香港水域夏季微型浮游动物摄食研究

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摘要:2000 年 8 月在香港牛尾海(A 站)和龙鼓水道(B 站)的 2 个典型站位采样,用半现场的稀释法研究了夏季香港水域浮游植物的生长率和微型浮游动物对浮游植物的摄食压力等。结果表明:A、B 站浮游植物主要以硅藻为主,但 A 站甲藻比重比 B 站要高。A 站$<5\mu m$ 的微型浮游植物比 B 站要少,从细胞大小上 B 站的浮游植物更易被微型浮游动物所摄食。A 站微型浮游动物类群主要以异养鞭毛藻为主,而 B 站为砂壳纤毛虫,其细胞丰度分别为 770 和 620 ind./L。A、B 站浮游植物碳/叶绿素 a 浓度比率分别为 27.15 和 88.66。A 站浮游植物的内禀生长率相似于 B 站,分别为 1.04 和 0.98 d^{-1}。浮游植物在 A 站的净生长率是 0.33 d^{-1},而在 B 站则出现了负增长,其净生长率是 -0.58 d^{-1}。微型浮游动物在 A、B 站的摄食率分别为 0.71 和 1.56 d^{-1},摄食压力分别占到了浮游植物现存量的 143.7%和 209.7%,初级生产力的 78.6%和 126.6%,对浮游植物碳的摄食率分别达到 351 和 552 $\mu gC/(L \cdot d)$。A 站的浮游植物生长要高于 B 站,B 站的微型浮游动物摄食压力要明显高于 A 站。与其它海区比较香港水域微型浮游动物摄食压力处于中等水平。黑暗长时间培养实验的结果表明此水域微型浮游动物摄食率稀释法实验应在适量添加营养盐并在有光的条件下 1d 之内完成。

关键词:微型浮游动物;摄食压力;浮游植物;稀释法;香港

Preliminary study of microzooplankton herbivory in Hong Kong in summer

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Abstract: Two typical stations, the Port Shelter (station A) and Urmston Rcad (station B) in Hong Kong, were chosen as sites for phytoplankton growth and microzooplankton herbivory studies which were completed using a semi- *in situ* dilution experiment in August 2000. PFW (particle-free water) was used to dilute sea water to five target dilutions of 0%, 20%, 40%, 60% and 80%. The microzooplankton grazing rate and phytoplankton growth rate were estimated by the linear regression of AGR (apparent growth rate) versus ADF (actual dilution factor). The grazing impact on phytoplankton by microzooplankton was estimated by calculating phytoplankton net growth rate, percentage of phytoplankton standing stock

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万方数据

ingested, percentage of prey potential production ingested, and ingestion rate of phytoplankton carbon. The phytoplankton carbon was estimated by converting the cell biovolume to carbon using assumed carbon conversion factors.

