ELSEVIER

Volume 47 15 September 2012 ISSN 0278-4343

CONTINENTAL SHELF RESEARCH

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Continental Shelf Research 47 (2012) 42–54

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

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

Research papers

Diversity of demersal fish in the East China Sea: Implication of eutrophication and fishery

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ARTICLE INFO

Article history:
Received 25 January 2012
Received in revised form
22 June 2012
Accepted 25 June 2012
Available online 20 July 2012

Keywords:
Demersal fish
Nutrients
Eutrophication
Hypoxia
East China Sea

ABSTRACT

The environment of the East China Sea has been greatly impacted by both fishing and land-based pollution over the past decades, with a concomitant decline of fishery resources. Imposition of a seasonal fishing moratorium and a trawling prohibition zone has failed to engender recovery of fish communities. To help understand the respective impacts of environmental factors and fishing activities in the East China Sea ecosystem, fish samples and environmental parameters were collected in prohibited and open fishing areas, during the seasonal fishing moratorium. The inshore area of the East China Sea, corresponding to the prohibited zone for trawling, had extremely high nutrient concentrations and relatively low dissolved oxygen. The diversity index of demersal fish showed significantly negative correlations with nutrient concentrations and positive correlations with bottom-water dissolved oxygen. The inshore area of the East China Sea was heavily dominated by small-sized fishes, such as Gobiids—*Amblychaeturichthys hexanema* and Apogonids—*Apogon lineatus*, reflecting low survival of most fish species. In contrast, the offshore areas, with lower nutrient concentrations and higher dissolved oxygen, had higher biodiversity. These findings suggest that eutrophication and subsequent hypoxia is responsible for the limited recovery of fishery resources in the trawling prohibition area of the East China Sea. Therefore, a multi-pronged fishery management that involves both fishing restriction and environmental improvement is urgently needed in the East China Sea.

1. Introduction

The East China Sea (ECS) possesses the largest continental shelf area in the northwestern Pacific Ocean of approximately 7.7×10^5 km^2. Water depth, salinity, nutrient and chlorophyll concentrations show gradients from the coast to offshore areas on the ECS continental shelf (Chen and Shen, 1995; Yu and Xian, 2009). This area has complex hydrology due to the influence of several currents and water masses, notably the Kuroshio Current, Kuroshio Branch Current (KBC), China Coastal Water (CCW) and Changjiang Diluted Water (CDW) (Chen et al., 1994; Katoh, 2000; Ichikawa and Beardsley, 2002); and the CDW affected area is especially characterized by high productivity in summer (Gong et al., 1996, 2003, 2006). As one of the most important fishing grounds in the west Pacific, the ECS has been heavily exploited since the 1980s. The total fishing power in the ECS increased by a factor of 7.6 between 1960 and the 1990s, whereas catch per unit of effort declined by a factor of 3 (Chen and Shen, 1995). Biodiversity and abundance of commercial fish species had significantly decreased (Cheng and Yu, 2004; Jiang et al., 2009). In order to restore fishery resources, the Chinese government implemented a summer fishing moratorium (from June 16th to September 16th) beginning in 1998. This measure was intended to protect the larvae and juveniles of commercial species and to restore the disturbed marine ecosystem. Since the surveys in 2000–2007 did not find effective recovery of the fish community structure and ecological function (Jiang et al., 2009), we hypothesize that other environmental factors, such as eutrophication, may play the major role in regulating the ecological process in the coastal areas of the ECS.

The ECS environment, especially coastal waters, also has been profoundly influenced by land-based pollution in the recent decades. The human population of Chinese provinces adjacent to the ECS exceeded 529 million by 2000 (Li and Daler, 2004) and continues to increase in main provinces and the cities in the Changjiang basin (Chai et al., 2009; Shen and Liu, 2009). Anthropogenic pollutants, including sewage, nutrients, and sediments, from this area enter the sea with river runoff. Nutrients are the most dominant pollutant in the Changjiang Estuary and the adjacent ECS (Li and Daler, 2004). Since 1960s, the application of

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http://dx.doi.org/10.1016/j.csr.2012.06.011

chemical fertilizer to the Changjiang river basin increased rapidly; and nutrient concentrations (dissolved inorganic nitrogen and phosphate) of the Changjiang water increased by a factor of 5 from the 1960s to the end of 1990s (Wang, 2006; Li et al., 2007b). Over-enrichment of nutrients has increased the frequency of red tide events from less than 10 times per year in the 1930s to more than 80 times per year in 2005 (Zhou et al., 2008). In addition, coastal hypoxia (dissolved oxygen < 2 mg l^{-1}) was first documented in August 1959 over an area of 1900 km^2. In recent decades, hypoxia has been seasonally recurrent off the Changjiang estuary with dramatically increased area up to more than 12,000 km^2 (Li et al., 2002; Chen et al., 2007; Wei et al., 2007). Hypoxia in the ECS generally occurs in late summer due to the elevated settlement of organic matters and strong stratification of water column, reaching minimal O_2 and maximal area in August, and disappears in late September to October (Chen et al., 2007; Wei et al., 2007).

Since pelagic and benthic ecosystems tend to be tightly coupled on the continental shelf, dead organic matter can reach the sea bottom and further deplete oxygen due to bacterial decomposition (Graf, 1992). Hypoxia can benefit fishery resources through upward trophic transfer merely within a narrow range of conditions that hypoxia-resistant fishes can consume stressed prey (e.g. crustacean). Even though ecological consequences of hypoxia may vary in magnitude, most of the time, hypoxia tends to damage or trigger collapses of local fish stocks (Caddy, 1993; Diaz and Rosenberg, 1995; Diaz, 2001).

An understanding of variability in fish assemblages and habitat characteristics is a prerequisite to the formulation of conservation advice for restoration of fish communities (Naiman and Latterell, 2005; Rice, 2005). Nevertheless, the relationships between fish assemblages and the environmental status of the ECS are still poorly known. Previous studies on ECS fish assemblages mainly focused on life history traits and stock dynamics of a few commercial species (Chen et al., 1997; Liu and Zhan, 1999; Lin et al., 2006). Some researchers investigated species composition and biodiversity of whole fish assemblages adjacent to the Changjiang Estuary (Li et al., 2006, 2007a) and others investigated environmental effects on fish assemblages (Yu and Xian, 2009). However these studies covered only limited areas around the Changjiang River estuary and might fail to reflect the anthropogenic impacts on benthic ecosystem of the ECS. Hence large scale of biological and environmental surveys across the ECS is necessary to provide a comprehensive understanding of the present status of the ECS ecosystem.

Over the past decades, the environment of the ECS has been impacted by both fishing and land-based pollution (Li and Daler, 2004; Jiang et al., 2009). In order to understand the possible effects of environmental factors and fishing activities, bottom trawl surveys were conducted during the summer fishing moratorium period. Trawls were also conducted within year-round fishing prohibition areas to test our hypothesis that it is environmental factors rather than fishing that affect ecological status in the coastal areas. Demersal fish are major components of the ECS ecosystem (Chen and Shen, 1995), and show quick responses to habitat degradation such as the enrichment of nutrients, organic matter load, and decrease of dissolved oxygen (DO) (Rosenberg et al., 1992; Diaz, 2001; Grall and Chauvaud, 2002). By sampling demersal fishes over a large scale and collecting in situ environmental variables, this study provides new insights into the ecological processes that drive the variability of fish assemblages in the ECS ecosystem.

2. Materials and methods

2.1. Sampling sites

Environmental characteristics were investigated on five inshore to offshore transects, among which three transects with nine sites were selected to collect the demersal fish. Sampling area in present study extended from 26°30′ to 30°30′N and from 121°00′ to 126°00′E (Fig. 1). Transects A and B were located in the northern ECS and transect C was in the southern ECS. Environmental observation conducted on the transect E1 and E2 help obtain the comprehensive variation of environmental variables. Among these investigated stations, A1, B1, E1-1 and E2-1 are adjacent to the Changjiang estuary and Hangzhou Gulf and inside the year-round trawling-prohibition zone (Fig. 1).

