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Research Article

Long-Term Variations in Chlorophyll *a* and Primary Productivity in Jiaozhou Bay, China

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Based on long-term data of measurements of nutrient and chlorophyll *a* concentrations as well as estimates of primary production, the response of phytoplankton to nutrient enrichment was evaluated in the highly urbanized Jiaozhou Bay. Results showed that phytoplankton biomass, as indicated by chlorophyll *a* concentration, did not show a direct linear response to increased nutrient concentrations. Instead, chlorophyll *a* concentration was maintained at a constant level in the last two decades in Jiaozhou Bay, so did primary productivity. However, a reduction of zooplankton biomass was observed during the same period. Analysis showed that although the scale of phytoplankton blooms might be limited by availability of silicate due to low Si/N ratio and low concentration, top-down control on phytoplankton biomass by bivalve grazing may be an important factor in Jiaozhou Bay ecosystem.

1. Introduction

In shallow coastal marine waters, total primary production and biomass of phytoplankton is generally assumed to be hyperbolically related to nutrient loadings from land [1]. Many coastal marine waters have been nutrient enriched, and their nutrient ratios altered, as a result of changes in riverine inputs related to changes in land use and anthropogenic nutrient emissions over the last century [2, 3]. Coastal ecosystems often respond to such changes in nutrient budgets by altering phytoplankton structure and abundance, thereby impacting the rest of the food web [4]. Long-term observations are important for documenting such variations and understanding the impact of anthropogenic perturbations in coastal ecosystems fwithin the context of natural variability [5].

Jiaozhou Bay is a semienclosed coastal ecosystem with a surface area of 367 km^2 and an average depth of 7 m and is connected to the Yellow Sea through a narrow mouth. Previous studies reveal that concentrations of dissolved inorganic nitrogen (DIN) and phosphate (DIP) have increased from the 1960s to the 1990s, while concentration of dissolved silicate (DSi) has decreased from the 1980s to the 1990s [6]. However, phytoplankton biomass, as indicated by chlorophyll *a* concentration, has remained roughly unchanged from the mid-1980s to the 1990s, while abundance of net phytoplankton has decreased since the 1960s [6, 7]. Therefore, it was hypothesized that phytoplankton growth was limited by silicate, and phytoplankton composition might have shifted from large-size species to small-size species [6, 7].

In this paper, we present data on long-term trends in primary productivity and phytoplankton biomass (measured as surface chlorophyll *a* concentration) in Jiaozhou Bay. The goal of our analysis was to identify factors controlling phytoplankton biomass within this ecosystem.

2. Data Collection

Jiaozhou Bay is a region in China receiving extensive marine research. Though there have been many surveys in Jiaozhou Bay, different studies have involved different sampling times, station locations, and frequencies of sampling. In order to ensure comparability of the data, only those datasets with high spatial coverage (i.e., at least two-thirds of the area of

Table 1: Data sources used for nutrient and chlorophyll *a* concentrations, primary productivity, and zooplankton biomass in Jiaozhou Bay.