At stations A and B, diatoms were dominant in the phytoplankton community, but when the species richness and cell abundance were completed, dinoflagellates were more important in stations A than B. The dominant phytoplankton species were *Chaetoceros curvisetus*, *Thalassionema frauenfeldii*, and *Chaetoceros lorenzianus* at station A, and *Lauderia annulata*, *Thalassionema frauenfeldii*, and *Ditylum sol* at station B. The phytoplankton assemblage at station A was characteristic of coastal warm water species, while brackish water species could be found in the phytoplankton assemblage at station B. The light conditions were good but the nutrient conditions (ammonium, phosphate, nitrate plus nitrite, and silicate were 0.30, 0.23, 0.56, 0.69 μm respectively) were poor at station A. In contrast, light conditions were poor and nutrient conditions (ammonium, phosphate, nitrate plus nitrite, and silicate were 3.42, 1.06, 49.57, 46.15 μM respectively) were good at station B. The < 5 μm fraction of phytoplankton in station A (24.3%) was less than station B (40.9%). This indicated that, according to cell size, the phytoplankter at station B was more easily preyed upon than that of station A. Heterotrophic dinoflagellates were the major component of microzooplankton at station A, and tintinnids were also commonly present in the microzooplankton sample. At station B, however, tintinnids were a major component of microzooplankton and few copepod nauplii were found. Microzooplankton abundances were 770 and 620 ind./L at stations A and B respectively. The carbon: chlorophyll a ratios were 27.15 and 88.66 at stations A and B respectively. The dilution experiment results showed that phytoplankton instantaneous growth rates were 1.04 and 0.98 d^{-1} at stations A and B respectively. The net growth rate was 0.33 d^{-1} at station A, which was greater than that of −0.58 d^{-1}at station B. The microzooplankton grazing rates were 0.71 and 1.56 d^{-1}, percentages of phytoplankton standing crop ingested by microzooplankton were 143.7% and 209.7%, percentages of phytoplankton potential production ingested by microzooplankton were 78.6% and 126.6%, microzooplankton ingestion rates of phytoplankton carbon were 351 and 552 μgC/(L·d) at stations A and B respectively. This demonstrated that the phytoplankton growth rate at station A was greater than at station B, and microzooplankton grazing pressure was less than that of station B. We can also deduce that the grazing pressure of tintinnids was higher than that of heterotrophic dinoflagellates. In spite of the good nutrient conditions at station B, high microzooplankton grazing pressure plus low light condition made the standing crop of phytoplankton at station B (chlorophyll a concentration is 9.00μg/L) lower than at station A (chlorophyll a concentration is 2.97μg/L). Compared with the other regions around the world, the microzooplankton grazing pressure in Hong Kong waters was in the middle of the range of measurements elsewhere.

The results of the long-time controlled dilution experiments (3 days) under dark conditions showed that further dilution experiments should be carried out under light conditions and finished within one day. Although the nutrient concentrations were high at station B, it was necessary to add nutrients when the dilution method studies were undertaken at this station.

Key words: microzooplankton; grazing pressure; phytoplankton; dilution experiment; Hong Kong

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香港位于中国的南部,地处亚热带,主要由新界、香港岛和大屿山 3 个大的岛屿组成,其附近有 200 多个岛屿,具有独特的地理特性。其西面沿海水域受到来自珠江的冲淡水的影响,南部毗邻中国南海,来自西南的南海表层水团、来自东南的黑潮,以及来自东北的沿岸流等都会影响香港东部水域。近几十年来,由于过度的土地开垦、不适当的污水排放、水产资源的过度开发、挖泥以及增长的海上交通等人类活动使其海岸带正在遭受巨大的压力,并显示出快速退化的迹象,赤潮在此区域频发就是典型的反映[1,2]。但香港海域的基本海洋生态系统还不是很清楚,所以此海域的生态系统动力学研究就十分必要。

海洋生态系统中一个关键的过程研究就是浮游生态系中浮游植物和浮游动物的摄食关系研究。浮游动物的摄食受各营养阶层组分粒级结构的影响[3~5]。在大细胞浮游植物占优势的海区,浮游植物被中型浮

游动物摄食的经典食物链是重要的,而在以小细胞植物为主的生态系统中则以微型浮游动物对小细胞的浮游植物及细菌摄食的微食物环(microbial loop)为主。由于近年来发现微型浮游生物在海洋生态系统中是重要的组分[6~8],所以国际上近 20 多年浮游动物摄食研究的重点就转向了微型浮游动物的摄食研究[9~27]。中国的海洋微型浮游动物摄食研究起步较晚,但也在一些典型海域有了基础工作[28, 29]。香港海域还未见微型浮游动物摄食研究的报道。本文在香港的牛尾海和龙鼓水道两个典型水域进行了微型浮游动物摄食的初步研究,评估微型浮游动物摄食对浮游植物现存量的影响,以期进一步观测和了解香港水域的有害微藻水华频发的动力学机制。

1 材料与方法

1.1 研究站位

香港水域的东西两面由于受不同水系的影响,水体性质截然不同。东部的 A 站位于香港科技大学附近的牛尾海中,此水域主要受广东沿岸流、黑潮和近岸生活用水及雨水径流等影响,温度和盐度均高,但营养盐较低。西部的 B 站位于龙鼓水道处,靠近伶仃洋-珠江口水域,主要受珠江口的影响,是典型的盐楔型河口区域,温度高、盐度低、营养盐丰富。本研究中,于 2000 年 8 月 23 日和 30 日分别在 A 站和 B 站及香港近岸卷流区进行了两次一天的小船取样(图 1)。