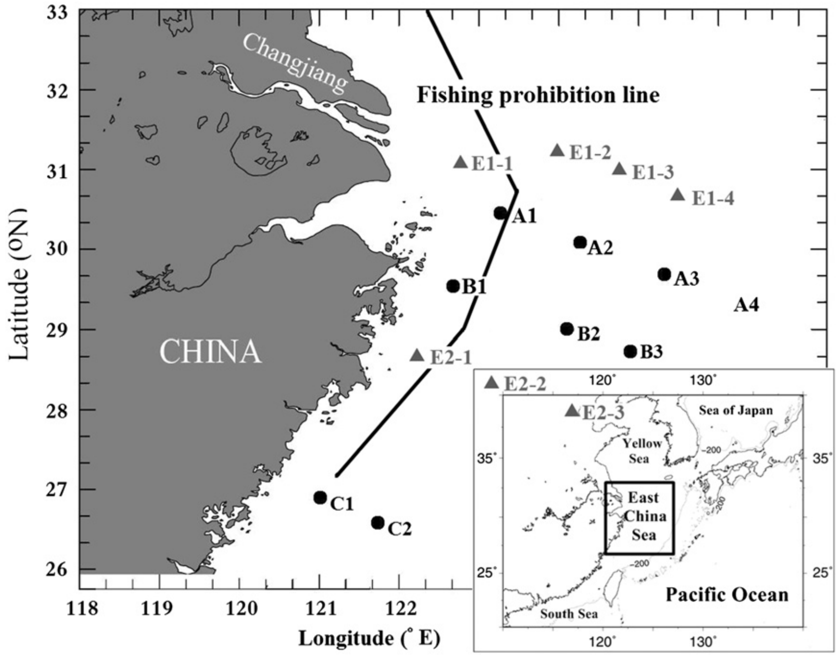

Fig. 1. Sampling sites in the East China Sea in July 2008. The solid line defines the coastal area within which trawling is prohibited year-round. Black circles: sampling sites for demersal fish collection; gray triangles: sampling sites for environmental observation.

2.2. Fish sampling and parameter measurements

Demersal fish were collected on the R/V Ocean Researcher I from 3 to 13 July 2008 with a bottom beam trawl, which was 4.7 m in width, 0.28 m in height and had a mesh size of $15 \times 15\ mm^2$. One trawl was conducted at each site and duration of each haul was 30 min with the average ship speed of 2.5 knots (1 knot= $1.852\ km\ h^{-1}$). In order to estimate the trawled area, the GPS locations were recorded at the times when the trawl first touched bottom and when the winch started to haul back. A total of nine trawls at depths between 45 and 102 m were conducted. For each trawl, the sampled organisms were frozen immediately and the species and number of demersal fishes were determined in the laboratory. Standard length from snout to the posterior end of the trunk was also measured (for macrourids, total length was measured). For species with more than 30 individuals collected in the same sampling site, measurements were conducted on a subsample of 30 randomly sampled individuals. The composition of subsample was used to estimate the length-frequency distribution (2 cm interval) of total catches. The length frequencies of all species in the same sample site were then examined to determine the overall size spectrum of each site. Hydrographic data including vertical temperature, salinity and DO profiles were measured by probes mounted on the CTD (SBE9/11plus, Seabird Inc., USA) with an interval of 1 m water depth. Before the cruising, the oxygen sensor (SBE43, Seabird Inc., USA) were manufacturer-calibrated with a precision of $\pm 1\ \mu M$. Reliability of the DO probe can be proved by the value of 102% oxygen saturation in sea surface measurement. Water samples for nutrients and chlorophyll *a* measurements were taken by the CTD rosette (Model 1015, General Oceanics Inc., USA) assembly. For chlorophyll *a* analysis, water samples were filtered through a GF/F filter paper (Whatman, 47 mm) and determined fluorometrically. Determination of inorganic nutrients was made using analytic methods described in Parsons et al. (1984), Welschmeyer (1994) and Gong et al. (2000). For inorganic nitrogen, concentrations of dissolved inorganic nitrogen (DIN), including nitrate (NO_3), nitrite (NO_2) and ammonium (NH_4), were all determined independently and then pooled as dissolved inorganic nitrogen (DIN) for calculation. The analytic precision for salinity, nitrate, phosphate, silicate, oxygen and Chlorophyll *a* were ± 0.003 psu, 0.3 μM, 0.01 μM, 0.5 μM, 0.5 μM and $0.02\ mg\ m^{-3}$, respectively.

2.3. Data analyses

Principal component analysis (PCA) was used to explore the main environmental characters that constituted variations among studied sites and to reflect the similarity/dissimilarity of environmental characters among sites by two dimensions. Close proximity of sites on these PCA graphs indicates similar environmental characteristics. Concentrations of nutrients and chlorophyll *a* were $\log_{10}$ transformed for analysis.

Pelagic fish were taken in a few trawls but were excluded from statistical analyses. *Amblychaeturichthys hexanema*, *Pennahia argentata* and *Apogon lineatus* were commonly found, and their standard lengths were compared among stations with one-way ANOVA when sample size was >30 individuals or by the Kruskal–Wallis rank test when sample size was <30 individuals. Tukey's multiple comparison analysis was used to identify groups that were significantly different from others.

Community properties, including species richness (S), Shannon diversity index (H') and Pielou's evenness index (J'), were calculated using the Plymouth Routines in Multivariate Ecological Research (PRIMER) statistical software package (v. 5) (Clarke and Gorley, 2001). Dominance curves, the plot of percentage cumulative abundance among fish species rank, were also used to demonstrate dominance patterns in the communities in each site. Similarity in demersal fish community structures among sites were displayed by group average clustering based on triangular matrices of Bray–Curtis similarity of fourth root transformed abundance data.

For the species-environment correlations, canonical correspondence analysis (CCA) was used to reveal the main environmental factors that corresponding to the distribution patterns of demersal fishes. Only those fish species whose abundance accounted for more than 2% were used for the computation because rare species may mislead the ordination (Snodgrass and Meffe, 1998). For the community–environment relationships, Spearman's rank correlations between biological indices (species richness, biodiversity, evenness and abundance) and environmental (latitude, temperature, salinity, depth, DO and nutrient concentrations) and biological (chlorophyll *a* concentration) variables were calculated to investigate relations between fish assemblages and environmental conditions.

3. Results

3.1. Environmental characteristics

The environmental properties were greatly different among sampling sites (Table 1). Most of the inshore sites, including E1-1, E2-1, A1 and B1 were affected by Changjiang Diluted Water (CDW), which is characterized by the salinity lower than 31 in

Table 1
Environmental information of the surveyed sites in the East China Sea.

Sampling sites	Depth (m)	Temperature (°C)	Salinity	Chlorophyll *a* ($mg\ m^{-3}$)	DIN (μM)	PO4 (μM)	SiO3 (μM)	DO (b) ($mg\ l^{-1}$)
A1	60	25.10	28.52	3.33	23.42	0.29	24.30	4.43
A2	59	27.41	33.28	0.13	1.57	0.07	1.70	5.56
A3	90	27.02	31.90	0.58	2.22	0.08	1.10	4.46
A4	102	28.81	32.63	0.14	1.44	0.06	2.20	4.97
B1	45	24.26	28.31	2.28	35.78	0.78	30.20	3.02
B2	69	27.35	33.89	0.17	1.31	0.06	3.20	5.41
B3	45	27.78	33.39	0.12	1.34	0.06	2.50	4.65
C1	50	26.57	33.76	0.12	0.94	0.10	1.40	5.54
C2	80	28.14	33.09	0.15	1.14	0.27	4.30	5.58
E1-1	46	22.76	25.62	3.27	32.67	0.84	35.70	2.54
E1-2	15	26.37	26.49	0.59	16.15	0.16	4.70	3.84
E1-3	54	27.63	29.29	0.46	8.34	0.13	6.60	5.30
E1-4	65	27.04	31.63	0.43	1.65	0.12	8.70	6.77
E2-1	35	25.48	30.91	3.84	19.95	0.47	20.30	2.20
E2-2	81	28.31	33.67	0.15	1.87	0.10	3.00	5.05
E2-3	98	29.31	33.86	0.13	1.09	0.08	2.80	5.40

DIN: dissolved inorganic nitrogen, b: bottom-water measurements.

the surface water (Gong et al., 1996). Principal components 1 (PC1, eigen value = 6.51) and 2 (PC2, eigen value = 1.13) explained 72.37% and 12.60% of the variations in environmental variables, respectively (Table 2). Environmental characteristics of inshore sites E1-1, E2-1, A1 and B1 differed distinctly from other sites (Table 2 and Fig. 2). These inshore sites were located on the right side of PC1, which was characterized by high trophic state, including enriched nutrient (DIN, PO_4 and SiO_3) and chlorophyll *a* concentrations. In contrast, offshore sites and southern sites were generally located on the left side of PC1, with the environmental characteristics of higher surface-water temperature, salinity and bottom-water DO. PC2 distinguish the latitudinal difference between the northern (trans. E1 and A at the upper part) and southern ECS (trans. E2-1 and C at the lower part). Overall, the northern sites group showed highest dissimilar environmental characteristics with other studied sites.

Table 2
Summary of principal component analysis (PCA) of 9 environmental variables in each study site.