Variables	Time	Sampling frequency	No. of stations	References
Nutrients (DIN, DIP, DSi*)	Feb. to Nov., 1981	Monthly	10	[8]
	1983–1986	Monthly (41 cruises in total)	11	[9]
	1991–1998	Seasonally (25 cruises in total)	9	[6]
	1997–1998	Seasonally (5 cruises)	6∼19	[10]
	1999	Seasonally (3 cruises)	9	[11, 12]
	2001-2002	Seasonally (4 cruises)	14	[13]
	2001-2002	Seasonally (4 cruises)	9	[14]
	2003	Monthly	9	[15]
	Mar., 2006 to Feb., 2007	Monthly	12	Unpublished data
Chlorophyll *a*	1984	Seasonally (4 cruises)	9	[16]
	1991 to 2002	Seasonally (4 cruises a year)	10	[17]
	1997-1998	Seasonally (5 cruises)	6∼19	[10]
	2001-2002	Seasonally (4 cruises)	9	[14]
	2003	Monthly	9	[15]
	May 2003 to Apr., 2004	Monthly	9	[18]
	Mar., 2006 to Feb., 2007	Monthly	12	Unpublished data
Primary productivity	1984	Monthly	9	[19]
	1991–1993	Seasonally (8 cruises in total)	9	[20]
	1991–1993	Seasonally (7 cruises in total)	9	[21]
	1995	Seasonally (5 cruises)	12	[22]
	1997	Seasonally (4 cruises)	9	[23]
	1999	Seasonally (4 cruises)	9	[23]
	2003	Monthly	9∼12	[18, 24]
	Mar., 2006 to Feb., 2007	Monthly	9	Unpublished data
Zooplankton biomass	1983	Monthly	9	[23]
	1984	Monthly	9	[23]
	1985	Monthly	9	[23]
	1991	Seasonally (3 cruises)	9	[25]
	1992	Seasonally (4 cruises)	9	[25]
	1993	Seasonally (4 cruises)	9	[25]
	2003	Monthly	9	[18]

*Started in 1985.

Jiaozhou Bay) and high sampling frequency (at least seasonally) were included in this study. The sources of collected data for nutrients, chlorophyll *a*, primary productivity, and zooplankton biomass are listed in Table 1.

Water samples for nutrients (ammonia, nitrate, nitrite, phosphate, and silicate) were measured using comparable analytical methods (colorimetry), and they were determined manually with spectrophotometer before 1983 and with a Technicon Autoanalyzer II or a SKALAR Flow Analyzer after 1983 [6, 14, 15]. Primary production was determined in incubated discrete water samples by measuring production of oxygen before 1991 [19] and uptake of $NaH^{14}CO_3$ after 1991 [18, 20–24]. Water samples for chlorophyll *a* analysis were determined spectrophotometrically before 2003 [17] and fluorometrically after 2003 [15, 18]. Zooplankton samples were collected using the same method, and zooplankton biomass was measured as wet weight [18, 23, 25].

Surface chlorophyll *a* concentration was used as a proxy for phytoplankton biomass and primary productivity as a proxy for phytoplankton growth rate. All sampling events allowed for seasonal resolution of phytoplankton dynamics. If there were two or more reports in the same period, they were analyzed separately. Nutrient concentrations and their ratios are presented as annual means based on data, at least seasonal sampling events in a year. The bathymetry of Jiaozhou Bay and sampling locations are shown in Figure 1.

3. Long-Term Variations in Nutrient Concentrations and Biological Variables

Long-term variations in mean concentrations of inorganic nutrients (DIN, DIP and DSi) and their ratios in the whole water column in Jiaozhou Bay are shown in Figure 2(a). DIN concentrations increased fivefold from the beginning of