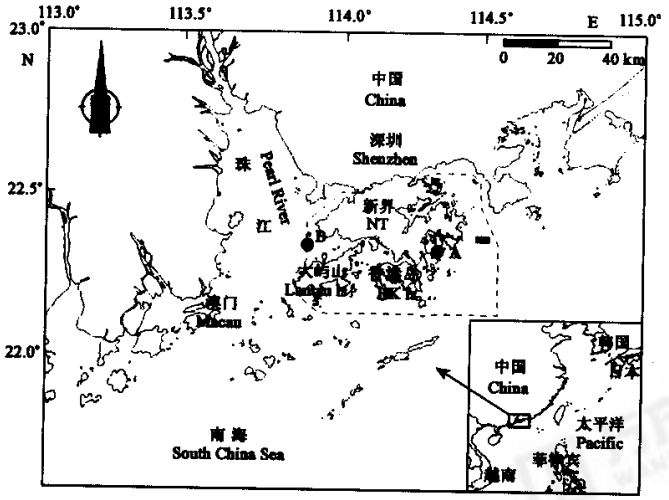

图 1 采样站位(虚线为香港特别行政区水域;A:牛尾海;B:龙鼓水道)

Fig. 1 Sampling stations (dashed line is the boundary of the Hong Kong territorial water; HK. Hong Kong; Is. Island; NT. New Territories; A. the Port Shelter; B. Urmston Rcad)

1.2 采样

每站位上应用预先校正过的 YSI®6600 获得盐度、温度、叶绿素 a 荧光值、pH 和浊度等参数,取样间隔为 0.25m,当船读取数据并存储于便携式计算机中。用水下光度计(QSL-101)测定水下光强的垂直剖面。用工厂制作的 5 L 有机玻璃采样器从 2 m 水层采水样。水样被转移到 10 L 水桶以备亚样品分样。400 ml 水样用来进行叶绿素 a 的粒级分离 (> 5 和 < 5 μm),水样先后通过 5 μm 聚碳酸酯滤膜 (Poretics®)和 Whatman® GF/F 滤膜 (25 mm)。微型浮游动物和浮游植物种类鉴定及丰度测定的样品用 1%(体积比)鲁戈氏液固定并保存于 500ml 聚乙烯瓶中[30]。营养盐样品用装载有预先灼烧过的 Whatman® GF/F 滤膜的 Swinnex®的 60 ml 注射器过滤到 30ml Nalgene 瓶中。所有塑料制品预先用 10%盐酸清洗。过滤的水样保存在放有干冰的冰盒中。营养盐的分析在 2 周内于实验室完成。微型浮游动物摄食率实验用水样,在通过 200μm 筛绢后用预先清洗过的 25 L 水桶黑暗下快速带回实验室。

1.3　微型浮游动物摄食率实验

微型浮游动物摄食率应用稀释法测量[31, 32]。在陆地上的实验室中,一部分水样用 0.2μm 的 Gelman 滤器过滤以获得无颗粒水(PFW, particle-free water),另一部分水样与无颗粒水按比例进行混合,轻轻倒入并定容至 4L 的聚碳酸酯培养瓶中。无颗粒水占培养水体的比例分别为:0%、20%、40%、60%和 80%。每个培养处理做 3 个重复样,0%比例是 7 个重复样。这些培养瓶分为均等的两组,放在屋顶暴露于自然光用自来水冷却的水槽中。培养温度用调节冷却水达到相似于表层海水温度的 28 C。其中一组水槽盖有一层中性密度网以减少水体中光强的 35%,另外一组是在完全黑暗情况下在水槽中培养。培养时间为 3d。每天当地时间 14:00 用 Turner Designs® 荧光计 (Model 10)测定活体荧光一次,应用以上方法采集叶绿素 a、微型浮游动物、浮游植物和营养盐的样品一次。