Principal component analysis	Axis I	Axis II
Cumulative percentage variance		
Eigen value	6.51	1.13
% Variation	72.37	12.60
% Cum. Variation	72.37	84.97
Factor-variable correlations (factor loadings)		
Depth	−0.68	−0.35
Latitude	0.52	0.77
Temp. (s)	−0.94	0.02
Sal. (s)	−0.88	−0.38
Chl *a* (s)	0.89	−0.24
DIN (s)	0.98	−0.07
PO_4 (s)	0.90	−0.31
SiO_3 (s)	0.94	−0.19
DO (b)	−0.83	0.28
Factor coordinates of cases		
A1	2.68	0.17
A2	−1.43	0.89
A3	−1.14	0.12
A4	−2.10	−0.12
B1	4.34	−0.96
B2	−1.69	0.07
B3	−1.88	−0.51
C1	−1.64	−0.70
C2	−1.94	−1.41
E1-1	5.82	−0.15
E1-2	1.64	2.36
E1-3	−0.14	1.70
E1-4	−1.05	1.42
E2-1	3.06	−1.46
E2-2	−1.94	−0.54
E2-3	−2.60	−0.87

Temp: temperature, sal: salinity, Chl *a*: chlorophyll *a*, TM: transmittance, DIN: dissolved inorganic nitrogen; (s): surface, (b): bottom.

Among the trawled sites, vertical profiles of water temperature, salinity of st. A1 and B1 exhibited obvious thermo- and halo-cline layers (Fig. 3) and DO sharply decreased below ca. 10–20 m depth (Fig. 4). DO concentrations in bottom waters reached 4.4 (60% O_2 saturation) and 3.0 mg l^{-1} (40% O_2 saturation) at st. A1 and B1, respectively. The other sites showed relatively constant salinity and gradually decreased temperature from surface to bottom water. In addition to st. A1 and B1, another two inshore sites also demonstrated strong water stratification and abruptly decreasing DO, which reached 2.5 (34% O_2 saturation) and 2.2 mg l^{-1} (29% O_2 saturation) at st. E1-1 and E2-1, respectively (Table 1 and Fig. 5).

3.2. Fish assemblage characteristics

3.2.1. Fish assemblage structure

A total of 71 species belonging to 42 families were found in 3935 individuals. About 80% of the total catch was composed of 7 species, which are *Amblychaeturichthys hexanema* (26%), *Champsodon snyderi* (15%), *Apogon lineatus* (13%), *Caelorinchus multispinulosus* (11%), *Lepidotrigla kishinouyei* (6%), *Cynoglossus interruptus* (5%), and *Repomucenus virgis* (4%). Cluster analysis of species composition placed the sites in 3 groups: southern, north-offshore and north-inshore (Fig. 6). Sites B1 and A3 showed the lowest similarity to other sites. Sites in the southern group were dominated by *Johnius grypotus* and other sciaenids, which were recorded as a wide-distributed species along the Chinese coast (Yamada et al., 2007). Sites of the north-inshore group were abundant in Apogonids—*Apogon lineatus* and Gobiids (*Amblychaeturichthys hexanema*), which are low trophic level organisms that are consumed by many commercial fishes (Yamada et al. 2007). Sites of the north-offshore group shared abundant Champsodontids (*Champsodon snyderi*). The greatest dissimilarity between the estuarine site B1 and other groups was attributed to the extreme dominance of *A. hexanema* in B1 (77%). The transitional site A3 was unique for its abundant *Caelorinchus multispinulosus* (Table 3).

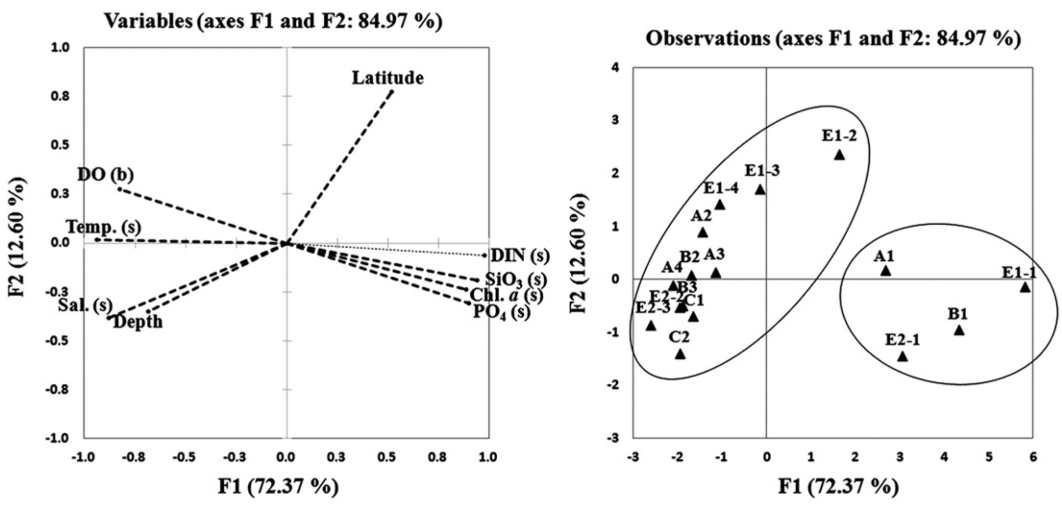

Fig. 2. PCA plot of 9 environmental variables at each site. The oval circles designate two major groups of the study sites.

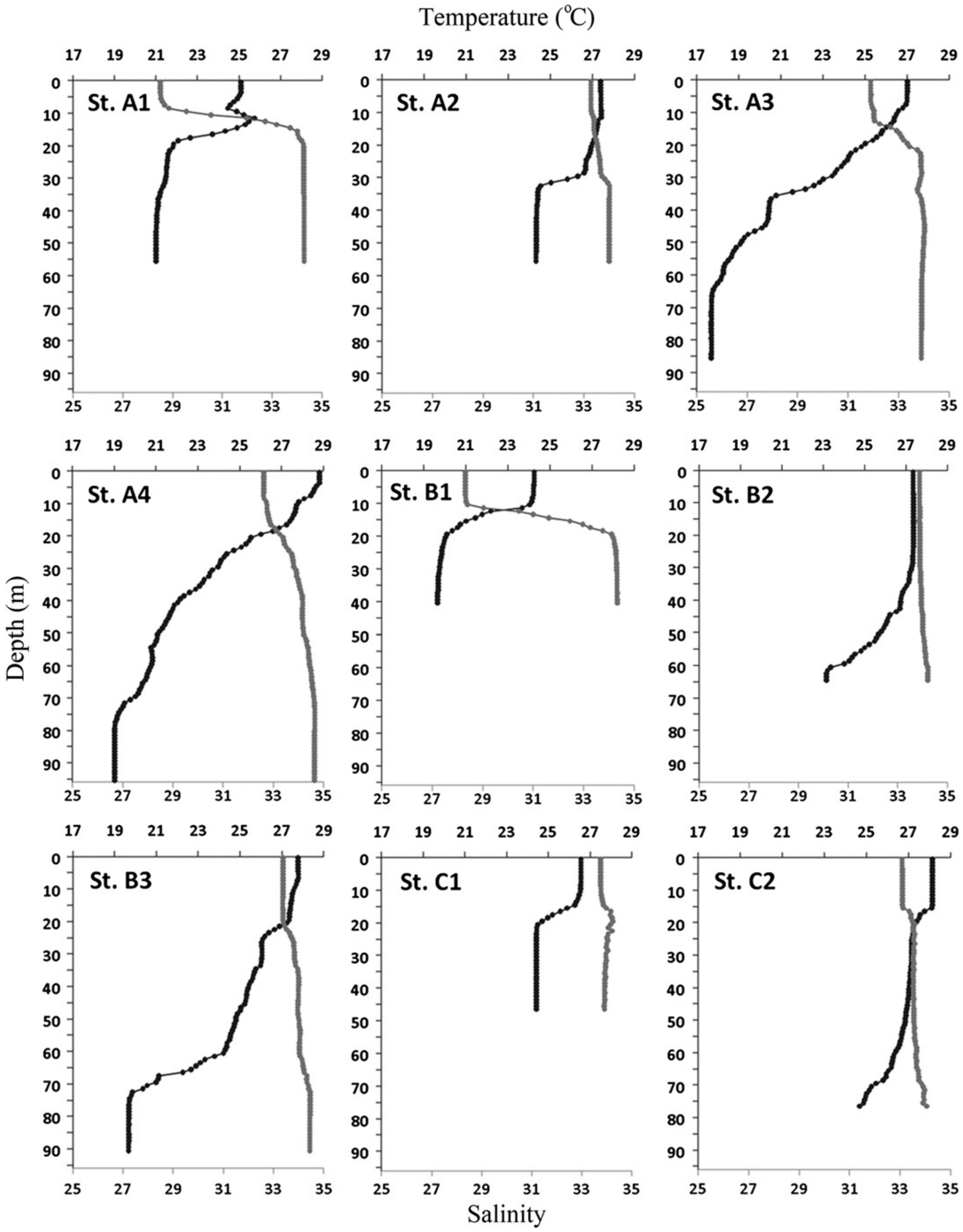

Fig. 3. Vertical profiles of water temperature and salinity at each fish collection site.

