Structural analysis of the essential environmental factors associated with the marine meiofauna

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ABSTRACT

A biogeochemical study was carried out from 2006 to 2007 in Bohai Bay, northern China, to investigate meiofauna and a number of environmental factors. A total of 18 environmental factors were selected to study their interrelations using Interpretive Structural Analysis. The results showed that these environmental factors could be divided into five levels according to their degree of impact; the results also showed clear links among these factors. The six factors designated as Level 1 included both biological and chemical factors. The other factors had indirect effects on meiofauna and affect these six factors in different ways. There was single factor, sediment grain size, in the fifth level. The structural analysis of the essential factors gave us more information than simple correlation analysis did. Both the water and sediment factors influenced the benthos community. The result is helpful in understanding the complex relationships between environmental factors, and could be used to grasp the main causes and their environmental linkages with further studies; it would be a good basis for integrative environmental management.

Key words | environment analysis, interpretive structural modelling, marine meiofauna, northern China, structural analysis

INTRODUCTION

Meiofauna are a group of organisms in the marine ecosystem, energetically important owing to their high abundance, small size and fast turnover rates (Higgins & Thiel 1988; Giere 2009). They also play an important role in nutrient recycling. For example, grazing by marine nematodes, a dominant taxon of meiofauna, can keep the colonies of bacteria on sediment grains in the active phase of growth, thus enhancing the nutrient recycling (Raghukumar et al. 2001), and thus also improving our understanding of benthic ecosystem functioning (Lacoste et al. 2018). As a good indicator of environmental quality, the importance of meiofauna has been recognized in the international academic field (Coull & Chandler 1992; Nozais et al. 2005). It is a useful tool for describing changes in the state of marine systems to analyse the benthic community structure (Heip et al. 1992). Therefore, the study of meiofauna is becoming an important element of benthic ecosystem research.

The effects of physico-chemical factors on meiofaunal distribution are important aspects of meiofaunal studies. The results of both observations in the field and experiments in the laboratory show that a variety of environmental factors, such as climate, sediment type, heavy metals and nutrients, affect meiofaunal distribution and community structure (Coull & Chandler 1992; Lee & Correa 2005; Sutherland et al. 2007). Most early studies pay attention to the correlation between environmental factors and meiofaunal assemblages (Gao & Liu 2018). Although these studies provide quite useful information for biological study and environment assessment, they often focus on certain individual environmental factors related to meiofaunal assemblages or attempt to identify the principal component factors from a number of environmental factors. Some results are also inconsistent or even sometimes contradictory. For example, some results proved the Chlorophyll a (Chl a) in sediment affected the meiofaunal distribution, but other studies showed a contrary result (Huang 2005). In fact, the effects of environmental factors are quite complex, as the influence/power of the effect would vary depending on the time and/or place studied. With regard to a case study, not all the environmental factors would affect the marine organisms obviously, some having strong direct influences but others showing indirect or weak
influences. Some factors also lead to chain-like interactions that affect marine organisms (Wang et al. 1994; Wang & Lian 1999). In such cases simple correlation analysis cannot account for the complexity of influences.

In order to understand these complex relationships and the main linkages between them, scholars have devised many study methods (Warfield 2003). In order to study the overall structure of a complex system, a useful approach is to clearly identify causal relationships among the various elements of the system, subsequently use graph theory to identify any relations between the elements, and finally clarify the relationships of the correlation structure of the overall system. Interpretive Structural Modeling (ISM), devised and named in the early 1970s by Warfield, is one such advanced technique for resolving the above problems. His ideas were first presented in a monograph from the Battelle Memorial Institute and later enhanced in his books Societal Systems: Planning, Policy, and Complexity and The Mathematics of Structure (Warfield 1976, 2003). This technique has succeeded in many fields including social science and natural science (Sarkis 1998; Inoko et al. 2011; Tseng et al. 2011). Based on the results of ISM analysis, Wang et al. (1994, 1997) also established a mathematical model to study the occurrence of red tides in a Chinese bay.

