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渤海生态系统的营养关系：碳同位素研究的初步结果

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摘要：1997 年 6 月 5～10 日在渤海 4 个站位上采集了悬浮体、浮游生物、底栖生物和沉积物样品，其目的是采用碳稳定同位素方法研究渤海生态系统的营养关系。浮游动物样品按其粒级分为＞1000μm，500～1000μm 以及 200～500μm 3 个组分。碳同位素分析结果表明，在春末渤海生态系统各级各类生物 $\delta^{13}C$ 值的范围为 $-25.67 \sim -17.42\times10^{-3}$，其中浮游生物群体（不包括游泳动物）$\delta^{13}C$ 值相差约 3.68×10^{-3}，相当于该生态系统有 3.2 个营养层次。中型浮游动物随粒径的增大，其 $\delta^{13}C$ 值增大，显示出营养层次的碳同位素富集作用，但不同粒级组分相互间 $\delta^{13}C$ 值也存在着相当程度的重叠，实际上这也是其生物组分有重叠的反映。营养层次随颗粒的增大而升高，这一趋势与 Rau 等，Sholto-Douglas 等，Fry 与 Quiñones 的结果是完全一致的。渤海底栖生物的 $\delta^{13}C$ 值一般要比浮游生物的 $\delta^{13}C$ 值高，这并不意味着底栖生物的营养层次要比浮游生物的高，而是反映其食物来源的差异和底栖与浮游两个食物网底部同位素组成的不同。有限的底栖生物样品的同位素分析结果表明渤海底栖生物食物网有 4 个营养层次。各种底栖生物的碳同位素组成也反映了它们的食物来源和营养位置。

关键词：生态系统；营养关系；碳同位素；渤海

Trophic relationships in the Bohai ecosystem: preliminary investigation from $\delta^{13}C$ analysis

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Abstract: The suspended matter, plankton, benthos and sediment samples were collected at four stations in the Bohai Sea during June 5 to 10, 1997 in order to study the trophic relationships in the Bohai ecosystem by using stable carbon isotope method. Zooplankton samples were separated into three size fractions: ＞1000μm, 500～1000μm and 200～500μm. The results of carbon isotopic analyses indicated the $\delta^{13}C$ values of the biome in late spring in the Bohai ecosystem ranged between $-25.67 \sim -17.42\times10^{-3}$, in which the planktonic community (not including necton) has a maximum $\delta^{13}C$ difference of about 3.68×10^{-3}, corresponding to there being 3.2 trophic levels in the ecosystem. There was enrichment of the heavier isotope of mesoplankton with increasing grain size, showing carbon isotope enrichment along trophic levels. Some overlaps of the $\delta^{13}C$ values, however, occur among the various mesoplankton size classes, which, in fact, reflects the overlap of organism species. The increasing tendency of trophic level with increasing mesoplankton size is coincident with the results of Rau *et al.*[1], Sholto-Douglas *et al*[2], and Fry and Quiñones[3]. Benthic organisms generally have higher $\delta^{13}C$ values than plankton in the Bohai Sea, which does not infer trophic levels of benthos being higher than those of the plankton, but reflects differences of their food sources and the isotopic composition of the bases in both benthic and planktonic food webs. Analytical results of limited samples of benthos indicated that four trophic levels occur in benthic food web

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in the Bohai Sea. The stable carbon isotope compositions of benthos also reflected their food sources and trophic locations.

Key words: ecosystem; trophic relationships; carbon isotopes; Bohai Sea
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1 Introduction

In studies on marine ecosystem dynamics the trophic relationships in food webs, the pathways of material and energy flow, the coupling between benthic and pelagic organisms are important key problems. In China the conventional dietary analysis methods were often used in such studies. As compared with the conventional dietary analyses which only provide a measure of ingested food, stable isotope analysis of food web structure has the advantage of providing time-integrated averages of assimilated foods and, thus, represents a complementary method for delineating patterns of trophic structure and energy flow[4,5]. Moreover, some direct errors in diet analyses may be caused by differences in digestion rate between food types[6]. Species composition and gut analyses provide only indirect information on trophic interactions and may be misleading, if assimilation is not considered[7]. In the present study, measurements of the $\delta^{13}C$ values were conducted for suspended matter, plankton, benthos and sediments at four stations in the Bohai Sea during June 1997 in order to inquire tentatively the trophic relationships in the Bohai ecosystem food webs.

2 Materials and methods

2.1 Sampling

Four stations were located at the center of the Bohai Sea, Laizhou Bay, Bohai Bay and Liaodong Bay, respectively. Their locations, water depths, and salinities were listed in Table 1.