3.2.2. Size spectra of fish

Overall, size range of sampled fish was 2.5–50 cm; 80.1% of the fishes were <10 cm in standard length and 96.5% of fish were <20 cm. Most fishes in site A1 ranged from 4 to 6 cm because of the dominant *A. hexanema* in the catch (Fig. 7). Mean standard length increased from sites A1 (5.9 ± 2.9) to A3 (13.9 ± 7.5). Due to the abundant small sized *L. kishinouyei* and *C. snyderi*, the size spectrum in site A4 was similar to A1 and there was no fish larger than 16 cm sampled in site A4. Site C2 in the southern ECS had the widest range of fish size, from 4 to >49 cm. Standard lengths of common species *A. hexenema*, *Pennahia argentata* and *A. lineatus* differed significantly among the sites (Table 4). *A. hexenema* were significantly larger in sites B1 and A1 and smaller in other stations ($F=289.53$; $p<0.001$). White croakers (*P. argentata*) were significantly smaller in site C1 than in A2 ($F=12.73$; $p<0.001$). Standard lengths of cardinal fish *A. lineatus* were significantly different among three sampled stations but the difference between sites A1 and A2 was actually small ($F=9.37$; $p<0.001$).

3.2.3. Biological indices

Biological indices, including species richness (S), Shannon diversity index (H') and Pielou's evenness index (J') showed an increasing trend toward offshore sites. Generally lower biodiversity and evenness were found in sites A1 and B1 and extremely low species richness occurred in st. B1, which was located in the fishing prohibited area and near the mouth of Changjiang River and Hangzhou Gulf. Biodiversity was highest at the offshore site B2 (Table 5). Total fish abundance was generally higher at sites of northern transects A and B, and lower in the southern ECS

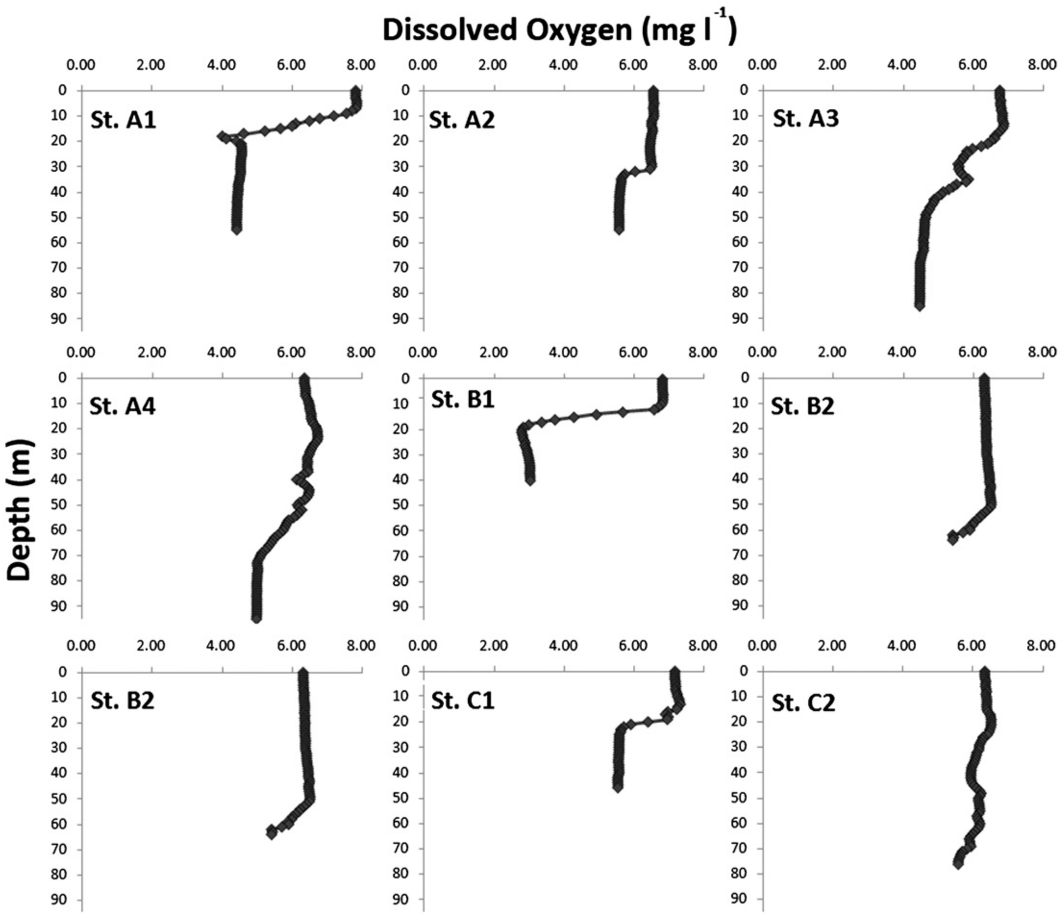

Fig. 4. Vertical profiles of dissolved oxygen of the sea water at each fish collection site.

(C1 and C2). The highest fish abundance was found in site A1. Nevertheless, the total abundance (*N*) did not show obvious trends with distance from shore.

k-Dominance curves based on the abundance data of each species allowed comparison of the pattern of dominance at each studied site (Fig. 8). Consistent with their low Pielou's evenness indices, more than 70% of catches at sites A1 and B1 were a single species, the Gobiid *A. hexanema*. Other sites displayed more even species proportions and less pronounced dominance ($<60\%$) by the leading species.

3.3. Biological–environmental relationships

Values of the Shannon biodiversity index (H') were significantly and negatively correlated with concentrations of chlorophyll *a*, all surface nutrient concentrations including dissolved inorganic nitrogen (DIN), phosphorus (PO_4) and silicate (SiO_3), and some bottom nutrients; while positively correlated with bottom-water dissolved oxygen ($p<0.05$, Table 6). Species richness and evenness showed similar relations with environmental factors. The significant relationships showed profoundly leading by the sites B1 and A1, which were characterized by high concentrations of nutrients and relatively lower bottom-water dissolved oxygen (Fig. 9). In addition to the negative correlations with nutrient concentrations, species richness showed significantly positive correlations with depth and surface temperature. Fish biomass increased significantly with latitude. All other correlations between environmental factors and abundance and biomass were not statistically significant.

Nine variables were used in Canonical Correspondence analysis (CCA). The first two CCA axes explained 71.39% of the total variation in the fish distribution and abundance (Supplemental Table 1). The first axis (Eigen value$=$0.86; canonical correlation$=$0.93) separated the inshore and offshore sites with water depth and some physiochemical properties, such as sea surface temperature, salinity and nutrient concentrations (Fig. 10). The second axis (Eigen value$=$0.56; canonical correlation$=$0.75) showed positive correlation to bottom-water DO ($r=0.91$). Occurrences of the Gobiids *A. hexanema* corresponded to the environmental characteristics of inshore sites (higher concentrations of nutrients and chlorophyll *a*) while the distribution and abundance of most analyzed species (*C. multispinulosus*, *C. snyderi*, *P. tosana and R. virgis*) corresponded to greater depth, temperature, salinity and bottom-water DO.

4. Discussion

The large-scale survey reported in this paper revealed high spatial heterogeneity in the demersal fish composition of the ECS. Varying environmental conditions may shape demersal fish assemblages. Distance to shore, depth, chlorophyll *a* and nutrient concentrations were strongly associated with the demersal fish community.

