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应用稳定同位素技术研究长江口及南黄海水域主要鱼类摄食生态和食物网结构

Studies on the feeding ecology of dominant fishes and foodweb structure in the Changjian estuary and southern Yellow Sea with stable isotope

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应用稳定同位素技术研究长江口
及南黄海水域主要鱼类摄食生态和食物网结构

摘要

海洋生态系统营养动力学是生态学家们长期关注的热点，了解海洋生态系统食物网结构及其时空变化，可为研究气候变化和人类活动对生态系统的影响，实现渔业资源生态系统水平的管理提供科学数据。生物间的摄食关系是食物网研究的重点，经典的食物关系研究方法是胃含物分析法，胃含物直观明了，但也存在分析周期长、饵料种类识别困难、饵料定量不准及定量指标不统一等诸多缺陷。稳定同位素法是一种生物内部标志法，因捕食者与其饵料的碳稳定同位素接近，氮稳定同位素沿食物链基本上是逐级递增，所以碳稳定同位素常用来判断捕食者的饵料组成，氮稳定同位素用于计算生物的营养级，其正确性也得到了广泛验证。在选定生态系统的基线生物后，即可构建生态系统的食物网，该法对生物营养级的计算和食物网时空变化的研究具有较强的优势。但在判断捕食者饵料组成及其贡献比时存在缺陷，只有在饵料间的碳稳定同位素差异较大时才具有较高的精确度，所以在判断食物组成时有时须辅以胃含物分析法。本文以稳定同位素法为主，胃含物分析法为辅对长江口及南黄海水域几种鱼类的食物组成、食物竞争、食物网结构与其时空变化进行了研究，并对稳定同位素法的正确性进行了验证。

（1）首先分析了虻鲉与鳀鱼的食物组成。稳定同位素法对虻鲉的营养级计算结果为 3.40~3.74，平均为 3.55，与胃含物法计算结果接近。虻鲉主要食物为大于 900 μm 的浮游动物，贡献率为 69%~75%，其它饵料的相对重要性依次为：细螯虾、太平洋褶柔鱼、脊腹褐虾、火枪乌贼、仔稚鱼、双喙耳乌贼和日本枪乌贼，贡献率分别为：21%~31%、0~7%、0~4%、0~2%、0~2%、0~1%和 0~1%。稳定同位素法能识别胃含物法不能识别的太平洋褶柔鱼、双喙耳乌贼、日本枪乌贼和火枪乌贼等软体动物和仔稚鱼。虻鲉的碳氮稳定同位素与其体长间不存在相关性，在体长 60mm 时虻鲉食性发

生较大转化。虻鲉的碳氮稳定同位素存在一定的站位差异，长江口北部海域的虻鲉与南黄海其它站位相比存在碳氮稳定同位素的显著差异。

长江口海域鳀鱼的碳氮稳定同位素与南黄海其它站位也存在显著的差异。长江口海域鳀鱼的碳氮稳定同位素与氮百分浓度与体长间不存在显著的相关性。但黄海中南部鳀鱼的碳氮稳定同位素与碳百分浓度与体长间却存在显著的负相关性。整个黄海中南部鳀鱼的营养级范围为 3.73~5.01，平均值为 4.26，稳定同位素法计算鳀鱼的食物基本上为仔稚鱼和>900μm 的浮游动物，仔稚鱼的贡献比较胃含物分析结果偏大，最高贡献比例达到了 74%。

(2) 在用稳定同位素法估算出鳀鱼和赤鼻棱鳀的食物贡献比的基础上，同时采用食物重叠指数法、聚类分析法和稳定同位素法三种方法对南黄海鳀鱼与赤鼻棱鳀的饵料相似程度进行计算。三种方法的平均计算结果相差不大，都在70%左右，三者间的计算偏差≤5%。仔稚鱼在两者的食物贡献中占了很大一部分比例，是两者首要的能量与营养源，两者的食物竞争可能也主要是针对仔稚鱼展开的。

小黄鱼的碳氮稳定同位素也存在长江口北部海域与南黄海间的站位差异，推测在所调查海域可能存在 3 个小黄鱼地方种群和 1 个皮氏叫姑鱼地方种群。小黄鱼与皮氏叫姑鱼的碳氮稳定同位素与体长间不存在明显的线性关系，但小黄鱼体长间的碳氮稳定同位素差异大于皮氏叫姑鱼。稳定同位素法分析小黄鱼与皮氏叫姑鱼的优选食物为红狼牙鰕虎鱼、六丝矛尾鰕虎鱼、中华栉孔鰕虎鱼、龙头鱼、葛氏长臂虾、口虾蛄六种生物饵料，两者在体长为 100-109 mm 左右时食物竞争达到顶值，食物重叠系数为 81.04%。从小黄鱼与皮氏叫姑鱼碳氮稳定同位素的站位差异及体长差异推测两者可能同时采取了不同栖息地的摄食分化策略和一定的食物资源分化来缓和食物竞争。

