 ± 0.17	1.48 ± 0.21	−14.1	4.086	0.000
TP (μg/L)	58.43 ± 9.59	48.12 ± 12.25	−17.8	2.071	0.050
COD (mg/L)	1.14 ± 0.25	0.99 ± 0.37	−12.7	2.373	0.026
DOC (mg/L)	0.15 ± 0.01	0.13 ± 0.03	−14.8	2.381	0.026
POC (mg/L)	6.81 ± 0.10	7.05 ± 0.07	3.4	−2.953	0.007
Transparency (cm)	23.4 ± 2.9	27.2 ± 5.2	16.3	−2.735	0.012
DO (mg/L)	8.08 ± 1.05	7.90 ± 0.77	−2.2	0.284	0.770
pH	7.45 ± 0.08	7.49 ± 0.12	0.5	−1.869	0.074
Salinity (‰)	10.95 ± 2.37	10.96 ± 3.56	0.1	−0.187	0.853

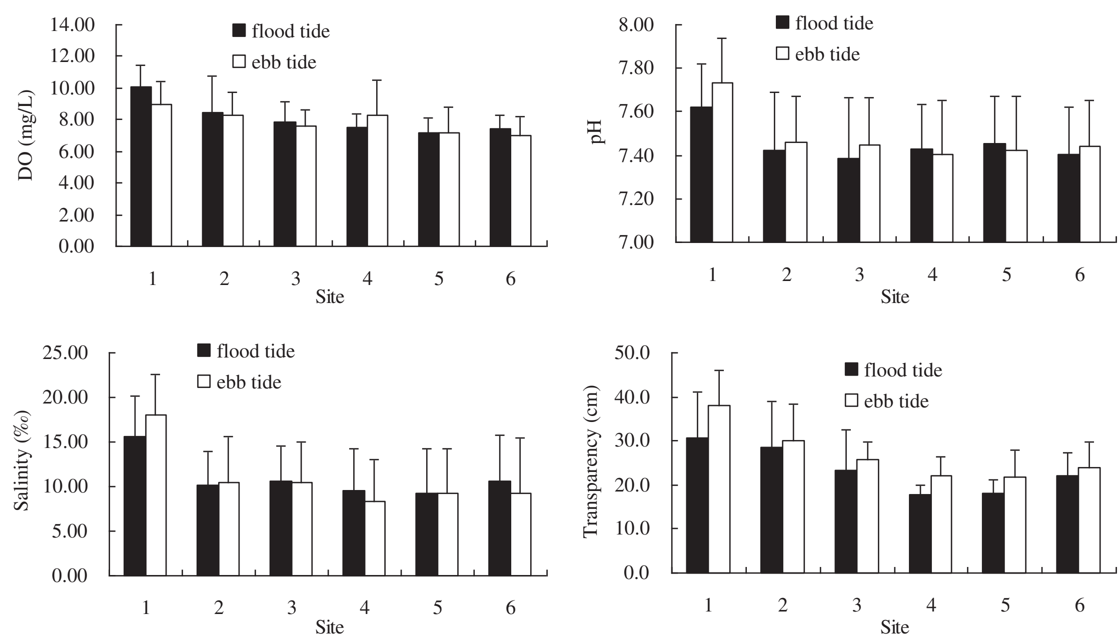

Fig. 7. Changes in the seasonal mean DO, pH, salinity, and transparency of the water at different sites in the Zhangjiang Estuary, Fujian, China. Site distributions see Fig. 1.

which mechanism is the most important in the field, because the complete soil N cycle has been studied in only three mangrove wetlands (Alongi, 2009).

Carbon export (not including leaf litter) was estimated directly by combining information on the movement of water though mangroves with the measurement of the POC and POD contents (Hogarth, 2007). About 81.8 g C/m^2/yr was exported from the Zhangjiang Estuary in the form of POC. This component comprised around 31.3% of the annual leaf-litter fall production, which was 534.3 g/m^2/yr (personal data, unpublished). This proportion is similar to the results (35.9%) from Hinchlnbrook Island in Queensland, Australia (Boto and Wellington, 1988). However, the estimated amount of carbon export at Zhangjiang Estuary in the form of POC was higher than that the amount exported at the Hinchinbrook Island mangrove (58.4 g C/m^2/yr) (Boto and Bunt, 1981).