4.1. Assemblage characters in the northern-inshore ECS

We found lower biodiversity and evenness of demersal fish adjacent to the Changjiang Estuary. These results were supported by previous studies (Yu and Xian, 2009; Shan et al., 2010). Salinity

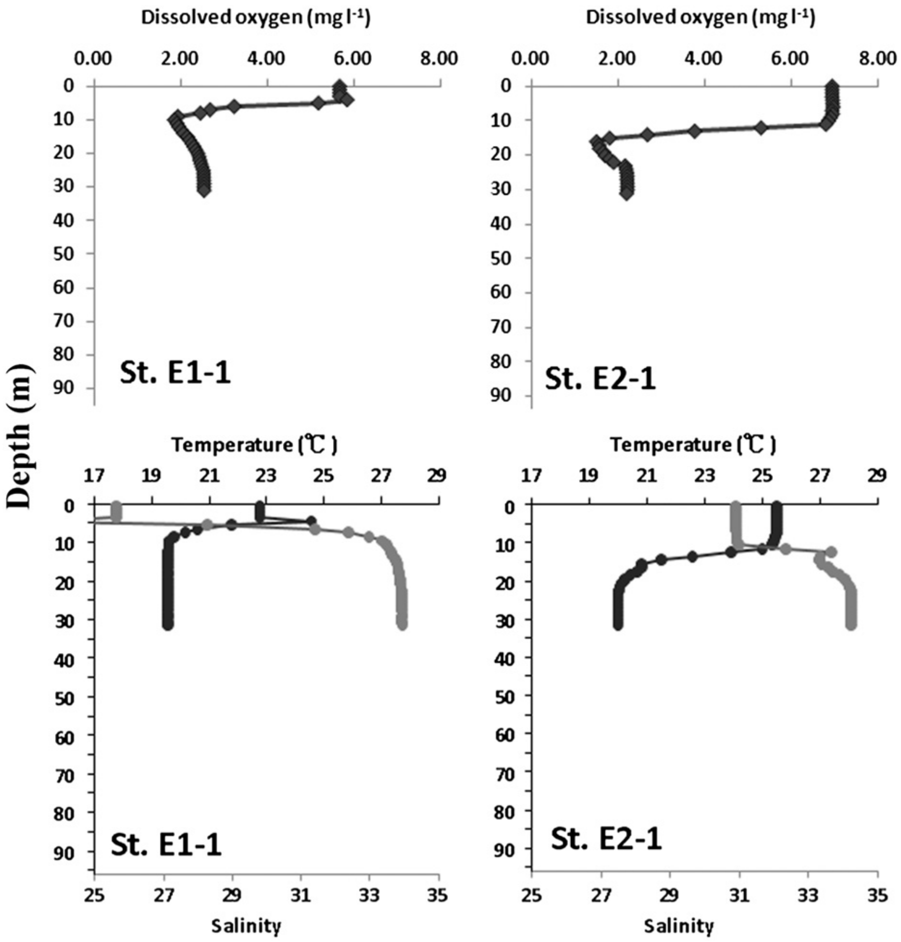

Fig. 5. Vertical profiles of dissolved oxygen (upper part), water temperature (black lines in lower part) and salinity (gray lines in lower part) at two inshore sites for environmental observation.

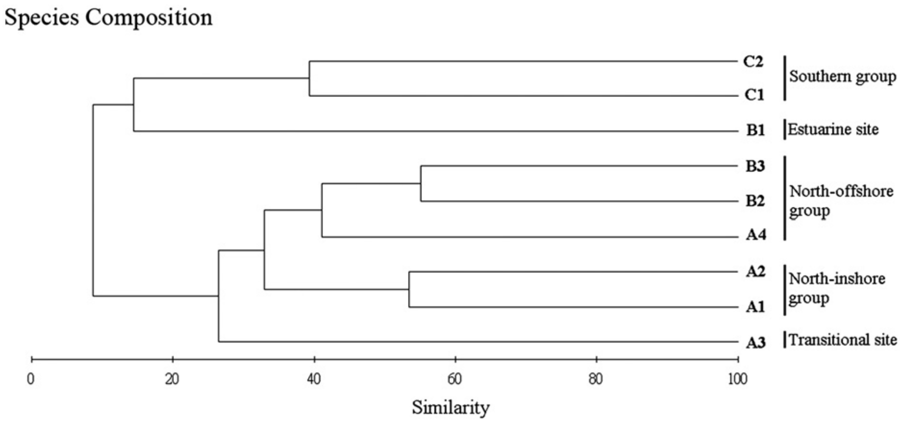

Fig. 6. Cluster analysis of demersal fish assemblages among the sampling sites. Refer to Fig. 1 for information on sampling sites.

has been identified as a key variable affecting the distribution of aquatic organisms (Attrill, 2002), especially the coastal areas with freshwater influence. In present survey, the Changjiang diluted water in the surface layer (above 20 m) did not reduce the salinity of bottom water, which varied in a small range (33.91–34.65) among all sampling sites (Fig. 3). Therefore, salinity did not play the major role in determining the distribution of demersal fish diversity.

In the 1960s, the Changjiang Estuary and adjacent waters were reported to be rich in fishery resources and dominated by yellow croakers (*Pseudosciaena crocea*), rays (*Raja porosa*) and Bombay duck (*Harpodon nehereus*) (Li et al., 2007a; Yu et al., 2010). However, the proportions of these commercially valuable fishes were extremely low in the present study; only few individuals of croakers were found in sites A1 and B1. Instead, the sites near the Changjiang Estuary and Hangzhou Gulf (north-inshore sites) were heavily dominated by small-sized and short-lived fishes, cardinal fish (*A. lineatus*) and gobies (*A. hexanema*) (Figs. 7 and 8). Previous study in this region, using data collected in 2006, also found the dominant fish species had low economic value, small size, simple age structure, and low trophic level (Shan et al., 2010). The Gobiids *A. hexanema*, which was recorded to be widely distributed

Table 3
Top 3 abundant species and their percentage of total abundance at each site.

Group	Site	Dominant species (in percentage)
Southern group	C1	*Johnius grypotus* (46.9) *Miichthys miiuy* (12.2)
	C2	*Cynoglossus interruptus* (44.0) *Pennahia argentata* (12.0) *Johnius grypotus* (12.0)
Estuarine site	B1	*Amblychaeturichthys hexanema* (77.1) *Pennahia argentata* (11.9) *Chelidonichthys kumu* (4.6)
North-offshore group	B2	*Repomucenus virgis* (31.1) *Psettina tosana* (15.5) *Champsodon snyderi* (12.5)
	B3	*Champsodon snyderi* (44.9) *Caelorinchus multispinulosus* (36.6) *Amblychaeturichthys hexanema* (3.2)
	A4	*Lepidotrigla kishinouyei* (51.7) *Champsodon snyderi* (14.5) *Aseraggodes kobensis* (8.0)
North-inshore group	A1	*Amblychaeturichthys hexanema* (69.8) *Apogon lineatus* (10.0) *Cynoglossus interruptus* (9.9)
	A2	*Apogon lineatus* (53.1) *Pseudorhombus pentophthalmus* (7.9) *Amblychaeturichthys hexanema* (6.9)
Transitional site	A3	*Caelorinchus multispinulosus* (50.0) *Psettina tosana* (15.5) *Apogon lineatus* (10.3)

in the Yellow Sea, Bohai Sea and East China Sea, is important link between benthic invertebrate and economically important fishes, including synodontids, platycephalids, paralichthyids and cynoglossids (Wu, 1984; Yamada et al., 2007). However, the co-occurrence of this goby and its predators was not common in this study. Among these predator species, some cynoglossids and paralichthyids were found in site A1, but rare predator was sampled in site B1. The low diversity and great quantity of small fishes in inshore areas have been regarded as the consequence of heavy exploitation in the ECS (Cheng et al., 2006; Li et al., 2007a; Jiang et al., 2009). Nevertheless, the inshore sites of present study were located in a year-round fishing prohibition area and this sampling was conducted during the fishing moratorium period. Hence our results suggest that factors other than fishing may have been controlling demersal fish assemblages in the inshore waters of the ECS.

4.2. Eutrophication and fish responses

4.2.1. Potential environmental disturbance in the inner shelf

Dominance curves are widely used to infer degree of environmental disturbance on fish populations. Shan et al. (2010) showed that the dominant fish species in the Changjiang Estuary and vicinity accounted for about 30% of the total fish abundance, suggesting an even dominance pattern and low disturbance. Nevertheless, an abundance-biomass comparison for the period 2000–2007 (Jiang et al., 2009) showed large disturbances in this area, with the dominant species ranging from 30% to 60% of total