1.4　样品分析

活体荧光用 Turner Designs® 荧光计 (Model 10)测定。先在黑暗中放置样品几分钟再测定,测定数据下载入计算机后计算平均值。

叶绿素 a 的样品在陆地实验室内参照[30]的叶绿素 a 荧光计分析方法。滤膜放入 10 ml 90%的丙酮,于黑暗冰水中超声波粉碎 10 min,在黑暗和冷冻中萃取 24 h,于 Turner Designs® model 10 应用荧光计法[30]进行叶绿素 a 浓度分析。

微型浮游动物和浮游植物样品于 Zeiss Axiovert 35 倒置显微镜下进行分析[33]。每 500ml 样品先静止沉降 7d,去除上清液,样品最终在 25ml Utermöhl 计数框中静止沉降 24h,于×400 放大倍率下进行纤毛虫、甲藻和浮游植物全片计数。每样品细胞个数统计不低于 200 个(细胞数量的统计和误差处理,公式从略),对于细胞丰度太高的样品随机选取 5 个视野进行计数。浮游植物只有大于 5 μm 的个体被计数,其中大于 5μm 的种类构成了浮游植物生物量的绝大部分(未发表资料。从操作的可行性上来说,在进行光学显微镜常规检测浮游植物样品时,对于大于 5 μm 种类的计数是可信的)。

所有营养盐用 Skalar® San Plus 进行检测。硝酸盐 (加上亚硝酸盐)和氨盐分别参照 Wood 等[34]和 Slawyk & MacIsaac[35]的分析方法。磷酸盐和硅酸盐分别参照 Hager 等[36]和 Armstrong 等[37]的方法。

1.5　稀释法分析微型浮游动物的摄食压力

根据稀释法原理[31,32]对每个培养瓶进行浮游植物表观生长率(AGR, apparent growth rate)(本研究中是以叶绿素活体荧光和叶绿素 a 浓度进行估算。重复样结果进行成对 t 检验,显著水平 $P<0.05$ 的结果才作为计算数据)和实际稀释因子(ADF, actual dilution factor)计算。微型浮游动物的摄食率(g, grazing rate)和浮游植物的内禀生长率(μ, instantaneous growth rate)可以用 AGR 和 ADF 的线形回归方程获得。方程应用最小二乘法计算,其中的截距为浮游植物的内禀生长率(μ, d^{-1}),斜率为微型浮游动物的摄食率(g, d^{-1})。微型浮游动物的摄食影响用浮游植物净生长率(NGR, net growth rate, d^{-1})、对浮游植物现存量的摄食压力(%P_p, percentage of phytoplankton standing crop ingested)、对浮游植物潜在初级生产力的摄食压力(%P_p, percentage of phytoplankton potential production ingested)和浮游植物碳的摄食率(I_c, ingestion rate of phytoplankton carbon, μgC/(L·d))来表示,计算公式如下:

$$NGR = \mu - g$$

$$\%P_s = \frac{(C_o e^{\mu} - C_o) - (C_o e^{\mu - g} - C_o)}{C_o} \times 100$$

$$\%P_p = \frac{(C_o e^{\mu} - C_o) - (C_o e^{\mu - g} - C_o)}{C_o e^{\mu} - C_o} \times 100$$

$$I_c = C_o e^{\mu} - C_o e^{\mu - g}$$

其中,C_o 为初始无稀释组分浮游植物的碳含量(μgC/L),$(C_o e^{\mu} - C_o)$,为浮游植物潜在生产力,$(C_o e^{\mu - g} - C_o)$为浮游植物实际生产力。