Table 1 Sampling stations in the Bohai Sea

Station No.	Location	Water depth (m)	Salinity
1	120°30′E, 38°30′N	29.8	30.08
2	119°30′E, 37°30′N	18.1	29.43
3	118°30′E, 38°30′N	19.3	29.77
4	119°30′E, 39°00′N	27.2	30.50

Seawater samples collected on deck were filtered with Whatman *GF/F* glass fiber filters to obtain the particulate organic matter (POM) samples. The zooplanktons were sampled using vertical tows of a plankton net (200μm mesh nets) and the specimen were sorted into 200～500μm, 500～1000μm and >1000μm escape diameter size-classes, by washing fresh samples through standard screens (200, 500 and 1000μm mesh nets) aboard ship with seawater. The bottom sediment samples were collected using a box corer (the area is 0.1 m^2). The benthic organisms were obtained by washing sediments through 0.5mm or 0.05mm mesh nets with seawater. All the samples obtained were frozen at −20℃ until analysis.

2.2 Stable carbon isotope analysis

A sample of 1 to 3 mg was loaded into a quartz breakseal tube with excess wire-form copper oxide and platinum wire. The tube was evacuated to below 0.5 Pa, sealed, and combusted in a furnace at 800℃ for 2 h. The isotopic ratios of the resultant CO_2 gases were measured using a Finnigen MAT-251 mass spectrometer. Isotopic ratios were calculated as:

$$\delta^{13}C\ (‰) = [(R_{sample} - R_{std})/R_{std}] \times 1000$$

where $R = {}^{13}C/{}^{12}C$, and std = Peedee Belemnite carbonate (PDB)[8,9]. The measurement error (standard deviation) for the laboratory standard sample material was $\pm 0.08\times10^{-3}$.

3 Results

The results of stable carbon isotope determinations of particulate organic matter (POM), plankton, benthos and sedimentary organic matter (SOM) in the Bohai Sea ecosystem at the end of spring are listed in Table 2.

The organism samples collected in the whole ecosystem had $\delta^{13}C$ values in the range of $-25.67 \sim -17.42 \times 10^{-3}$, with a $\delta^{13}C$ maximum difference of 8.25×10^{-3}. Within the planktonic community (not including necton) the $\delta^{13}C$ ranged from -25.67×10^{-3} for POM[10] to -21.99×10^{-3} for *Centropages mcmurrichi*, which showed a step-wise enrichment with trophic levels of 1.7×10^{-3} based on the results of both in situ in Laoshan Bay and laboratories culture measurements[11]. We used this enrichment value to construct a simple isotopic food-web model to establish trophic relationships within this marine ecosystem. This model confirms a food web consisting of approximately 3.2 trophic levels. The trophic level within the planktonic community can be calculated according to the relationship:

Table 2 Analytical results of stable carbon isotopes in the Bohai Sea ecosystem

Sample	Station No.	$\delta^{13}C(10^{-3})$
POM (GF/F 377)	1	−24.33
Sediment #1	1	−22.51
200～500 μm (*Centropages mcmurrichi* Willey, *Acartia bifilosa* (Giesbrecht), *Tortanus spinicaudatus* Shen et Bai)	1	−25.67～−25.27
500～1000 μm (*Calanus sinicus* Brodsky, *Centropages mcmurrichi* Willey)	1	−24.01～−24.04
>1000 μm (*Sagitta crassa* Tokioka, *Calanus sinicus* Brodsky)	1	−22.88
Sagitta crassa Tokioka	1	−23.89～−23.90
Calanus sinicus Brodsky	1	−22.33
Syngnathidae	1	−19.50
Nephtyidae	1	−21.97
Praxillella praetermissa (Malmgren)	1	−19.05
POM (GF/F 270)	2	−25.67
Sediment #2	2	−22.42
200～500 μm *Noctiluca scintillans* (Macartney)	2	−22.51
500～1000 μm *Centropages mcmurrichi* Willey	2	−21.99
>1000 μm (*Sigitta crassa* Tokioka, Fish larvae)	2	−22.25
Tube of polychaeta	2	−20.84～−20.28
Dosinia corrugata (Reeve)	2	−19.38～−19.15
Nemertinea	2	−19.10～−19.06
Lumbrineris heteropoda (Marenzeller)	2	−19.04
Nephtys oligobranchia Southern	2	−18.46
Trachypenaeus curvirostris (Stimpson)	2	−17.64～−17.59
POM (GF/F 389)	3	−24.52
200～500 μm (*Acartia bifilosa* (Giesbrecht), *Paracalanus parvus* (Claus))	3	−24.61
500～1000 μm (larvae of *Calanus sinicus* Brodsky, *Labidocera euchaete* Giesbrecht)	3	−24.60～−24.62
>1000 μm Fish larvae	3	−23.81～−22.99
>1000 μm (*Sagitta crassa* Tokioka, *Calanus sinicus* Brodsky)	3	−23.67
>1000 μm (Fish larvae, *Sagitta crassa* Tokioka)	3	−23.73～−23.79
Stichopodidae	3	−20.65
Protankyra bidentata (Woodward et Barrett)	3	−19.30
Cymothoidae	3	−18.65～−19.31
Amphipholis japonicus Matsumoto	3	−17.97
Leptochela gracilis Stimpson	3	−17.88
Undefined sp.	3	−17.42
POM (GF/F 386)	4	−24.98
200～500 μm (*Centropages mcmurrichi* Willey)	4	−25.61～−25.48
500～1000 (m larvae of *Calanus sinicus* Brodsky	4	−25.07
>1000 μm (*Sagitta crassa* Tokioka, *Calanus sinicus* Brodsky)	4	−24.48
Marphysa sanguinea	4	−20.95～−21.08
Alpheus japonicus Miers	4	−18.20～−19.65