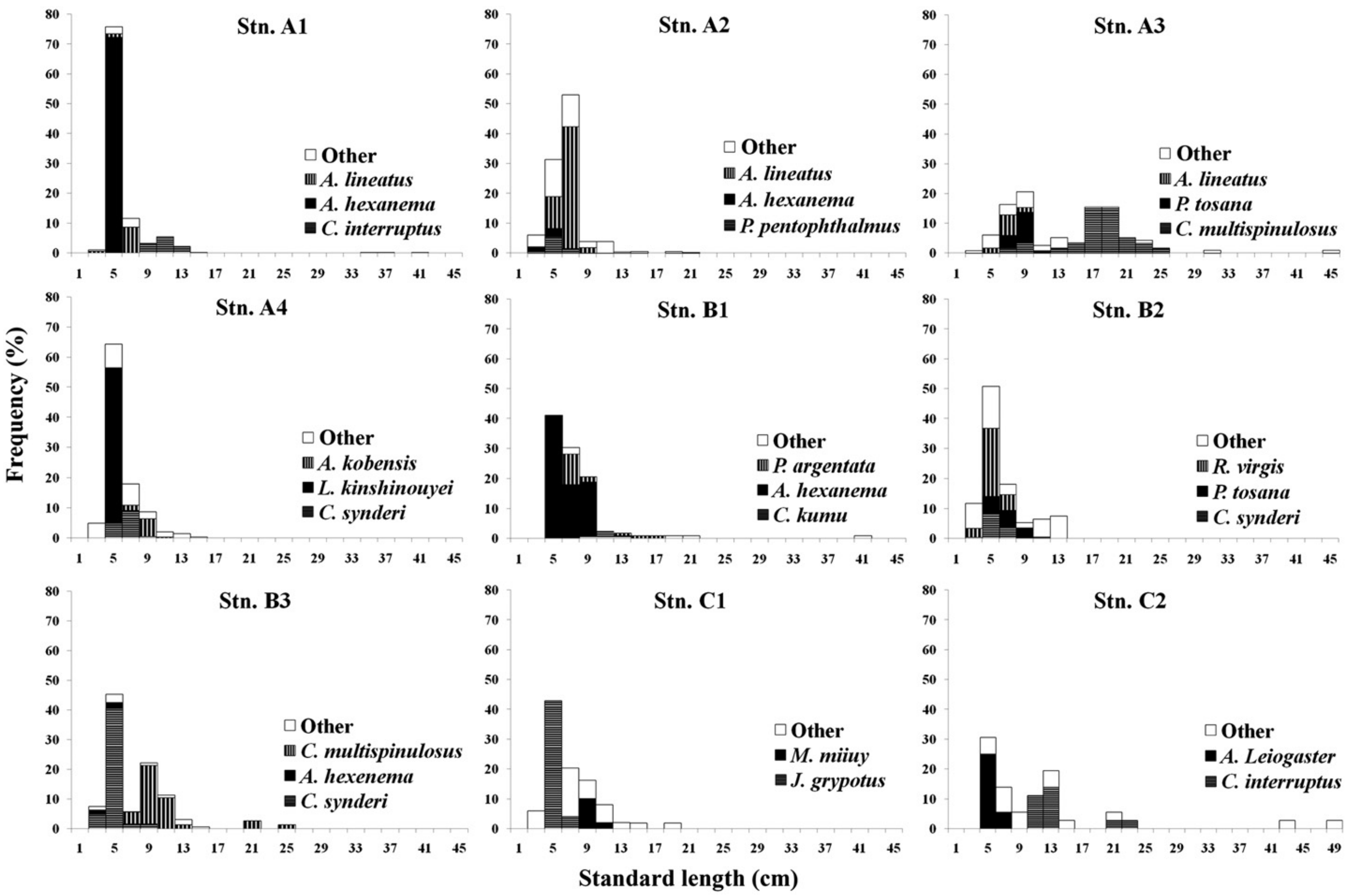

Fig. 7. Length-frequency distributions of standard lengths of fishes collected at each site. The proportions of the top 3 abundant species in each site are shown separately. Other represents the pooled proportions of the remaining species.

Table 4
Standard lengths (SL) of three widely-occurring demersal fish species.

Species	Station	Individuals	SL	Total df	F	p value
Amblychaeturichthys hexanema						
	A1	869	4.9 ± 0.2^{b}	1034	289.53	$p<0.001$
	A2	49	4.0 ± 0.3^{c}			
	B1	84	6.6 ± 2.2^{a}			
	B3	33	4.1 ± 0.5^{c}			
Pennahia argentata						
	A1	2	14.6 ± 0.0^{ab}	25	12.73	$p<0.001$
	A2	2	20.5 ± 0.5^{a}			
	B1	16	8.7 ± 9.7^{bc}			
	C1	3	6.8 ± 0.0^{c}			
	C2	3	13.6 ± 0.4^{ab}			
Apogon lineatus						
	A1	125	6.6 ± 1.0^{b}	513	9.37	$p<0.001$
	A2	377	6.4 ± 0.4^{c}			
	A3	12	7.2 ± 1.1^{a}			

Different superscript letters indicate significant differences among the sites.

Table 5
Community data of each site. s=number of species, n=individual number, N=standardized abundance (n km^{-2}), S=species richness, J'=Pielou's evenness, H'=Shannon diversity index and trawled area (km^2) for each sampling.

Station	s	n	N	S	J'	H'	Trawled area[a]
A1	18	1245	124,950	2.39	0.40	1.47	0.00996
A2	23	710	93,134	3.35	0.59	1.85	0.00762
A3	17	116	12,612	3.37	0.64	1.81	0.00919
A4	29	387	40,542	4.70	0.56	1.88	0.00954
B1	7	109	15,607	1.28	0.41	0.80	0.00698
B2	17	264	31,610	2.87	0.77	2.18	0.00835
B3	20	1019	116,189	2.74	0.47	1.40	0.00877
C1	11	49	4535	2.57	0.77	1.84	0.01080
C2	11	36	2394	2.80	0.80	1.90	0.01044

[a] Trawled area was the product of the GPS distance and width of beam trawl.

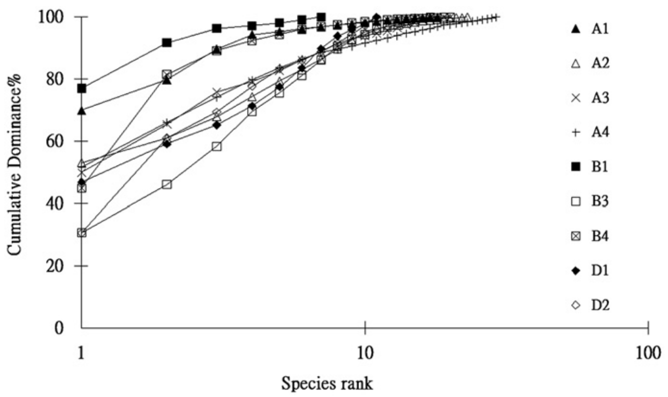

Fig. 8. *k*-Dominance curves of the fish composition in each site. Species within the station are ranked in descending order by relative abundance.

abundance. These two studies pooled samples across stations e.g., from inshore to offshore areas, and thus did not incorporate spatial heterogeneity of fish communities in dominance analysis. Spatial averaging of community parameters (e.g. dominance curves) can mask negative impacts of eutrophication (Breitburg et al., 2009); and obscure the disparate responses of fish assemblages. In the present study, site-specific dominance patterns were calculated. Dominance levels were much higher in north-inshore sites (A1, B1) than elsewhere, suggesting higher disturbance in these areas (Fig. 8). Such disturbance, namely low DO environments, was mainly caused by nutrient overloading. According to the Swedish eutrophication classification system for coastal marine surface water (Smith, 2003; modified from Swedish EPA, 2000), nutrient pollution at site A1 was high (concentration of chlorophyll $a > 3.2\ \mu g\,l^{-1}$, categorized as eutrophic state); at site B1 was moderate (chlorophyll $a > 2.2\ \mu g\,l^{-1}$, categorized as mesotrophic state); and at all other sites was low (chlorophyll $a < 1.5\ \mu g\,l^{-1}$, categorized as oligotrophic state).

4.2.2. Historical trends of hypoxia

Previous studies reported that concentrations of the lowest DO in the ECS were continuously dropping during the past 50 years, reaching 1 mg l^{-1} at the location (123°59′E, 30°51′N) close to our studied site A1 since August 1999, and even decreased to 0.94 mg l^{-1} in summer 2006 (Li et al., 2002; Shan et al., 2010). Most benthic organisms, especially the fishes and crustaceans cannot survive under such chronically low DO. Most fishes would likely escape or died before the DO reaches 2 mg l^{-1} (Vaquer-Sunyer and Duarte, 2008). Therefore, our results of significantly negative correlations between nutrient concentrations and biological indices i.e., species richness (S), biodiversity (H') and evenness (J'), and positive correlation between bottom DO and biological indices (Table 6 and Fig. 9) provide compelling evidence that most demersal organisms within the fishing moratorium area were experiencing the negative impacts of over-enriched nutrients and subsequently depleted DO.

4.2.3. Eutrophication and low DO impacts on ECS biota

Nutrients supplied in moderate quantities by land runoff can benefit fishery yields, but in eutrophic systems excess nutrients can lead to severe problems (Diaz, 2001). Algal blooms caused by excessive nutrient loads can decrease light penetration, inhibit benthic algal growth, disrupt benthic food chain, and cause deposition of organic matter whose decomposition depletes DO from bottom waters (Diaz, 2001; Grall and Chauvaud, 2002). The low DO conditions of hypoxia ($O_2 < 2$ mg l^{-1}) and anoxia ($O_2 < 0.2$ mg l^{-1}) are the most critical factors that damage benthic ecosystems. Low DO forces the departure of mobile fauna and causes mortality of sessile fauna (Baden et al., 1990; Pihl et al., 1992; Grall and Chauvaud, 2002). In the ECS, chronic nutrient overloading, accompanied by strong summer stratification as shown in Figs. 3 and 5, has exacerbated hypoxic conditions (Chen et al., 2007; Shan et al., 2010) that probably beyond the tolerance of most organisms (Diaz and Rosenberg, 1995).

