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An approach to analyzing spatial patterns in annual dynamics of planktonic ciliate communities and their environmental drivers in marine ecosystems

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ABSTRACT

The environmental drivers to shape the spatial patterns in annual dynamics of the planktonic ciliate communities were studied based on an annual dataset from a bay, northern Yellow Sea. Samples were biweekly collected at five stations with different environmental condition status during a 1-year period. The second-stage-analysis-based multivariate approaches were used to reveal the internal dynamics in annual patterns of the ciliate assemblages. Results showed that: (a) there was a clear spatial variability in annual dynamics among five stations; (b) the dominant species represented different succession dynamics among four samples stations during the 1-year cycle; and (c) the spatial variations in annual patterns of the ciliates were significantly correlated with nutrients, alone or in combination with salinity and dissolve oxygen (DO). Thus, it is suggested that the nutrients may be the main drivers to shape the spatial patterns in annual dynamics of planktonic ciliate communities in marine ecosystems.

1. Introduction

Planktonic ciliates are an important component of zooplankton fauna, and play a cruel role in the functioning of microbial food webs by mediating the flux of carbon and energy from bacteria, pico- and nano-algae to high trophic levels in aquatic ecosystems (Montagnes and Lynn, 1989; Dolan and Coats, 1990; Sime-Ngando et al., 1995; Crawford et al., 1997; Kchaou et al., 2009). The changes in both taxonomic composition and community structure of the ciliate assemblages may result in significant variations in functional structures of aquatic food webs (Finlay and Esteban, 1998; Jiang et al., 2011, 2013a,b).

Recently, the planktonic ciliates have been successfully used as a useful bioindicator for bioassessment of water quality in marine ecosystems because of their short life cycle, rapid response to environmental changes and the easy comparison on temporal and spatial scales (Jiang et al., 2011, 2014, 2016; Feng et al., 2015; Xu et al., 2011, 2015, 2016). So far, a number of investigations on planktonic ciliates have been carried out on both community research and monitoring programs (Madoni and Braghiroli, 2007; Jiang et al., 2011, 2013a, b; Xu et al., 2013, 2015, 2016). So far, however, in regard to environmental drivers to shape the spatial patterns of annual dynamics of the ciliate assemblages, little information have been known.

In this study, the spatial changes in annual dynamics of planktonic ciliate communities were studied based on an annual dataset from Jiaozhou Bay, near Qingdao, northern China. The aims of this study were to demonstrate the internal patterns annual dynamics of the ciliate assemblages and their potential environmental drivers in marine ecosystems.

2. Materials and methods

2.1. Study areas and sample collection

Jiaozhou Bay, with an area of about 390 km^2 and an average depth of 7 m, is a part of the Yellow Sea and is surrounded by Qingdao, northern China (Fig. 1). In recent decades, since several streams, with varying water and sediment loads, have become seasonal sources of pollutants entering the bay by discharging industrial effluents and urban wastewaters from Qingdao city (Shen, 2001; Liu et al., 2004, 2005). This result in a high heterogeneity in water conditions status (Liu et al., 2005; Jiang et al., 2011).

Five sampling stations were selected in Jiaozhou Bay (Fig. 1): station A was located in area far from the polluted sources; station

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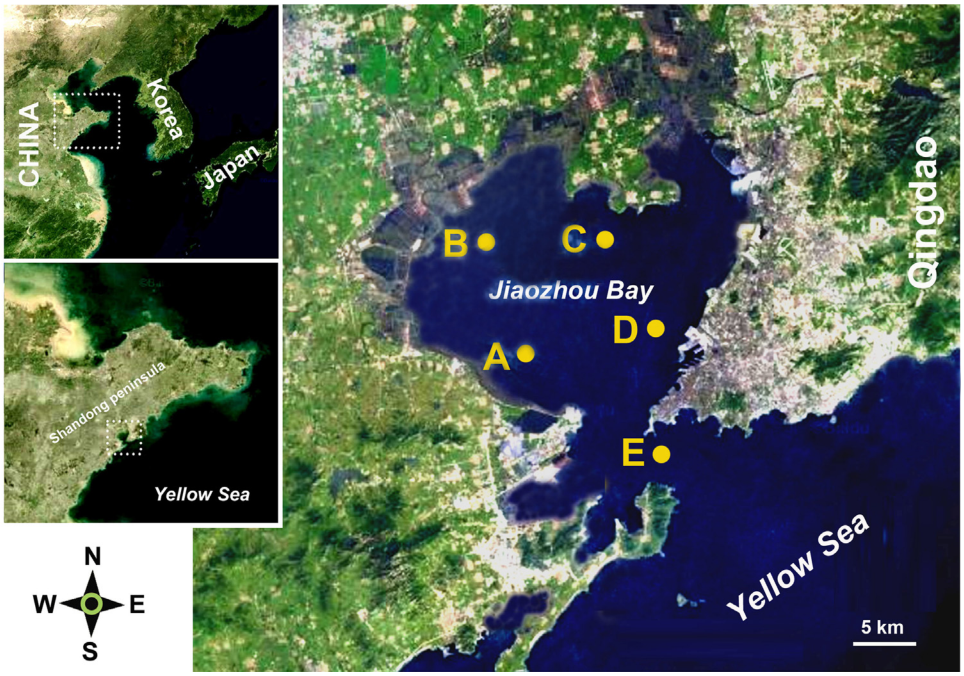