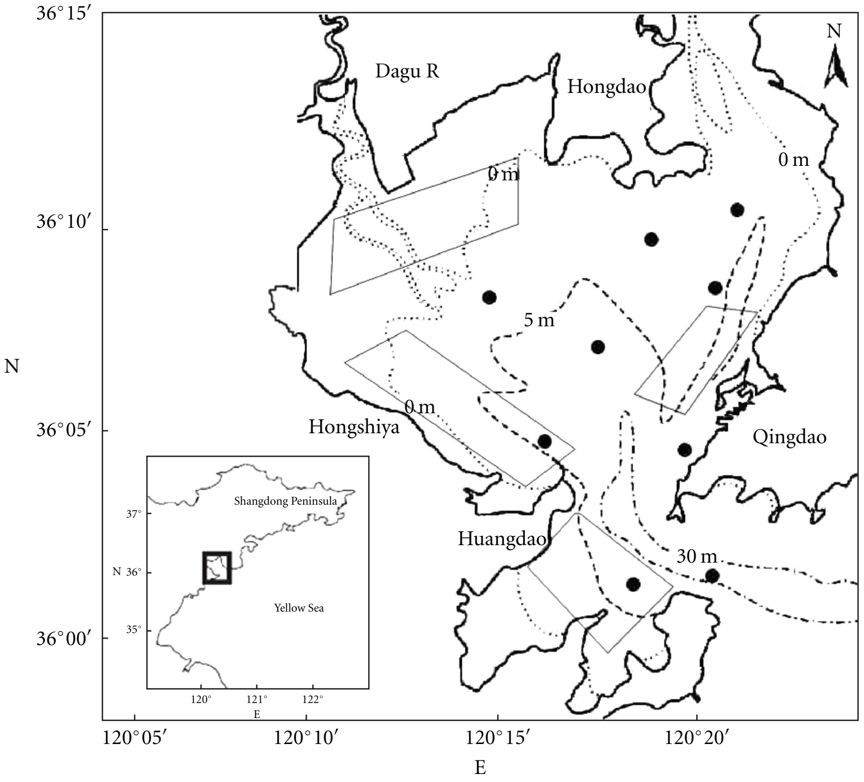
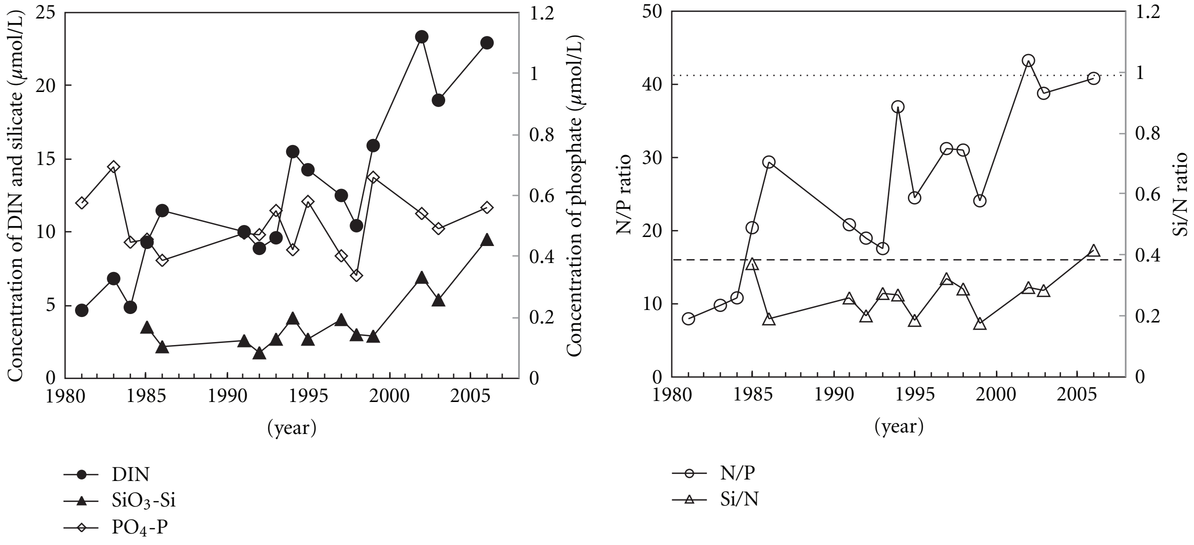


Figure 1: Map of Jiaozhou Bay showing sampling sites (dots) (quadrilaterals with solid and dotted lines were regions for clam and scallop aquaculture, resp. in the 1990s).