The discharge of DOC to the adjacent ocean may be one of the dominant outputs of a mangrove forest. There was a net export of DOC (56 g C g/m^2/yr) in a riverine mangrove wetland along Shark River, FL (Romigh et al., 2006). According to Twilley (1985), DOC accounts for up to 75% of the total carbon export for infrequently flushed basin forests (64 g C g/m^2/yr). In North Brazil, DOC and POC were exported from the mangrove to the estuary in similar proportions (Dittmar and Lara, 2001). In Southeast Brazil, DOC was the major form of carbon exported to Sepetiba Bay (60%) (Rezende et al., 2007). By using a modeling approach, Machiwa and Hallberg (2002) found that DOC accounted for 80% of the total organic carbon export. In comparison, the DOC exchange at Zhangjiang Estuary was minimal, amounting to a net import of 13.7 g C/m^2/yr. A higher level of POC export and a lower level of DOC import were also reported for the Mngazana Estuary mangroves in South Africa (Rajkaran and Adams, 2007).

The export of plant litter or macro-particulate matter from mangroves is also important (Ayukai et al., 1998). However, no general consensus has been reached regarding other materials, such as nutrients and dissolved and particulate organic matter (Twilley, 1985; Dittmar and Lara, 2001). After reviewing published data, Hogarth (2007) concluded that no generalization regarding the import/export of carbon can be made. Wolanski et al. (1998) found that POC is imported into mangrove swamps particularly during spring tides in the Hinchinbrook Channel mangrove in Australia. In a microtidal semi-arid mangrove system in northwestern Mexico, Sánchez-Carrillo et al. (2009) found that TOC and DOC showed net imports during spring tides, while export occurred during neap tides. The mangrove system acted as a POC sink during the summer and as a source in the winter. Local environmental conditions (biotic and abiotic) have a site-specific influence on the magnitude of mangrove nutrient exchange, complicating the comparison of results between ecosystems (Sánchez-Carrillo et al., 2009).

Stable coastal boundary layer water can form on shorelines fringed by straight mangroves sheltered by headlands (Wolanski, 1992). Under such conditions, export effects will only be present over restricted distances. Geomorphologically, Zhangjiang Estuary is not sheltered by a headland (Fig. 1). However, constant and significant salinity changes between Sites 1 and 2 and almost no salinity changes from Sites 3 to 6 (Fig. 7) suggest that a coastal boundary layer also occurs within the Zhangjiang Estuary. This boundary layer is located between Sites 1 and 2. The existence of a coastal boundary layer will effectively reduced the extent of export from the mangroves to offshore areas and export effects will only be present over restricted distances (Lee, 1995). This is the case at the Zhangjiang Estuary. The export of POC was limited between Sites 1 and 2 (about 300 m from the edge of the mangroves). At Site 1, the variation in the mean POC contents in the water between the flood and ebb periods was only 0.07 mg/L (Fig. 6B). Thus, mangrove POC export had only very local effects and almost no effect on water quality at Site 1. Our results are consistent with the results from south Florida (Fleming et al., 1990), the Berry Islands of the Bahamas (Moran et al., 1991), and northern Brazil (Dittmar and Lara, 2001). Semi-enclosed topography, small tidal range (2.32 m), and the lack of rainfall during sampling periods may be the reasons for the reduced POC export distance.

Acknowledgements

The work was supported by the Natural Science Fund of China (Nos. 40876046 and 40376025) and Program for Innovative Research Team in Science and Technology in Fujian Province University. We thank the Administrative Bureau of Zhangjiang Estuary National Reserve for their help with the sampling. We are thankful to C.H. Song, Z.Y. Huang, Z.G. Geng, R.M. Qiu, M.R. Mu, Q.L. Jiang, and R.J. Zhang for their assistance in the field and laboratory.

References

Alongi, D.M., 1988. Bacterial productivity and microbial biomass in tropical mangrove sediments. Microb. Ecol. 15, 59–79.

Alongi, D.M., 1994. The role of bacteria in nutrient recycling in tropical mangrove and other coastal benthic ecosystems. Hydrobiologia 285, 19–32.

Alongi, D.M., 1996. The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests. J. Mar. Res. 54, 123–148.

Alongi, D.M., 2009. The Energetics of Mangrove Forests. Springer.

Ayukai, T., Miller, D., Wolanski, E., Spagnol, S., 1998. Fluxes of nutrients and dissolved and particulate organic carbon in two mangrove creeks in northeastern Australia. Mangroves Salt Marshes 2, 223–230.

Boto, K.G., Bunt, J.S., 1981. Tidal export of particulate organic matter from a Northern Australian mangrove system. Estuar. Coast. Shelf Sci. 13, 247–255.

Boto, K.G., Wellington, J.T., 1988. Seasonal variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove waterway. Mar. Ecol. Prog. Ser. 50, 151–160.