1.6　浮游植物碳/叶绿素 a 浓度(C:Chl-a)比率

浮游植物的碳含量计算应用细胞体积转换碳含量法[38]。对初始无稀释组分样品的浮游植物进行细胞

体积估算，然后根据 Eppley 公式[39]计算出每个细胞的转换碳含量。根据细胞丰度获得水体中浮游植物碳含量，其后计算出浮游植物碳/叶绿素 a 浓度比率。

2 结果与讨论

2.1 水文条件和环境因子

调查站位水文条件和环境因子的垂直剖面如图 2。A 站位于香港的东部水域，这里主要受暖海外洋水的影响，温度和盐度都较高。温度的范围是 22.4～30.4 ℃，平均值为 25.5 ℃，表层到 3.4m 层水温都在 30 ℃以上，然后到 10m 层逐渐降至 23.4 ℃，直到水底无多大变化。盐度的范围是 29.4～33.6，平均值为 32.3，表层到 3.4m 层盐度都在 30 以下，然后到 10m 层逐渐升至 33.4，直到水底无多大变化。以上可以看出在 3.4m 水层处出现了跃层，这是由于此处的水体稳定度较好，盐度高和温度低的水体处于下层，表层时常会有路源或降水补充淡水。浊度的变化在表层不是很明显，但在底层则急剧增加，说明此海域底层水体受潮汐等物理扰动的影响较明显。pH 值范围是 8.07～8.70，平均值为 8.28，其变化趋势同温度变化相似，表层到 3.4m 层盐度都在 8.60 以上，然后到 10m 层逐渐降至 8.10，直到水底无多大变化。这说明跃层的存在使浮游植物在此海域形成两种不同的生长类型，表层的浮游植物较底层生长迅速，水体中 CO_2 被快速利用，以致 pH 值增高。叶绿素荧光值的垂直变化不明显，但表底层叶绿素 a 的测值却有较大区别，分别为 9.00 和 4.26 μg/L。B 站位于香港的西部水域，位于珠江河口的卷流区域，主要受珠江口的影响，盐度较低，水体稳定性差。温度的范围是 26.4～28.4 ℃，平均值为 27.6 ℃，表层到底层温度变化不大，底层温度低于表层。盐度的范围是 25.2～29.2，平均值为 26.8，表层到 2.3m 层盐度都在 26 以下，然后到底层逐渐升至 29.2。浊度的变化趋势同 A 站，在表层不是很明显，但在底层则急剧增加，说明此海域底层水体受物理扰动的影响较明显。pH 值范围是 8.83～8.88，平均值为 8.85，表底层变化不大，表层比底层略高。叶绿素荧光值的垂直变化不明显，表底层叶绿素 a 的测值，分别为 2.97 和 2.42 μg/L。从以上的数据可以看出，B 站的水体混合较均匀，不存在明显的跃层。比较两站位的水文和其它环境因子发现，A 站的温度比 B 站为低，而盐度、pH 值和水体稳定度都要高。

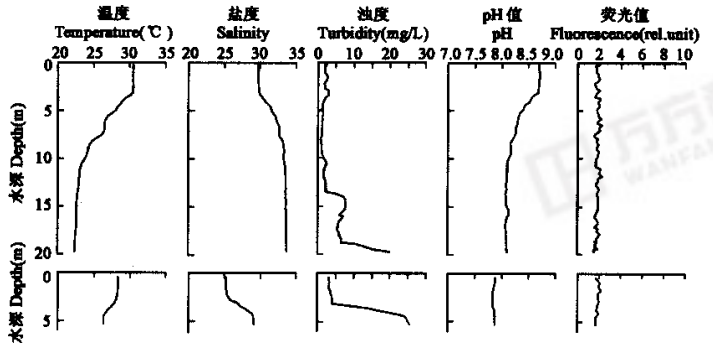

图 2 A 站(牛尾海)和 B 站(龙鼓水道)温度、盐度、浊度、pH 值和叶绿素荧光值的垂直剖面

Fig. 2 Vertical profile of temperature, salinity, turbidity, pH and chlorophyll fluorescence at station A(the Port Shelter) and B (Urmston Rcad)

研究站位的营养盐分布如表 1 所示。A 站的营养盐浓度要远小于 B 站，这是由于 B 站受珠江带来的陆源营养盐的影响。叶绿素 a 浓度却是 A 站要高于 B 站，这可能是 B 站的浮游植物生长受到光限制的缘故。B 站位于珠江河口的卷流区域，水体浑浊，水下光衰减很快，在 5m 就达到了表层光强的 1%以下(图 3)，浮游植物由于湍流作用将经常处于真光层以下，所以此海域的浮游植物受到光的限制。相比较而言，A 站的浮游植物光条件则要好得多，基本上整个水柱都处在真光层，限制浮游植物生长的因子是营养盐。