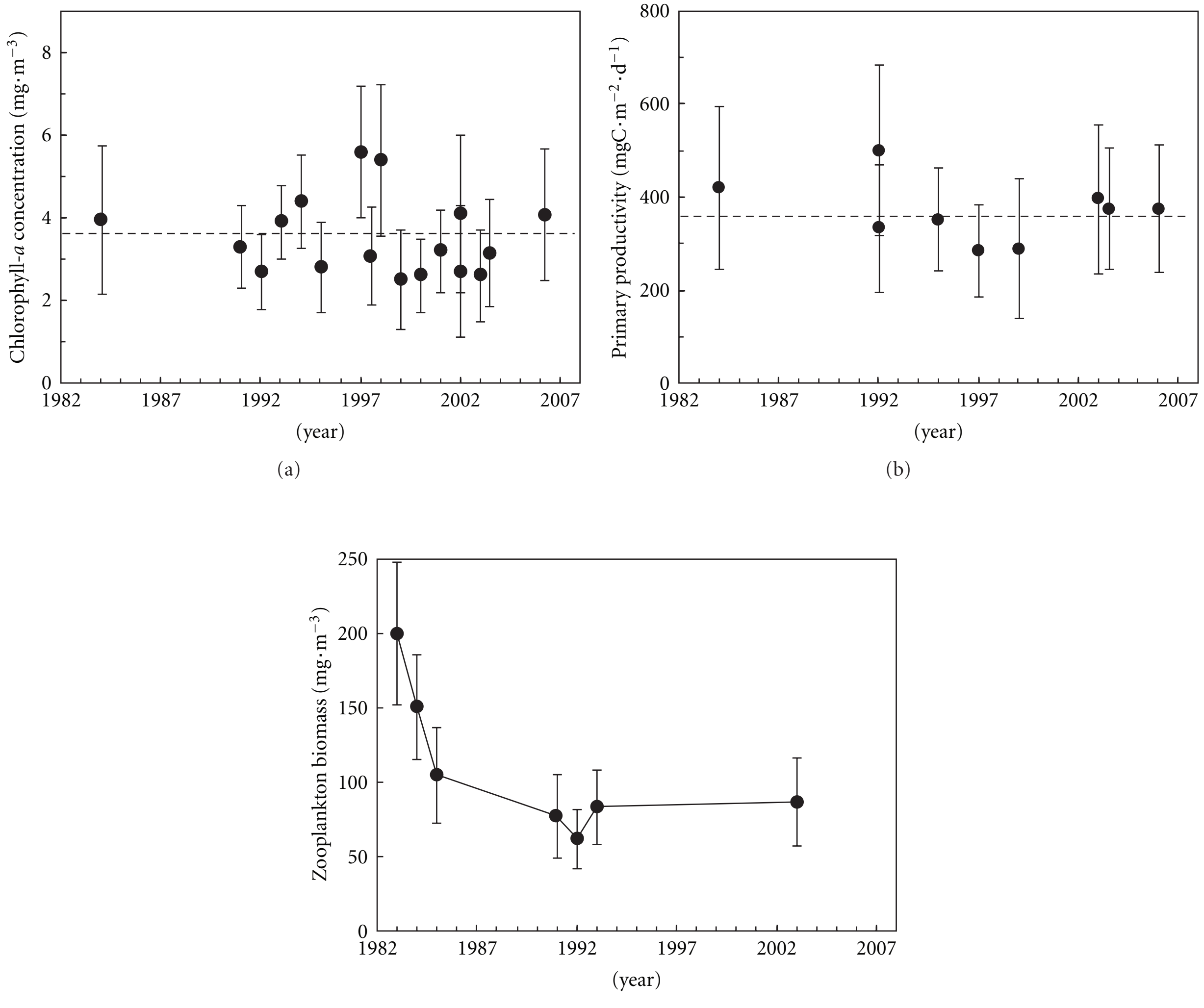


(a) (b)

Figure 2: Long-term variations in nutrient concentrations (μmol L^{-1}) (a) and their ratios (b) in Jiaozhou Bay (the dashed line indicates Redfield value for N/P, the dotted line for Si/N).

the 1980s to the middle of the 2000s, and DIP concentrations increased in the late 1990s (Figure 2(a)). Silicate concentration remained near 3.0 ± 0.5 μM in the last two decades of the 20th century but increased 5 μM more in the beginning of the 21st century (Figure 2(a)).