The areas around Bohai Bay are becoming some of the fastest developing in China, and while rapid development results in higher economic output it may also cause serious environmental problems. Recently, considerable attention has been paid to biochemical dynamics in this area (Zhang et al. 2012a, 2012b; Hu & Zhang 2013; Hu & Zhang 2016). Marine meiofauna in Bohai Bay has become an important study topic in recent national projects because of its application in environmental monitoring. Meiofauna in the Bohai Sea, outside the present area, has been extensively reported, but there are only a few studies dealing with meiofauna in Bohai Bay (Zhang et al. 2012a; Zhang & Hu 2015). This new attempt using ISM was carried out on the basis of existing data, derived mainly from the four seasonal cruises between 2006 and 2007 in Bohai Bay. The main aim is to identify the main relationships among complex environmental factors affecting the meiofauna.

**MATERIALS AND METHODS**

**Sites arranged for this study**

Bohai Bay (Figure 1) is the westernmost of the three major bays of the Bohai Sea, China. The Jiyunhe River, Haihe River, Duliujianhe River and other small rivers flow into this bay. Generally, the sediment here is constituted of mud and fine silt. There are popular tourist resorts in its northern part, and there are also three harbors around the Bay. Some important economic development areas have been set up around the Bay in the past three decades; thus the area is facing rapid development and has changed greatly.

A total of 15 sites were located within the area of 38.5°–39.5° N, 117.5°–118.1° E (Figure 1). Biological and chemical samples were collected on four occasions: July 2006, December 2006, April 2007 and October 2007. Samples of meiofauna (except for site BH06 in winter) and water were collected in all the cruises, while sediment samples were only collected in the last two cruises.

**Sampling and processing in situ**

Sediment samples were brought on deck using a 0.05 m² box-corer. Then, with the help of Perspex tubes (2.4 cm inner diameter), four subsamples were taken from the box-corer to a depth of 10 cm, taking care to avoid core compression. The biosamples were quickly treated with MgCl₂ solution (75 g/L) to anaesthetize the meiofauna; after a 10 minute wait a 10% formalin solution was added. At the same time, sediment samples were also collected for analysis of environmental factors. Some parameters in the water column, e.g. water temperature, salinity, pH as well as nutrients, were also monitored or sampled. The samples were processed in situ and/or kept in the refrigerator before being analysed (CTSB 2008).

**Processing of samples and data**

Samples for meiofaunal analysis were processed according to the monitoring specification and the study paper (CTSB 2008; Zhang et al. 2010). The abundance and biomass of both the total and the main taxa (nematode, copepod and polychaete) were counted and calculated, respectively. The physical and chemical parameters, including water temperature (T_w) and salinity monitored in situ, were also measured.

The monitored water parameters included temperature, salinity, dissolved oxygen (DO), total alkalinity, pH, nutrients (nitrogen, phosphorus and silicon), water depth, and suspended particulate matter (SPM). Sediment parameters included heavy metals (Fe, Cd, Zn, Pb, Cu, Hg and Cr), sulphide, organic matter, nutrients (total nitrogen and total phosphorus), water saturation (WS), grain size (median diameter, sorting coefficient and mean diameter), petroleum
pollutant, redox potential ($E_h$), Chlorophyll $a$ (Chl $a$) and phaeopigment (Pha). In conclusion, a total of 29 parameters (10 water parameters and 19 sediment parameters) were monitored for this study.

In order to assess relationships between meiofaunal parameters and environmental factors, Spearman rank correlation analysis was performed using software SPSS® v19.

**ISM analysis**

Based on the results of correlation analysis, the environmental factors that showed significant or highly significant correlation were selected for ISM analysis. These data were processed with DOMODEL which was one of three pieces of software written (in Microsoft DOS) by Warfield (2003).

**RESULTS AND DISCUSSION**

The details of meiofaunal distribution and environmental analysis have been reported in other papers (Zhang et al. 2012a, 2012b) and the figures and analysis showing meiofauna variation could be found in those cited papers; this paper just focuses on the structural analysis.