$$TL = (D + 25.67)/1.7 + 1$$

where D is the $\delta^{13}C$ value of the organism, −25.67 refers to the value of POM, and TL is the organism's trophic level. The variations of $\delta^{13}C$ value in the benthic food web have a range from −22.51 to -17.42×10^{-3}, with a difference of 5.09×10^{-3}. For simplicity, if sedimentary organic matter (SOM) is the food source of benthos, this difference will correspond to the occurrence of 4 trophic levels in the benthic food web in case that the coupling between benthic and pelagic food webs is not considered.

4 Discussions

4.1 Primary producers and allochthonous nutrient material as well as their carbon isotope compositions in the Bohai ecosystem food webs

The primary producers and allochthonous nutrient material are the base of food web in the Bohai Sea. Because the Bohai Sea is a semi-enclosed inner sea, the nutrient material driving this ecosystem food web comes from the terrigenous material carried by some rivers around the sea (such as the Huanghe (Yellow River), the Haihe, the Luanhe, the Dalinghe, the Liaohe, and so on), in addition to the phytoplankton and benthic diatom. Of these rivers the most famous is the Huanghe, which is the second largest one in the world in terms of suspended load. Its annual flux of particulate organic carbon can be up to 2.33×10^{6} t/a[12]. The terrestrial organic material carried by these rivers, therefore, is also one of the important sources of organic matter in the bottom sediments in this region. In addition, there are small amounts of nutrient material from the Huanghai or open ocean carried by the Huanghai warm current via the Bohai strait into a part of the region.

The results of determination in Laoshan Bay by the authors indicated the stable carbon isotopic compositions of phytoplankton had seasonal variation[10]. They are mainly influenced by seawater temperature, components of dominant species, CO_2 supply etc. The $\delta^{13}C$ values of POC on the GF/F filters measured in this project may basically represent isotopic compositions of phytoplankton (see Table 3). Strictly speaking, the particulate matter on *GF/F* filters is > 0.7μm in size. Most authors think it can represent the marine phytoplankton in the pelagic environment. However, particulate organic matter couldn't be seen the same as phytoplankton in the Bohai Sea, which is an inner sea into which a lot of terrestrial material were discharged. The particles on the *GF/F* filters are just approximate to phytoplankton to some extent, because it could not be eliminated that the particles contain some terrestrial components. The POC $\delta^{13}C$ values in the Huanghe River have a range of −28.7 to -26.8×10^{-3} during May and June, with an annual mean of -26.2×10^{-3}[12]. It can be seen from the horizontal distribution of POC $\delta^{13}C$ values that station No. 1 is located at the center of the Bohai Sea, its POC $\delta^{13}C$ values (-24.33×10^{-3}) is closest to that of phytoplankton. Station No. 2 is in Laizhou Bay, which is near the mouth of the Huanghe River. It has the most negative value (-25.67×10^{-3}), reflecting that it is influenced remarkably by the Huanghe-derived material. Station No. 4 is quite close to the Luanhe Estuary, so it may also be affected by land-derived material to some extent. Of course, it can not be eliminated that there might be some differences between the phytoplankton species of these four stations.