Following rapid increase in DIN concentration, N/P ratio increased from 8 in the beginning of the 1980s, which was lower than the Redfield ratio (N/P = 16), to 38 more in the beginning of the 21st century (Figure 2(b)), which was two times higher than the Redfield ratio, whereas Si/N ratio



(a)

(b)

(c)

Figure 3: Long-term variations in chlorophyll *a* concentration (mg m^{-3}), primary productivity (mg·C m^{-2}·d^{-1}), and zooplankton biomass (mg m^{-3}) in Jiaozhou Bay (the dashed lines indicate average values).

remained near 0.27 ± 0.07 throughout the last two decades, much lower than the Redfield ratio (Si/N = 1) (Figure 2(b)), suggesting potential silicate limitation of phytoplankton growth in Jiaozhou Bay.

Long-term variation in total phytoplankton biomass, as indicated by chlorophyll *a* concentration, was small compared to nutrient concentrations. Mean chlorophyll *a* concentrations remained near 3.5 ± 0.9 μg/L over the study period, with no significant tendency over time (Figure 3(a)).

Mean primary productivity showed no significant upward or downward trend over the study period (Figure 3(b)). Compared with other temperate enclosed coastal ecosystems, primary productivity in Jiaozhou Bay (370 ± 66 mgC·m^{-2}·d^{-1}) was at a moderate level.

Zooplankton biomass declined sharply from 200 mg·m^{-3} in 1983 to 100 mg·m^{-3} in 1985 then remained near 85 mg·m^{-3} for the rest of study period (Figure 3(c)).

4. Factors Controlling the Phytoplankton Biomass

Estuarine systems that do not show a response in phytoplankton biomass to increased nutrient loadings will instead accumulate elevated nutrient concentrations. Such a situation has been discussed recently [1, 26] and was considered analogous to the oceanic high-nutrient, low-chlorophyll condition [27]. High-nutrient concentrations in estuaries should be indicators of eutrophication, but a question that should be asked in such a situation is why are primary production and phytoplankton biomass not responsive to increase in nutrient concentrations?

Processes that may regulate primary production and phytoplankton biomass in marine ecosystems are nutrient availability, light intensity, and grazing loses [1, 4, 5]. In Jiaozhou Bay, bottom-up control is potentially related to availability of

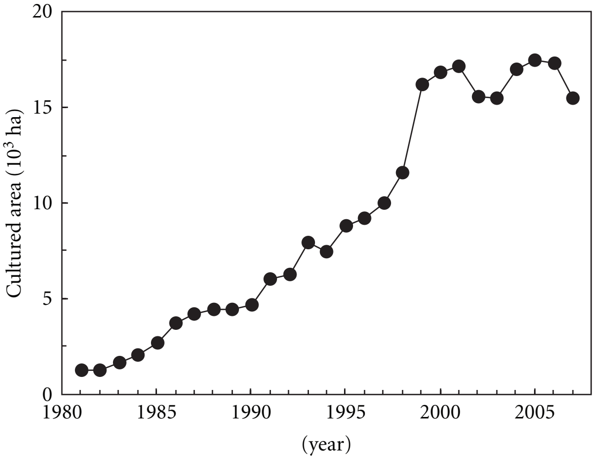


Figure 4: Historical changes in areas of aquaculture of bivalves in Jiaozhou Bay.

silicate since Si/N ratios (0.30 ± 0.07) are much lower than the Redfield ratio (Si/N = 1) [6]. However, silicate concentration was quite low (<1 μM) in February and September when phytoplankton biomass was high, but relatively high (>1.5 μM) in the other ten months when phytoplankton biomass was low (Figure 2(a)). Since diatoms were the dominant species in phytoplankton biomass (>90%) and composition (>80%) in Jiaozhou Bay [15], it is argued that silicate concentration may have limited scales of summer and/or winter blooms of phytoplankton, but it does not limit phytoplankton growth during other time of a year in Jiaozhou Bay.