**Correlation analysis and factors selected for ISM**

The Spearman rank correlations were calculated using SPSS® software, and the results were listed in Table 1. Among the 29 selected factors, a total of 25 factors (10 water parameters and 15 sediment parameters) showed significant or highly significant effects on meiofaunal
abundance or biomass. Both significant and highly significant results are marked simply as significant in Table 1, as we do not need to distinguish them in this study.

The correlation results were quite complex, and a few correlations varied with seasons and taxa. The complexity was consistent with previous reports from the Bay (Zhang et al. 2012b). Usually, the result could not meet the demand for detail about the relationships among the environmental factors; hence our interest in whether ISM analysis would help in this regard. In order to simplify the analysis, the three nutrient factors, nitrogen, phosphorus and silicon, were considered as one: ‘nutrients’ for ISM analysis. Similarly, we used ‘heavy metals’ to replace Cd, Hg, Cu and Pb; and used grain size of sediment to represent the sediment features (sorting coefficient, mean diameter and median diameter).

So the following 18 environmental factors, which present significant positive or negative effects, were chosen for further analysis: grain size, water saturation, $E_h$, sulphide, organic matter, Chl $a$, Pha, water temperature, salinity, pH, nutrients, DO, SPM, petroleum pollutant, heavy metals, total alkalinity, and water depth.

**Result of ISM analysis and discussions**

The result of ISM analysis is illustrated in Figure 2. This shows that these environmental factors affected the meiofaunal abundance at different levels, and also indicates the abundance or biomass. Both significant and highly significant results are marked simply as significant in Table 1, as we do not need to distinguish them in this study.

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Table 1 | Spearman rank correlation between the environmental variables and taxa, which includes the total abundance and biomass of meiofauna and the three main taxa (nematode, copepod and polychaete)

| Environmental factor | Abundance | | | | | Biomass | | | |
|----------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                      | Meiofauna | Nematode  | Copepod   | Polychaete| Meiofauna | Nematode  | Copepod   | Polychaete| Meiofauna | Nematode  | Copepod   | Polychaete|
| Water depth          | *         |           |           |           |           |           |           |           |           |           |           |           |
| pH                   |           |           |           |           |           |           |           |           |           |           |           |           |
| Temperature          |           |           |           |           |           |           |           |           |           |           |           |           |
| Salinity             |           |           |           |           |           |           |           |           |           |           |           |           |
| Total alkalinity     | –*        |           |           |           |           |           |           |           |           |           |           |           |
| Dissolved oxygen     | –*        |           |           |           |           |           |           |           |           |           |           |           |
| Nitrogen             | –*        | *         |           |           |           |           |           |           |           |           |           |           |
| Phosphorus           | –*        |           |           |           |           |           |           |           |           |           |           |           |
| Silicon              | –*        |           |           |           |           |           |           |           |           |           |           |           |
| Suspended particulate matter | –* |           |           |           |           |           |           |           |           |           |           |           |
| Sediment             |           |           |           |           |           |           |           |           |           |           |           |           |
| Water saturation     |           |           |           |           |           |           |           |           |           |           |           |           |
| Organic matter       |           |           |           |           |           |           |           |           |           |           |           |           |
| Sulphide             |           |           |           |           |           |           |           |           |           |           |           |           |
| Total nitrogen       |           |           |           |           |           |           |           |           |           |           |           |           |
| Cd                   |           |           |           |           |           |           |           |           |           |           |           |           |
| Hg                   |           |           |           |           |           |           |           |           |           |           |           |           |
| Cu                   |           |           |           |           |           |           |           |           |           |           |           |           |
| Pb                   |           |           |           |           |           |           |           |           |           |           |           |           |
| Chlorophyll $a$      |           |           |           |           |           |           |           |           |           |           |           |           |
| Phaeopigment         |           |           |           |           |           |           |           |           |           |           |           |           |
| Sorting coefficient  |           |           |           |           |           |           |           |           |           |           |           |           |
| Mean diameter        |           |           |           |           |           |           |           |           |           |           |           |           |
| Median diameter      |           |           |           |           |           |           |           |           |           |           |           |           |
| Petroleum pollutant  |           |           |           |           |           |           |           |           |           |           |           |           |
| Redox potential ($E_h$) |           |           |           |           |           |           |           |           |           |           |           |           |