Table 6
Spearman correlation coefficients and significance levels between the biodiversity index and environmental factors.

	Depth	Latitude	Temp (s)	Sal (s)	DO (s)	Chl *a* (s)	TM (s)	DIN (s)	PO_4 (s)
N	0.201	0.49	0.121	0.041	0.023	0.057	0.531	−0.076	−0.31
W	0.039	**0.738***	−0.041	−0.19	0.314	0.288	0.395	0.031	−0.263
S	**0.729***	0.069	**0.828****	0.533	−0.413	−0.561	0.544	−0.705	**−0.75***
J′	0.053	**−0.709***	0.517	**0.748***	−0.398	**−0.694***	−0.054	**−0.695***	−0.457
H′	0.341	−0.285	**0.723***	**0.769****	−0.334	**−0.646***	0.379	**−0.843****	**−0.818****
	SiO_3 (s)	Temp (b)	Sal (b)	DO (b)	Chl *a* (b)	TM (b)	DIN (b)	PO_4 (b)	SiO_3 (b)
N	−0.045	−0.107	0.418	0.041	−0.097	0.334	−0.066	−0.003	0.022
W	0.056	−0.098	0.094	0.05	−0.019	0.221	−0.156	−0.124	−0.036
S	**−0.704***	−0.141	0.205	0.533	−0.600	**0.857****	−0.381	−0.495	−0.542
J′	**−0.68***	0.615	−0.619	**0.761***	−0.061	0.294	**−0.704***	**−0.774***	**−0.794***
H′	**−0.801****	0.436	−0.334	**0.893****	−0.270	**0.687***	**−0.822***	**−0.909****	**−0.907****

N: abundance, *W*: biomass, *S*: species richness, *J′*: Pielou's evenness, *H′*: Shannon diversity index; Temp: temperature, Sal: salinity, DO: dissolved oxygen, Chl *a*: Chlorophyll *a*, TM: transmittance, DIN: dissolved inorganic nitrogen; (s): surface measurements, (b): bottom measurements.

* $p < 0.05$.
** $p < 0.01$.

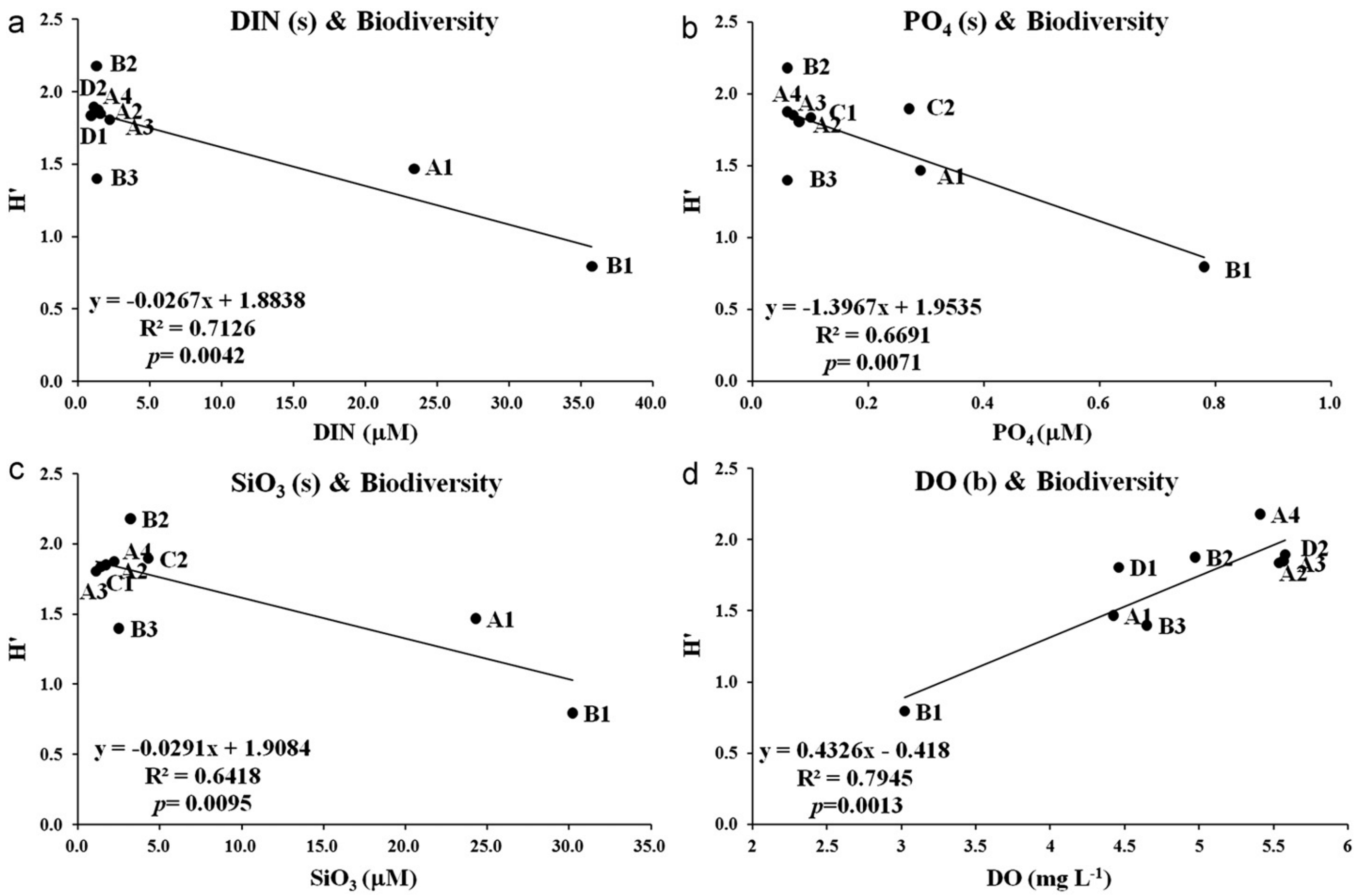

Fig. 9. Simple linear regressions of surface water nutrient—(a) dissolved inorganic nitrogen, (b) phosphate, (c) silicate and (d) bottom-water dissolved concentrations versus Shannon diversity.

The reported areas of hypoxia in the Changjiang Estuary and ECS continental shelf dramatically increase since the last decades, with an area of $>12{,}000\ km^2$ in August 2003 and ca. $15{,}400\ km^2$ in August 2006 (Chen et al., 2007; Zhu et al., 2011). Within these areas, a thick layer (>20 m) of low DO was observed in present and previous studies (Fig. 4; Chen et al., 2007; Li et al., 2002; Zhu et al., 2011). Breitburg (2002) suggested that low DO conditions are usually not uniform through the water column and the ability of fishes to locate at higher O_2 saturation areas will determine the effects of low DO on fish population. Several demersal fishes were reported to avoid low DO conditions indeed, such as croakers, flounder, etc. (Pihl et al., 1991; Wannamaker and Rice, 2000). The marbled Sale (*Pleuronectes yokohamae*) can even swim through DO rich sea surface for hours in an environment with 2–5 m water depth (Karim et al., 2003). Nevertheless, the demersal fish probably cannot survive as long as the time required to escape from large-scale and prolonged hypoxia and most fish will die within 1 day (Karim et al., 2003; Pihl et al., 1991). Moreover, most of benthic