(3) 从鳀鱼、虻鲉及小黄鱼与皮氏叫姑鱼的碳氮稳定同位素比值站位间的差异及前人的研究结果判断，所调查海域因受长江径流、沿岸流等多种因素的影响而大致分为两部分，即30.5°~32.5°N (包括32.5°N)和32.5°N~33.5°N (分别以CS1和CS2表示)。

在统一基线生物氮稳定同位素值对营养级计算的影响后，春季 CS1 海域中的生物与 CS2 海域相比除脊腹褐虾与鹰爪虾的营养级维持不变，六丝矛尾鰕虎鱼和细螯虾的营养级些微增大外，其它生物的营养级都是减少的。同胃含物分析法一样，稳定同位素法对生物食性类型的判断也存在时空差异。春季 CS1 与 CS2 两海域 21 种共有生物

只有 10 种生物的食性类型一致、秋季 CS1 与 CS2 两海域 18 种共有生物只有 14 种生物的食物类型一致、CS2 海域春秋两季 12 种共有生物只有 7 种生物的食性类型一致、CS1 海域春秋两季 1 6 种共有生物中只有 8 种生物的食性类型一样。总体判断，秋季生物的底栖饵料贡献比春秋低。春季或秋季 CS1 与 CS2 海域生物间碳或氮稳定同位素的变化幅度及 CS1 海域春秋两季生物的碳或氮稳定同位素变化不同步，但 CS2 海域春秋两季生物间的碳或氮稳定同位素变化幅度基本是一致的。

尽管 CS1 与 CS2 两海域生态系统的结构存在时间与空间的差异，但在同海域不同季节、同季节不同海域及不同海域不同季节时生态系统中生物间的碳、氮稳定同位素或碳氮比基本上都存在显著的相关性。推测可能是生态系统中生物的摄食结构基本一致才使得这种相关性普遍存在。

从 CS1、CS2 及东黄海水域生物间碳氮稳定同位素及碳氮比在不同时空尺度基本上都存在显著的相关性推测，在影响生态系统营养结构的四大假说中(能量限制假说、最佳觅食假说、动力稳定性假说和体形限制假说)，可能是生物的"最佳摄食"假说起主要作用。

Studies on the feeding ecology of dominant fishes and foodweb structure in the Changjian estuary and southern Yellow Sea with stable isotope

Abstract

The ocean trophic dynamics always are the important researches to ecologists. In order to research the effects of climatic change and human activities to the ecosystem, to manage the ecosystem scientifically and use the fishery resources continually, we should know the food web structures of ocean ecosystems, and their space and spatial changes. The researches of feeding relationships among organisms are the base researches of food web. The classic research method to food web is stomach analysis method, the results of the method are obvious, but it has some faults, such as needing too much analysis time, having difficulties in identifying food items, having no unify quantitative indexes, and not quantifying its food items contributions exactly. Stable isotopes have been used in many research areas as natural labels, and are becoming the more appropriate option for the aquatic ecological studies. An organism's stable isotope ratios($\delta^{15}N$ and $\delta^{13}C$ etc) are an integration of the isotopic signatures of preys that have been assimilated through time, the organism will come into isotopic equilibrium with its diets depending on growth and tissue turnover rates, the ratios can change with different food, are good labels of organism living conditions. Stable nitrogen isotope ratio consistently fractionate among organisms, approximately 3 to 4‰, which provides a powerful analytical tool to quantify relative trophic position. The trophic level can be calculated according to the isotopic baseline and the trophic fractionation constant. In contrast, stable carbon isotope fractionate very little in organisms, with around 0 to 1‰ enrichment per trophic level, the stable carbon isotope values of organisms reflect the average $\delta^{13}C$ of their diets. Stable isotope technology has advantage in constructing food webs, but has difficulties in judging all the food items and their contributions of some organism when the stable isotope signatures of food items having not obvious discrimination. Some times, stable isotope technology and stomach analysis are used in judging all the food items at the same time. The research analyzed the

feeding habits, feeding overlaps of some important fish species and food webs structure with stable isotope technology mainly, with stomach analysis as the assistant method.