Briggs, M.R.P., Funge-Smith, S.J., 1994. A nutrient budget of some intensive marine shrimp ponds in Thailand. Aquacult. Res. 25, 789–811.

Burford, M.A., Glibert, P.M., 1999. Short-term nitrogen uptake and regeneration in early and late growth phase shrimp ponds. Aquacult. Res. 30, 215–227.

Chen, G.Z., Chen, G.K., Tam, N.F.Y., Wong, Y.S., 2000. Purifying effects of *Avicennia marina* simulated wetland system on sewage. Mar. Environ. Sci. 19 (4), 23–26 (in Chinese).

Chu, H.Y., Chen, N.C., Yeung, M.C., Tam, N.F.Y., Wong, Y.S., 1998. Tide-tank system simulating mangrove wetland for removal of nutrients and heavy metals from wastewater. Water Sci. Technol. 38, 361–368.

Clough, B.F., Boto, K.G., Attiwill, P.M., 1983. Mangroves and sewage: a reevaluation. In: Teas, H.J. (Ed.), Biology and Ecology of Mangroves. Dr. W. Junk Publishers, The Hague, pp. 151–161.

Corredor, J.E., Morell, J.M., 1994. Nitrate depuration of secondary sewage effluents in mangrove sediments. Estuaries 17, 295–300.

Costanzo, 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. Pollut. Bull. 48, 514–525.

Csavas, I., 1994. Important factors in the success of shrimp farming. World Aquacult. 25, 34–56.

Dittmar, T., Lara, R.J., 2001. Driving forces behind nutrient and organic matter dynamics in a mangrove tidal creek in north Brazil. Estuar. Coast. Shelf Sci. 52, 249–259.

Fleming, M., Lin, G., Sternberg, L.daS.L., 1990. Influence of mangrove detritus in an estuarine ecosystem. Bull. Mar. Sci. 47, 663–669.

Funge-Smith, S.J., Briggs, M.R.P., 1998. Nutrient budgets in intensive shrimp ponds: implications for sustainability. Aquaculture 164, 117–133.

Gautier, D., Amador, J., Newmark, F., 2001. The use of mangrove wetland as a biofilter to treat shrimp pond effluents: preliminary results of an experiment on the Caribbean coast of Colombia. Aquacult. Res. 32, 787–799.

Gong, W.K., Ong, J.E., 1990. Plant biomass and nutrient flux in a managed mangrove forest in Malaysia. Estuar. Coast. Shelf Sci. 31, 519–530.

Grant, J., Hatcher, A., Scott, D.B., Pocklington, P., Schafer, C.T., Winters, G.V., 1995. A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities. Estuaries 18, 124–144.

Hogarth, P.J., 2007. The Biology of Mangroves and Salt Marches, third ed. Oxford University Press, Oxford.

Huang, F., Xia, B., Dai, X., Chen, G., 2004. Bacteria ecology in planting–culturing system. Chin. J. Appl. Ecol. 15, 1030–1034 (in Chinese).

Jackson, C., Preston, N.P., Thompson, P.A., Burford, M., 2003. Nitrogen budget and effluent nitrogen components at an intensive shrimp farm. Aquaculture 218, 397–411.

Jones, A.B., O'Donohue, M.J., Udy, J., Dennison, W.C., 2001. Assessing ecological impacts of shrimp and sewage effluent: biological indicators with standard water quality analyses. Estuar. Coast. Shelf Sci. 52, 91–109.

Lee, S.Y., 1995. Mangrove outwelling: a review. Hydrobiologia 295, 203–212.

Lin, C.K., 1989. Prawn culture in Taiwan. What went wrong? World Aquacult. 20, 19–20.

Machiwa, J.F., Hallberg, R.O., 2002. An empirical model of the fate of organic carbon in a mangrove forest partly affected by anthropogenic activity. Ecol. Model. 147, 69–83.

McKinnon, A.D., Trott, L.A., Alongi, D.M., Davidson, A., 2002. Water column production and nutrient characteristics in mangrove creeks receiving shrimp farm effluent. Aquacult. Res. 33, 55–73.

Mishra, R.R., Rath, B., Thatoi, H., 2008. Water quality assessment of aquaculture ponds located in Bhitarkanika mangrove ecosystem, Orissa, India. Turkish J. Fish. Aquat. Sci. 8, 71–77.