Light intensity, besides grazing, is agreed to be another controlling factor for phytoplankton abundance through influencing the productivity rate, especially in estuaries [28] and coastal waters [29, 30]. For the long-term data on underwater light intensity is not available in Jiaozhou Bay, instead, the data of water transparency is used to discuss the influence of light intensity on phytoplankton abundance. The water transparency was 2.0 m in the beginning of the 1980s [23], 1.7 m in the 1990s [23], and 1.6 m in 2006 (unpublished data), indicating a slight decreasing tendency. This decline in underwater light intensity might influence, to some extent, the productivity rate in Jiaozhou Bay. However, since water depth is less than 5 m in more than three-fourth of the total area in Jiaozhou Bay, it is unlikely that the productivity rate be limited by light intensity in this ecosystem.

Zooplankton grazing on phytoplankton may control phytoplankton biomass in some ecosystems [31]. In Jiaozhou Bay, however, zooplankton biomass declined by one-fourth from the 1980s to present (Figure 3(c)), suggesting a decrease in grazing pressure by zooplankton on phytoplankton biomass. Usually, the highest zooplankton biomass occurred in August which followed phytoplankton blooms, and lowest zooplankton biomasses were found in autumn when phytoplankton biomasses were also low, indicating dependence of zooplankton development on phytoplankton as food supply. Since zooplankton biomass declined during the last decades, it is suggested that top-down control on phytoplankton biomass by zooplankton grazing is not a main factor in Jiaozhou Bay.

Bivalves are often the most abundant suspension feeders in estuarine systems, and bivalve grazing may impose top-down control of phytoplankton biomass and composition [32, 33]. The first inference of control of phytoplankton biomass on the scale of an entire estuary was made for San Francisco Bay [34, 35]. Since then, there has been a proliferation of studies indicating that bivalve grazing may control phytoplankton biomass at a range of estuarine systems [32, 36–38].

Jiaozhou Bay has traditionally been an area for mariculture. Shellfish culture has been increasing in the bay since the 1980s (Figure 4). The most important cultured species are Manila clam (*Ruditapes philippinarum*), blue mussel (*Mytilus edulis*), Chinese scallop (*Chlamys farreri*), and bay scallop (*Argopecten irradians*). The averaged number of *Ruditapes philippinarum* currently in Jiaozhou Bay was 3×10^{10} individuals [39]. Raft culture of scallops began in the 1980s, and culturing area reached 1,300 hectare with a total number of 1.6×10^9 individuals during the 1990s [40]. Taken the average clearance rate of *Ruditapes philippinarum* as $300\,\text{mL}\cdot\text{hr}^{-1}$ [39], estimated clearance time for all the seawater in the bay by clams would be 12 days. A similar calculation can be made for scallop in the bay. Taken the average clearance rate of scallop as $500\,\text{mL}\cdot\text{hr}^{-1}$, estimated clearance time of seawater in the bay would be 135 days. Combining the filtration rates of clams and scallops, net clearance time would be 11 days, which is shorter than the average resident time of seawater in Jiaozhou Bay that is, 80 days [41].

In term of ingestion rate of bivalves, a similar calculation can be made for clams and scallops in the bay. Taken the average ingestion rate of clam and scallop as $1\,\text{mgC}\cdot\text{h}^{-1}$, the total amount of phytoplankton ingested by clams and scallops would be $2.8 \times 10^{11}\,\text{gC}\cdot\text{yr}^{-1}$. By comparison, estimated total primary production in the bay would be *ca.* $5\times 10^{10}\,\text{gC}\cdot\text{yr}^{-1}$, assuming primary productivity as $360\,\text{mgC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. The net result is that the potential annual phytoplankton loss due to bivalve grazing is higher than estimated gains from primary production.

Our calculation can be viewed as an underestimate for loss because filtration rates of smaller clams with shell size less than 2 cm are not included in our estimate. A significant impact of bivalve grazing can be expected when bivalve clearance time is approximately equal to turnover time of phytoplankton and shorter than water residence time [38]. Since the area of mariculture has increased continuously and by a factor of ten from 1981 to present in the bay (Figure 4), it has led to increase in grazing pressure on phytoplankton. Thereforesuspension feeding activity of bivalves, especially clams, may strongly influence or even control phytoplankton biomass, helping to explain the relatively low phytoplankton biomass observed in Jiaozhou Bay.