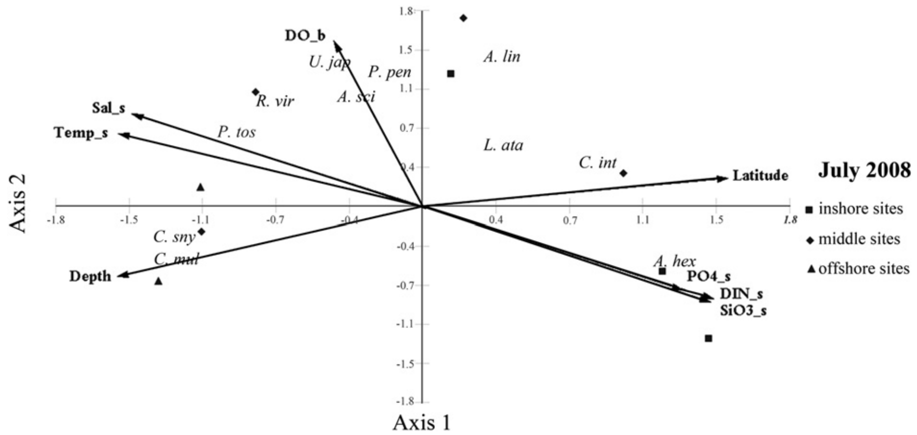

Fig. 10. Triplot of Canonical Correspondence Analysis (CCA) using 9 selected environmental variables: depth, latitude, temperature (Temp), salinity (Sal), chlorophyll *a* concentration (Chl *a*), and nutrients (DIN, PO_4 and SiO_3) of surface water (s); and dissolved oxygen (DO) of bottom water (b). The projections of fish species on axes show fishes' preference for this environmental gradient (ter Braak and Verdonschot, 1995). Square, rhombus, and triangle symbols represent inshore (A1, B1 and C1), middle (A2-3, B2, and C2) and offshore (A4 and B3) sites, respectively. *A. hex*: *Amblychaeturichthys hexanema*; *A. lin*: *Apogon lineatus*; *C. mul*: *Caelorinchus multispinulosus*; *C. int*: *Cynoglossus interruptus*; *C. sny*: *Champsodon snyderi*; *L. ala*: *Lepidotrigla alata*; *P. pen*: *Pseudorhombus pentophthalmus*; *P. tos*: *Psettina tosana*; *R. vir*: *Repomucenus virgis*; *U. jap*: *Upeneus japonicus*.

species that inhabit in deeper waters such as flatfish and gobies cannot easily use the upper, oxygenated water surface (Breitburg, 2002). Therefore, most of the demersal fish in the ECS are unlikely to locate and use the higher DO saturated upper layers due to the thick and large-scale (regional scale) low DO area in the inner shelf. Once the hypoxia-induced habitat loss occurred in bottom waters of the ECS, demersal fish are probably prone to death.

Paradoxically, the gobiids *A. hexanema* became abundant and dominant in the inner shelf. The tolerance of low oxygen for *A. hexanema* has never been reported before but may be comparable to the goby *Sufflogobius bibarbatus*, which survive well in large scale hypoxic, sulfidic and low DO (even anoxic) condition in Namibia (Utne-Palm et al., 2010). Therefore, the significantly larger body sizes of *A. hexanema* at inshore sites (A1 and B1) may be attributed to the integrated effects of enriched prey, low competition for the resources with other fish species, and the lack of predators under low DO conditions (Table 4). Unless the environment is improved, fishing prohibitions applied to this area will be unable to achieve their goal of restoring the abundance of commercially important fishes (Jiang et al., 2009). Therefore, not only the fishing prohibition policies, but also the environmental improvement (i.e. reduction of nutrient inputs) should be taken into account for sound fisheries management in the ECS. Management of nutrients inputs has virtually eliminated dead zones and benefited the recovery of benthic community densities in several systems (Diaz and Rosenberg, 2008).

4.3. Global change impacts

In addition to the overloaded nutrient inputs, ocean warming since the past decades is also a key factor controlling the extent of hypoxia (Conley et al., 2009; Vaquer-Sunyer and Duarte, 2011). The ECS has been reported to experience an abrupt ocean warming in the sea surface temperature (SST), at a rate of 1.4 °C per decade or >10 times the global rate (Belkin, 2009). Ocean warming may aggravate hypoxic conditions by decreasing oxygen solubility of sea water and strengthening water stratification. Furthermore, Vaquer-Sunyer and Duarte (2011) indicated that benthic organisms tend to have shorter survival time and higher O_2 requirement for survival (oxygen-thresholds) under hypoxia with increasing temperature. In the ECS, the synergistic effects of eutrophication, fishing and ocean warming increased the vulnerability of benthic macrofauna to environmental degradation, and the impacts of hypoxia may be greater than hitherto anticipated. Moreover, growing number of jellyfish blooms that probably caused by over-exploitation of predator fishes, introductions of nonindigenous species, climate change and eutrophication occurred in marginal seas worldwide over recent decades (Malakoff, 2001; Mills, 2001; Richardson et al., 2009). These dramatically increased jellyfish populations have also been observed in the ECS since the end of 1990s (Jiang et al., 2008; Uye, 2008; Yan et al., 2004). In the ECS, the CPUE of jellyfish (*Cyanea nozakii* and *Stomolophus meleagris*) increased from 963 kg/h in 2000 to >3000 kg/h in 2003; meanwhile, the CPUE (kg/h) of several economic important fishes such as yellow croakers (*Pseudosciaena polyactis*) and hairtail (*Trichiurus lepturus*) kept decreasing (Yan et al., 2004). As a result, the energy that previously contributed to fisheries production is probably now replaced by the production of pelagic jellyfish (Mills, 1995), and this would be one of the critical threats to fishery sustainability in the ECS.

4.4. Biological and environmental characters in offshore and southern ECS

4.4.1. Potential causes of higher diversity

In this survey, higher biodiversity was found in the offshore and southern ECS, which is consistent with previous work (Yu et al., 2010). At the southern sites C1 and C2, evenness was highest and fish abundance was lowest among all sites (Table 5). This result may indicate higher competition for limited resources in the southern ECS. The offshore areas sampled in the present study partly covered the Zhoushan Fishing Ground (29°30′–31°00′ N; 121°30′–125°E), which was the most productive area on the Chinese coast. The rich fishery resources within Zhoushan Fishing Ground were the consequences of suitable environmental conditions and adequate food availability (Yu et al., 2010). High DO in offshore areas not only directly contributes to fish survival but also enables an abundant benthic macroinvertebrate fauna that increases food availability for fish and thus enhance the sustainability of demersal fish production (Powers et al., 2005).

4.4.2. Fishing impacts

Despite the higher biodiversity at offshore sites in present study, the average Shannon diversity value ($H'=1.82$) of the northern ECS (sites A1 and B1 excluded) was still lower than earlier conditions e.g., diversity indices H' of 2.59 in the 1960s and 2.10 in 2000 (Li et al., 2007a; Jiang et al., 2009). Moreover, the community structures were greatly different from previous records. Before the 1980s, the key dominant species in the ECS were hairtail (*Trichiurus haumela*), small yellow croakers (*Pseudosciaena polyactis*), and silver pomfret (*Pampus argenteus*) which are of large size, good quality and high value. However, these above species declined sharply to less than 50% in the 1990s (Chen and Shen, 1995). Furthermore, these areas were now dominated by low economic values and low trophic fishes, including bentooth (*C. snyderi*), grenadier (*C. multispinulosus*) and dragonet (*R. virgis*) (Fig. 7). Although our sampling gear was not efficient for sampling benthopelagic fishes that hover over the sea floor, most recorded fishes and large size fishes (>40 cm) were indeed collected at some sites. Therefore, the overwhelming dominance of these low trophic and small-sized fishes at both inshore and offshore stations might not be mainly resulted from sampling bias but implied the recovery from continuous fishing mortality by species with early reproduction and fast growth in the ECS (Blanchard et al., 2004). Nevertheless, the biodiversity in exploited areas was even higher than in protected areas. This phenomenon implies that benthic eutrophication has had a greater impact than fisheries exploitation on benthic ecosystems of the ECS.

5. Summary and conclusions

In conclusion, environmental characteristics showed strong spatial heterogeneity across the ECS continental shelf. In addition to depth, trophic status and bottom-water dissolved oxygen also shaped demersal fish assemblages. In nutrient-enriched systems, eutrophication often creates spatial mosaic habitat, which may further alter the physiological fitness, species composition and prey–predator interactions of local biota (Breitburg et al., 2009). Accordingly, the traits of fish assemblages in the ECS showed distinct spatial variations. The present study provides first evidence that environmental degradation caused by eutrophication was the principal cause of the failure in fish stock recovery on the ECS inner shelf, where the fishing moratorium applied. In exploited systems, the removal of larger fishes reduces the effect of top–down predatory control, thus allowing bottom-up processes to play an increased role in community dynamics (Jackson et al., 2001). Systems that were moderately to overly exploited, like the ECS, were probably more subject to eutrophication than pristine and healthy ecosystems; therefore, a multi-pronged approach to fisheries management that takes environmental improvement and fishing restriction into consideration is urgently needed in the East China Sea. The synergy of eutrophication, fishing, ocean warming and even jellyfish blooms may aggravate the impacts of hypoxia on the ECS benthic ecosystem and hinder the fishery resources from recovery. Necessarily, more studies are needed to evaluate and disentangle the cumulative effects of multiple forcings.

Acknowledgment

We thank Dr. David Cairns and Dr. Kim Bell for critical comments and valuable suggestions, and for the assistance from the crew of the Ocean Researcher I. This study was supported by the National Science Council (NSC), Taiwan under Grant no. NSC-98-2611-M-002-004-MY3.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.csr.2012.06.011.

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