The organic matter in bottom sediments of the Bohai Sea may have four sources: (1) the primary producers such as benthic algae, detritus of benthic macroalgae, (2) the sunk material such as the remains, feces, etc of plankton, (3) land-derived organic material, and (4) small amount of material transported from the waters out of the Bohai Sea. The isotopic compositions of sedimentary organic carbon in this work might mean a marker of the mixture of these sources. If isotopic compositions of these sources are measured individually, it will be conducive to interpret clearly different food sources of organisms.

Table 3 The distributions of stable carbon isotopes in the Bohai ecosystem food web (×10⁻³)

	Station No. 1	Station No. 2	Station No. 3	Station No. 4	$\delta^{13}C$ value range	Mean value
SOM	−22.51	−22.42			−22.51～−22.42	−22.46
POM	−24.33	−25.67	−24.52	−24.98	−25.67～−24.33	−24.87
200～500μm	−25.47	−22.51	−24.61	−25.55	−25.55～−22.51	−25.33
500～1000μm	−24.03	−21.99	−24.61	−25.07	−25.07～−21.99	−24.05
>1000μm	−22.88	−22.25	−23.81	−24.48	−24.48～−22.25	−23.62
Zooplankton			～−22.99			
Calanus sinicus	−22.33		−23.79		−23.79～−22.33	−23.38
			～−23.67			
Sagitta crassa	−23.90				−23.90	−23.90
Necton	−19.50				−19.50	−19.50
Polychaetes	−21.97	−20.84		−21.02	−21.97～−18.46	−20.06
	～−19.05	～−18.46				
Bivalves		−19.27			−19.27	−19.27
Echinoderms			−20.65		−20.65～−17.97	−19.31
Benthos			～−17.97			
Nemertinea			−19.30		−19.30～−18.65	−18.98
			～−18.65			
Crustaceans		−17.62	−17.88	−19.65	−19.65～−17.62	−18.34
				～−18.20		
Undefined sp.			−17.42		−17.42	−17.42

4.2 Carbon isotopic compositions of different plankton size fractions

The isotopic measurements of different plankton size fractions indicated that there were some changes of $\delta^{13}C$ values across the plankton size fractions. It can be found that the average $\delta^{13}C$ values increased from -25.33×10^{-3} in the 200～500μm size class to -23.62×10^{-3} in the 1000μm>size class, which corresponds approximately to the change of 1 trophic level. Fry and Quiñones[3] also observed similar changes in 7 zooplankton size fractions ranging from 64 to 8000μm. The results also indicated a large degree of trophic level overlap among various zooplankton size classes, reflecting there was an overlap of biological components among these size fractions. For example, *Calanus sinicus* appeared both in the 500～1000μm fraction and in the >1000μm fraction. *Centropages mcmurrichi* is a dominant species both in the 200～500μm and in 500～1000μm fractions (see Tab. 2). Generally speaking, the increasing tendency of trophic level with increasing mesoplankton size is coincident with the results obtained by Rau *et al.*[1], Sholto-Douglas *et al.*[2], and Fry and Quiñones[3].

4.3 The isotopic composition of the benthic food-web of the Bohai Sea and the significance of its trophic structure

As mentioned above, the $\delta^{13}C$ values of organisms in the benthic food web are mostly higher than those in the planktonic food web. This does not mean the trophic levels of benthos must be higher than those of zooplankton, but reflects the differences of their food sources. It may be found that the $\delta^{13}C$ values of sedimentary organic matter (SOM) are on an average about 2.4×10^{-3} enriched in ^{13}C than those of the suspended particulate organic matter (POM) as the isotopic compositions of the base of the benthic food web are enriched in ^{13}C relative to those of the planktonic food web if pelagic-benthic coupling is not taken into consideration. The carbon isotopic data show that Nephtyidae in station No. 1 feeds on food in bottom sediments, whereas *Nephtys oligobranchia* and *Lumbrineris heteropoda* in station No. 2 seem to be carnivorous or omnivorous.

The current theories of food web dynamics suggest that trophic "levels" are dynamic rather than fixed and that "multichannel omnivory" is an important feature of food webs[13]. The isotopic measurements may provide more empirical support for the theories.

5 Conclusions

5.1 It can be known from the measurements of the stable carbon isotope compositions of the various kinds of biotic samples in the Bohai Sea ecosystem that the planktonic food-web consists primarily of 3.2 trophic levels, whereas the benthic one 4 trophic levels.

5.2 The planktonic size classes have a positive correlation with trophic levels; however, there is a large degree of trophic level overlap among the various zooplankton size classes.

5.3 The amounts of biological specimens collected in this work are limited, particularly the food sources of benthos have not fully been studied. Even then it still can be seen from this work that the stable isotope methods may have wide prospects of application to studies on some more complicated problems such as the pelagic-benthic coupling, etc.

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