Fig 1. Sampling stations in Jiaozhou Bay, near Qingdao, northern China. A–E = stations A–E.

B, an area near two rivers with organic pollutants, nutrients and heavy metals (e.g., Pb, Zn) entering the bay; station C, a mariculture area; station D, an area near a small river with both organic and heavy-metal pollutants (e.g., Cr, Cu); and station E was located in the mouth of the bay and subjected strong water exchanges (Fig. 1) (Liu et al., 2005).

A total of 120 samples were collected biweekly at a depth of 1 m from each sampling station during a 1-year cycle (June 2007–May 2008). Sampling strategy, sample processes, enumeration, species identification and measurement of environmental variables were followed that described by Jiang et al. (2011). The functional groups of the ciliates were determined according to Jiang et al. (2013a).

Salinity (Sal), pH, and the concentrations of dissolved oxygen (DO) were detected *in situ*, using a multi-parameter sensor (MS5, HACH). Soluble reactive phosphate (SRP), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and nitrite nitrogen (NO_2-N) were measured according to the 'Standard Methods for the Examination of Water and Wastewater' (APHA, 1992).

2.2. Data analyses

Multivariate analyses were carried out with the software package PRIMER v7.0.10 and the PERMANOVA+ for PRIMER (Clarke and Gorley, 2015; Anderson et al., 2008). The Bray-Curtis similarity matrices among communities were computed on fourth root transformed species-abundance data, while the Euclidean distance matrices for environmental variables were obtained from log-transformed/normalized abiotic data (Clarke and Gorley, 2015). The second-stage (2DTSGE) analysis was used to summarize the internal patterns of the annual dynamics of the ciliates and of the annual variability of water conditions (Clarke and Gorley, 2015). Metric multidimensional scaling (mMDS) ordinations were used to show the trajectory of annual dynamics of the ciliate assemblages, while the spatial patterns of the ciliate annual dynamics and annual water condition status were summarized using the routine PCoA (principal coordinate analysis) of PERMANOVA+ (Anderson et al., 2008). The seasonal variations in community patterns at each station were summarized using the routine Bootstrap Average on Bray-Curtis similarity matrices from species abundance data. (Clarke and Gorley, 2015). Mental analyses were done by running the routine RELATE to signify the relationships between similarity matrices, and the routine BIOENV was used to identify the environmental drivers to the spatial variations in annual distribution of the protozoa with the significance at the P value < 0.05 level (Clarke and Gorley, 2015).

3. Results

3.1. Spatial gradient of environmental conditions

The average values of environmental conditions at five sampling stations are showed in Table S1. Temperature and pH showed minor differences at five sampling sites. Salinity ranged from 29.5 psu to 31.3 psu with minimum value at station B and maximum at station A. DO were generally higher than 8 mg l^{-1} at five stations, with the minimum value at site D and the maximum at site B. Concentrations of NO_3-N were generally high at sites B and C and low at the other three stations, although NH_4-N reached maximum values at site D, mainly (Table S1).

3.2. Spatial variations in annual succession of dominant species

A total of 64 planktonic ciliates were identified during the study period. The individual abundance, occurrence frequency and dominance were summarized in Table S2.

A total of 19 dominant species with >20% of relative abundance were determined, of which 5, 9, 7, 9 and 10 taxa predominated the samples at stations A, B, C, D and E, respectively (Fig. 2). It should be noted that only one species *Leprotitinnus bottnicus* dominated the samples in August and/or September at all five stations (Fig. 2).

Among five stations, these dominants represented a variety of temporal successions, for example, the ciliate *Tintinnopsis parvula* dominated the samples in February at stations B, C, D and E, while its dominance was replaced by the taxa *Rimostrombidium orientale* and *Mesodinium pupula* in this month at station A (Fig. 2).