The symbols * and –* denote positive and negative significant correlation, respectively ($p < 0.05$).
linkages among some factors. These 18 environmental factors were separated into five levels according to the levels where they have impact: thus six environmental factors showed direct effects on the meiofauna in this study area and were placed in Level 1. The other factors had indirect effects on meiofauna and affect these six factors in different ways. Level 1 included both biological and chemical factors. The six factors in Level 1 were the dominant factors affecting the meiofauna in this study, and need special attention in further ecological analysis.

Changes in pH and total alkalinity were affecting the meiofauna, indicating the impact of ocean acidification on the marine benthos. This was a relatively independent and simple way to affect meiofauna. Then the meiofauna may have quick responses to climate or weather change, to which we should pay attention (Hua et al. 2019). Sediment grain size showed an important effect on multiple levels of the environmental factors, so it was also essential to consider in meiofaunal studies. This was consistent with former reports that sediment grain was a basic environment for meiofauna (Giere 2009). Huang (2005) considered that phaeopigment and Chl a in sediment had the same origin (usually micro algae) in some places. This graph showed the similar relationship between Pha and Chl a.

The relationships between environmental factors and marine benthos were complex, and this complexity had been shown in many studies; some results were even contrary (Huang 2005). Meiofaunal distribution is actually affected by a variety of environmental factors directly or indirectly. The conventional analysis of correlation cannot reflect the circumstantiality, and may cause contrary results sometimes. The result of ISM analysis could provide more information than the common correlation analysis. It would be helpful to grasp the main line of the relationship from among the complex environmental factors. In some studies, some environmental factors did not show obvious effects on meiofauna, which may be due to their good quality conditions or something else. In addition, the dominant environmental factors might be changed with the temporal and special variation. More ISM analysis was essential for marine benthos study.

It could not be avoided that this was just a preliminary study; not all the mechanism of linkages could be explained in the current status. For example, what direction and how much speed of the suspended matter (SPM) would affect the change of the DO, and then lead to the increase or decrease of meiofauna, and so on. More detailed studies were needed to answer these questions. But, the result of this study was a good attempt at environmental analysis; it gave us a variety of information and ideas for further study. Once we grasp the quantitative relationships among environmental factors, we can create a model to analyze...
and predict benthic ecological changes like the red tide studies (Wang et al. 1994, 1997). The success of ISM would encourage us to conduct more studies in the marine benthos area.

**CONCLUSIONS**

The ISM results of this study showed a simple hierarchical relationship of complex environmental factors, which was helpful to facilitate the analysis and prediction of biological change. The 18 environmental factors were divided into five levels according to their influence in this study. Finally, there were eight water variables and 10 sediment variables that demonstrated effects on meiofauna among the all factors, as well as a variety of sediment factors showing direct influence that were placed in Level 1. The results also emphasized the coupling of factors between the water column and sediment: the meiofauna were not only affected by sediment factors. On the other hand, although the sediment grain size was in the fifth level, it affected four other sediment features and cannot be ignored for meiofaunal analysis. It indicated that the grain size of sediment was a basic factor, which could affect the meiofauna in many ways.

Although this was only a preliminary study, its results illustrate the complex relationship among the environmental factors, as well as providing much useful information that common correlation analysis could not provide. Maybe the influence of each environmental factor would change with location and time, so more studies are needed to complete this kind of analysis. The results of this study are a good basis from which to learn the relationships between the meiofauna and environment, and could also be used for the study of ecological restoration. After grasping the quantitative relationships among environmental factors people could create models to assess and predict benthic ecological changes. This would promote the development of environmental management.

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