Moran, M.A., Wicks, R.J., Hodson, R.E., 1991. Export of dissolved organic matter from a mangrove swamp ecosystem: evidence from natural fluorescence, dissolved lignin phenols, and bacterial secondary production. Mar. Ecol. Prog. Ser. 76, 175–184.

Moriarty, D.J.W., 1997. The role of microorganisms in aquaculture ponds. Aquaculture 151, 333–349.

Naylor, R.L., Goldburg, R.J., Mooney, H., Beveridge, M., Clay, J., Folke, C., Kautsky, N., Lubchemco, J., Primavera, J., Wiliams, M., 1998. Nature's subsidies to shrimp and salmon farming. Science 282, 883–884.

Nedwell, D.B., 1975. Inorganic nitrogen metabolism in a eutrophicated tropical mangrove estuary. Water Res. 9, 221–231.

Paez-Osuna, F., Guerrero-Galvan, S.R., Ruiz-Fernandez, A.C., Espinoza-Angulo, R., 1997. Fluxes and mass balances of nutrients in a semi-intensive shrimp farm in north-western Mexico. Mar. Pollut. Bull. 34, 290–297.

Preston, N.P., Jackson, C., Thompson, P.A., Austin, M., Burford, M., 2000. Prawn Farm Effluent: Composition, Origin and Treatment. Fishing Research and Development Corporation Final Report 95/162. FRDC, Canberra.