(1) Firstly, we researched the feeding habits of the *spotted velvetfish* and anchovy. The trophic level range of the *spotted velvetfish* was 3.40~3.74, mean trophic level is 3.55, closing to the result of stomach analysis. Between the 1~99% proportion frequency range. plankton >900μm was the most important food source, accounting for 69-75% of the total food by weight. The others were lesser glass shrimp, common squid, Japanese sand shrimp, Beka squid, larvae and juvenile, Lantern cuttlefish and Common Japanese squid in turn, according to their proportions. The proportion were 21%~31%, 0~7%, 0~4%, 0~2%, 0~2%, 0~1% and 0~1% respectively. Stable isotope technology can judge the prey of mollusk, such as common squid, Beka squid, Lantern cuttlefish, Common Japanese squid, and larvae and juvenile, these organisms are digested easily in stomach, can't be recognized by stomach analysis most of the time. Cluster analysis dived the body lengths of the *spotted velvetfish* into two groups according to stable isotope ratios, > 60mm and <60mm, respectively. The carbon or nitrogen stable isotope of the *spotted velvetfish* had significant difference between the northern part of the Changjiang Estuary and the southern Yellow Sea.

The carbon or nitrogen stable isotope of the anchovy also had significant difference between the northern part of the Changjiang Estuary and the southern Yellow Sea. The carbon or nitrogen stable isotope of the different size classes' anchovy hadn't significant difference in the northern part of the Changjiang Estuary, but that of the different size classes' anchovy in the southern Yellow Sea had significant difference. The trophic level rang of the anchovy in the southern Yellow Sea was 3.73~5.01, mean trophic level was 4.26. the main preys of the anchovy were larva and juvenile and plankton >900μm, the proportion result of larva and juvenile from the stable isotope technology was higher than that of the stomach analysis, the most highest proportion was 74%.

(2) According to the prey proportions of the anchovy and the rednose anchovy calculated by stable isotope technology, we calculated the prey overlap index between the two species of fishes with three methods, mathematic diet overlap index, Cluster analysis and stable isotope technology, respectively. The mean prey overlap index of each method was about 70%, no significant difference being among the results of three methods, the calculate error

were less than 5% among the three results. The larva and juvenile had the highest proportion, was the main energy and trophic source of the two species of fishes. The prey competition was mainly carried on the larva and juvenile.

There were significant difference in the carbon or nitrogen stable isotope of small yellow coaker between the northern part of the Changjiang estuary and the southern Yellow Sea. We speculated that there were three endemic branch tribes of small yellow croaker and one endemic branch tribes of Belanger's croaker. And there were no significant difference in the carbon or nitrogen sable isotopes of different size classes of the two species of fish, but the difference in the carbon or nitrogen sable isotopes of different size classes of small yellow croaker is higher than that of Belanger's croaker. The $\delta^{13}C$ and $\delta^{15}N$ values showed that six diets, including *Odontamblyopus rubicundus*，*Amblychaeturichthys hexanema*，*Ctenotrypauchen chinensis*，*Harpadon nehereus*，*Palaemon gravieri*, *Oratosquilla oratoria* were the preferential food compared with the others at the same time. The diet competition of the two species of fish attained climax at the body length of 100-109 mm, the diet overlap index is 81.04%. From the station difference and body length difference of carbon and nitrogen stable isotope of small yellow croaker and Belanger's croaker, we speculated that the two species of fish adopted inhabiting different habits and feeding difference preys to reduce diet competing.

(3) Eliminated the effect of nitrogen stable isotope of different base line organism in different ecosystems to the trophic level, we found that except Japanese sand shrimp and Southern rough shrimp, the trophic levels of the other organisms in CS1 waters (30.5°~32.5°N, including32.5°N) were different from that of those in CS2 waters (32.5°~33.5°N), the trophic levels of Sixthread lancettail goby and lesser glass shrimp in CS1 waters were higher than that of them in CS2 waters, in contrast, the others was less. Like the stomach analysis results, there were space and spatial difference in ecological group of feeding habits of the same organism estimated by stable isotope technology. In spring, there were only 10 species organisms in 21 species organisms having identical ecological group of feeding habits between CS1 and CS2 waters, while in autumn, there only were 14 species organisms in 18 species organisms having identical ecological group of feeding habits between CS1 and CS2 waters. In CS2 waters, there were only 7 species organisms in 12 species organisms having identical ecological group of feeding habits

between spring and autumn, while in CS1 waters, there only were 8 species organisms in 16 species organisms having identical ecological group of feeding habits between spring and autumn. The benthic prey proportions to organisms were almost higher in spring than in autumn. The changing direction of carbon or nitrogen stable isotope of all organisms were different between CS1 and CS2 waters in spring or autumn or between in spring and in autumn in CS1 waters on the whole, but changing direction of carbon or nitrogen stable isotope of all organisms were consistent between in spring and in autumn in CS2 waters.

Although the ecosystem structure had space and spatial difference between CS1 and CS2 waters or others, there were significant correlations between carbon or nitrogen stable isotopes of organisms between different waters in the same season, different seasons in the same waters or different waters in different seasons. We speculated that the consistence of the feeding habits structure of all organisms had the significant effects on the carbon or nitrogen stable isotopes of organisms in ecosystem.