The potential importance of top-down control of phytoplankton biomass by bivalve grazing implies that bottom-up control of phytoplankton development (nutrient or light limitation) may be less important. As was pointed out by Herman and Scholten, this means that such an ecosystem can be more resilient to changes in external nutrient loading [42].

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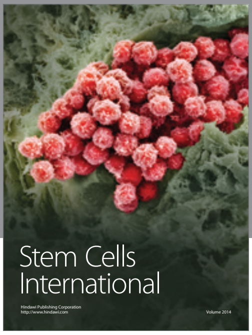
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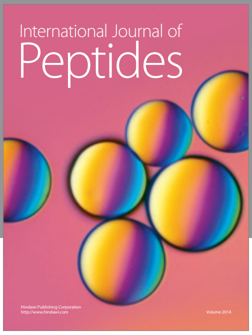
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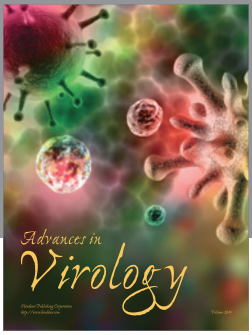
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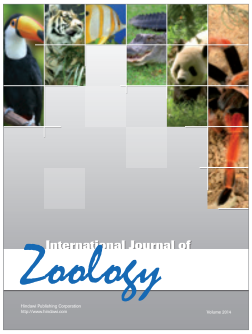
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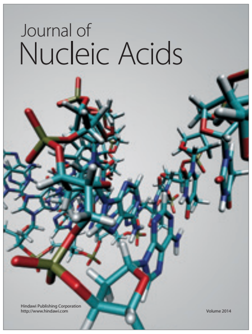
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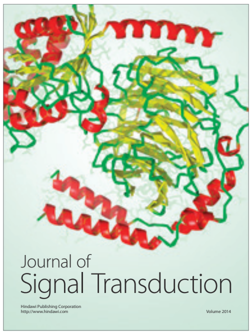
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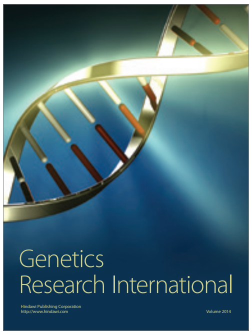
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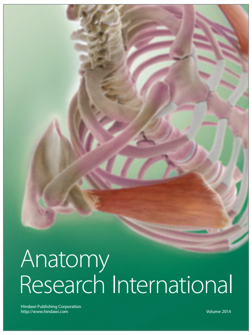
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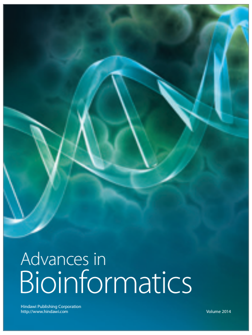
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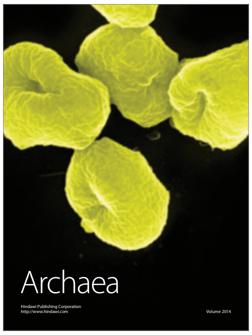
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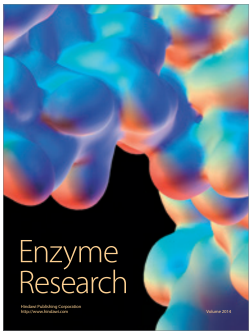
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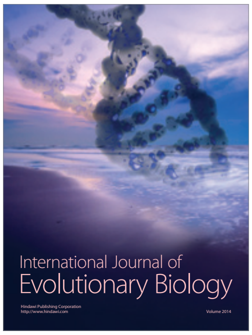
Research


International Journal of
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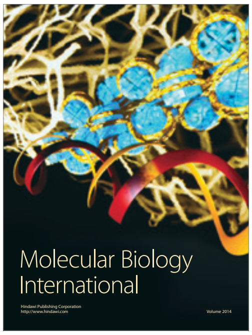
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