Rajkaran, A., Adams, J.B., 2007. Mangrove litter production and organic carbon pools in the Mngazana Estuary, South Africa. Afr. J. Aquat. Sci. 32, 17–25.
Rezende, C.E., Lacerda, L.D., Ovalle, A.R.C., Silva, L.F.F., 2007. Dial organic carbon fluctuations in a mangrove tidal creek in Sepetiba bay, Southeast Brazil. Brazilian J. Biol. 67, 673–680.
Rivera-Monroy, V.H., Torres, L.A., Bahamon, N., Newmark, F., Twilley, R.R., 1999. The potential use of mangrove forests as nitrogen sinks of aquaculture pond effluents: the role of denitrification. J. World Shrimp Aquacult. Soc. 30, 12–25.
Robertson, A.I., Phillips, M.J., 1995. Mangroves as filters of shrimp pond effluent: predictions and biogeochemical research needs. Hydrobiologia 295, 311–321.
Romigh, M.M., Davis, S.E., Rivera-Monry, V.H., Twilley, R.R., 2006. Flux of organic carbon in a riverine mangrove wetland in the Florida Coastal Everglades. Hydrobiologia 569, 505–516.
Saenger, P. (Ed.), 2002. Mangrove Ecology, Silviculture and Conservation. Kluwer Academic Publishers, Dordrecht.
Samocha, T.M., Lawrence, A.L., 1997. Shrimp farms effluent waters, environmental impact and potential treatment methods. In: Keller, B.J., Park, P.K., MacVey, J.P., Takayanaji K., Hosoya, K. (Eds.), Interactions Between Cultured Species and Naturally Occurring Species in the Environment. UJNR Technical Report No 24. Texas A & M University, Corpus Christi, Texas, pp. 33–57.
Sánchez-Carrillo, S., Sánchez-Andrés, R., Alatorre, L.C., Angeler, D.G., Álvarez-Cobelas, M., Arreola-Lizárraga, J.A., 2009. Nutrient fluxes in a semi-arid microtidal mangrove wetland in the Gulf of California. Estuar. Coast. Shelf Sci. 82, 654–662.
Sansanayuth, P., Phadungchep, A., Ngammontha, S., Ngdngam, S., Sukasem, P., Hoshino, H., Ttabucanon, M.S., 1996. Shrimp pond effluent: pollution problems and treatment by constructed wetlands. Water Sci. Technol. 34, 93–98.
Shimoda, T., Fujioka, Y., Srithong, C., Aryuthaka, C., 2007. Effect of water exchange with mangrove enclosures based on nitrogen budget in *Penaeus monodon* aquaculture ponds. Fish. Sci. 73, 221–226.
Shimoda, T., Srithong, C., Aryuthaka, C., 2005a. Attempt at purification of effluent and sediment in shrimp aquaculture ponds using mangrove trees. Japan Agri. Res. Quart. 39, 139–145.
Shimoda, T., Srithong, C., Aryuthaka, C., 2005b. Phosphorus budget in shrimp aquaculture pond with mangrove enclosure and aquaculture performance. Fish. Sci. 71, 1249–1255.
Spain, A.V., Holt, J.V., 1980. The Elemental Status of the Foliage and Branchwood of Seven Mangrove Species from Northern Queensland. Division of Soils Divisional Report, No. 49. CSIRO, Australia.
State Bureau of Oceanic Administration of China, 1991. National Marine Monitoring Standard of China. Ocean Press, Beijing.
Tam, N.F.Y., Wong, A.H.Y., Wong, M.H., Wong, Y.S., 2009. Mass balance of nitrogen in constructed mangrove wetlands receiving ammonium-rich wastewater: effects of tidal regime and carbon supply. Ecol. Eng. 35, 453–462.
Tam, N.F.Y., Wong, Y.S., 1993. Retention of nutrients and heavy metals in mangrove sediment receiving wastewater of different strengths. Environ. Technol. 14, 719–729.
Tam, N.F.Y., Wong, Y.S., 1999. Mangrove soils in removing pollutants from municipal wastewater of different salinities. J. Environ. Qual. 28, 556–564.
Tam, N.F.Y., Wong, Y.S., 1996. Retention of wastewater-borne nitrogen and phosphorus in mangrove soils. Environ. Technol. 17, 851–859.
Tilley, D.R., Badrinarayanan, H., Rosati, R., Son, J., 2002. Constructed wetlands as recirculation filters in large-scale shrimp aquaculture. Aquacult. Eng. 26, 81–109.
Trott, L.A., Alongi, D.M., 2000. The impact of shrimp pond effluent on water quality and phytoplankton biomass in a tropical mangrove estuary. Mar. Pollut. Bull. 40, 947–951.
Trott, L.A., McKinnon, A.D., Alongi, D.M., Davidson, A., Burford, M.A., 2004. Carbon and nitrogen processes in a mangrove creek receiving shrimp farm effluent. Estuar. Coast. Shelf Sci. 59, 197–207.
Twilley, R.R., 1985. The exchange of organic carbon in basin mangrove forests in a southwest Florida estuary. Estuar. Coast. Shelf Sci. 20, 543–557.
Twilley, R.R., 1988. Coupling of mangroves to the productivity of estuarine and coastal waters. In: jansson B.O. (Ed.), Coastal-offshore Ecosystems: Interactions. Lecture Notes Coastal Estuarine Stud. 22. Springer-Verlag, Berlin, pp. 155–180.
Twilley, R.R., Bodero, A., Robadue, D., 1993. Mangrove ecosystem biodiversity and conservation in Ecuador. In: Potter, C.S., Cohen, J.I., Janczewski, D. (Eds.), Perspectives on Biodiversity: Case Studies of Genetic Resource Conservation and Development. AAAS Press, Washington, DC, USA, pp. 105–127.
Wang, W.Q., Wang, M. (Eds.), 2007. The Mangroves of China. Science Press, Beijing.
Werry, J., Lee, S.Y., 2005. Grapsid crabs mediate link between mangrove litter production and estuarine planktonic food chains. Mar. Ecol. Prog. Ser. 293, 165–176.
Wolanski, E., 1992. Hydrodynamics of mangrove swamps and their coastal waters. In: Jaccarini, V., Martens, E. (Eds.), The Ecology of Mangroves and Related Systems. Kluwer Academic Publisher, Belgium, pp. 141–161.
Wolanski, E., Spagnol, S., Ayukai, T., 1998. Field and model studies of the fate of particulate carbon in mangrove-fringed Hinchinbrook Channel, Australia. Mangroves Salt Marshes 2, 205–221.
Wong, Y.S., Lan, C.Y., Chen, G.Z., Li, S.H., Chen, X.R., Liu, Z.P., Tam, N.F.Y., 1995. Effect of wastewater discharge on nutrient contamination of mangrove soils and plants. Hydrobiologia 295, 243–254.
Wong, Y.S., Tam, N.F.Y., Chen, G.Z., Ma, H., 1997. Response of *Aegiceras corniculatum* to synthetic sewage under simulated tidal conditions. Hydrobiologia 352, 89–96.
Wu, Y., Chung, A., Tam, N.F.Y., Pi, N., Wong, M.H., 2008. Constructed mangrove wetland as secondary treatment system for municipal wastewater. Ecol. Eng. 34, 137–146.
Ye, Y., Tam, N.F.Y., Wong, Y.S., 2001. Livestock wastewater treatment by a mangrove pot-cultivation system and the effect of salinity on the nutrient removal efficiency. Mar. Pollut. Bull. 42, 512–520.
Zhang, J.H., Li, M., Chen, G.Z., 1999. The absorption and the potential capability in purificating N and P in sugar wastewater by mangrove wetland. Chongqing Environ. Sci. 21 (6), 39–41 (in Chinese).