There were four hypotheses to the changing food web structure: the energy constraints hypothesis, the optimal foraging hypothesis, the dynamic stability hypothesis and the design constrains hypothesis. From the results of the paper, we speculated that the optimal foraging hypothesis had the mainly effect to the food web structure.

Key words: Changjiang estuary and adjacent southern Yellow Sea; food composition; food proportion; food competition; food web

目录

第二章 长江口及南黄海水域鱼类的食性研究

为了生存，生物必须摄食。水生生物因其栖息环境的特殊性，其食性研究相对陆生生物要困难许多，但鱼类的食性研究，对鱼类的人工饲养、研究鱼类的生长、发育和繁殖及探寻其制约因素和制定科学的保护对策都具有重要意义。明白水生生物中捕食者与饵料间的捕食关系也是研究食物网的基础，最早的食性研究是 Hardy[1]在 1924 年对北海鲱鱼食性的定性研究。随着研究的深入，定量研究逐渐取代了定性研究，这为渔业生物学家估算各种生物的消耗量、评估渔业捕捞对捕食者与饵料关系的影响及食物网动力学对渔业的影响提供了有力帮助[2]。

鱼类摄食生态及其种间食物关系在时间尺度上的细分研究，是认识海洋鱼类群落、乃至整个生态系统服务功能的关键所在[3,4]，也是提高海洋生态系统生产力和进行多鱼种渔业管理及研究全球气候变化对海洋生态系统影响的基础[5]。食性分析的经典方法胃含物分析法比较直观，但也存在许多缺陷，它需要大量的生物样品数量和娴熟的生物，尤其是浮游生物的种类识别能力，分析过程长，且存在生物偶食性和饵料消化吸收难易所带来的计算误差。也正是这些缺点，使得食物网中小型生物的食性研究较少。稳定同位素技术所取样品是生物体的一部分或全部，反映生物长期生命活动的结果，可对生物的营养来源进行准确测定，能准确定位生物种群间的相互关系及整个生态系统的能量流动[6-9]。稳定同位素技术与胃含物分析法结合使用能真实地反映生物的营养状况。

第一节 长江口及南黄海水域春季虻鲉的食性

虻鲉*(Erisphex pottii)*属前鳍鲉科*(Congiopodidae)*，分布于北太平洋西部，我国见于南海、东海和黄海，为近海常见的肉食性底层鱼类，在日本 、朝鲜都有分布。体无磷，而被密集的绒粒状皮质小突起。眼前骨下缘有 2 尖棘，前鳃盖骨后缘有 4 尖棘。背鳍始于眼后缘上方。腹鳍喉位，有 1 鳍棘、2 鳍条。各鳍鳍条均不分枝。体侧有许多不规则的暗色小斑点。暖温性小型鲉类，体长一般在 100 毫米以内。栖息于较深的泥沙底质海区。以小型甲壳动物等为食。春季产卵。

由于过度捕捞和环境变化的影响，黄、东海生态系统的许多传统渔业优势种个体变小、性成熟提前或被其它鱼种替代，一些小型鱼类，如虻鲉、细条天竺鲷(*Apogon lineatus*)、七星底灯鱼(*Benthosema pterotum*)、颚齿鱼(*Champsadon capensis*)及龙头鱼(*Harpadon nehereus*)等的生物量逐年增大(内部资源调查数据)。小型鱼类，特别是小型广食性型饵料鱼适应性强，对环境变化的响应时间短，在生态系统演替中起着方向性作用。虻鲉与系统中许多优势种和经济种的食物重叠程度较高[10]，对生态系统的演变和产出起着重要作用。本文采用碳氮稳定同位素技术对春季长江口及南黄海水域小型杂食型饵料鱼虻鲉的摄食习性及其随体长的变化情况进行研究，以对在水域环境变化等外界压力条件下海洋生态系统的演化趋势进行探讨。

1.1 材料与方法

1.1.1 样品的采集

虻鲉样品取自 “北斗”号海洋综合调查船于2005年4－5月在长江口及南黄海水域(30°30′~33°32′N ,122°30′~ 125°00′E)进行的定点底拖网调查取样(图1.1)。浮游动物采用标准中型和大型浮游动物网，从水底至水表垂直拖网采样，用筛绢将其分成＞900 μm、500~900 μm、300~500 μm和100~300 μm 4种粒级，在>900 μm的浮游动物中，将样品中数量大且容易进行种类鉴定的生物单独挑出。以5 mm体长段为取样间隔单位对虻鲉进行取样，每个体长段取5尾左右。调查共收集虻鲉样品125尾,样品的体长为23~95 mm。所取饵料样品的粒径基本涵盖虻鲉摄食粒径谱范围，每种游泳类饵料的样品量也在5~10尾左右，4种粒级的浮游动物样则全取，共取得14种虻鲉可能饵料种类。