2.2 浮游植物和微型浮游动物种类组成特征及丰度

研究站位的浮游植物组成如表 2。A 站共发现浮游植物 34 种,种类丰富度和细胞丰度以硅藻为多。但甲藻在种类数上亦不占少数,共 10 种其中 5 种是赤潮原因生物[40]。此外还出现了常见金藻种类六等刺硅鞭藻(*Dictyocha fibula*)。A 站的浮游植物种类组成多为暖海大洋性种类,群落优势种依次为:旋链角毛藻(*Chaetoceros curvisetus*)、佛氏海线藻(*Thalassionema frauenfeldii*)和洛氏角毛藻(*Chaetoceros lorenzianus*)。其细胞丰度为 102.3×10^3 ind./L。B 站共发现浮游植物 45 种。种类丰富度和细胞丰度以硅藻为多,共 37 种,出现了一些淡水和半咸水种类如细筒藻(*Leptocylindrus minimus*)和颗粒直链藻(*Melosira granulata*)说明了河口冲淡水的影响,同时也出现了假性浮游(*Tychopelagic*)种类如长耳齿状藻(*Odentella auriata*)表明了海水扰动对此区浮游植物群落分布的影响。甲藻 7 种多为近岸性种类。同时出现了蓝藻铜绿微囊藻(*Microcystis aeruginosa*),其丰度是较高的,但因个体微小有是团聚群体所以未将其进行细胞丰度计数。其群落优势种依次为:环纹劳德藻(*Lauderia annulata*)、佛氏海线藻和太阳双尾藻(*Ditylum sol*)。其细胞丰度为 44.2×10^3 ind./L。比较两站位的浮游植物群落组成表明它们的差异是较显著的,A 站是暖海近岸性群落种类少细胞丰度高,而 B 站是河口区群落种类多细胞丰度低。

表 1　研究站位的营养盐浓度

Table 1　The nutrient concentrations at the studying stations

站位 Station	氨盐 NH_4 (μM)	磷酸盐 PO_4 (μM)	硝酸盐和亚硝酸盐 NO_3+NO_2 (μM)	硅酸盐 SiO_4 (μM)
A	0.30	0.23	0.56	0.69
B	3.42	1.06	49.57	46.15

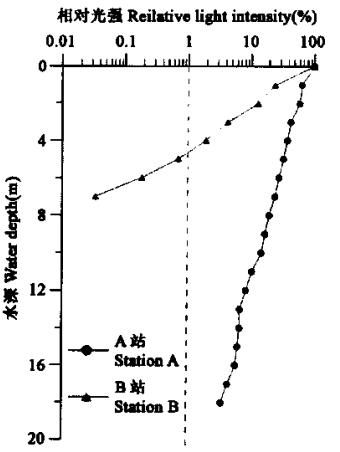

图 3　研究站位水下相对光强垂直剖面

Fig. 3　The vertical profile of relative light intensity under water at study stations

微型浮游动物在 A 站以异养鞭毛藻(*Heterotrophic dinoflagellates*)为主,也有少量的砂壳纤毛虫,而在 B 站则主要以砂壳纤毛虫和桡足类幼体为主。A 站的主要异养鞭毛藻是螺旋环沟藻(*Gyrodinium spirale*)、海洋尖鼻藻(*Oxyrrhis marina*)、斯氏多沟藻(*Polykrikos schwartzii*)和苍白卡托藻(*Katodinium glaucum*),这些种类主要是吞噬营养型(*phagotrophy*),它们在很大程度上可以控制赤潮生物的数量,在赤潮发生时常伴随而大量出现。曾有报道这些种类与其被摄食对象相应出现[41]。另外,在浓缩的标本中也发现少量的血红色裸甲藻(*Gymnodinium sanguineum*),它是营养缺乏型(auxotrophy)也就是在某些情况下需要摄取溶解有机物以维持生存,说明此海区的初级生产是较高的。另外海洋尖鼻藻和斯氏多沟藻有时也是营养缺乏型。相比较于异养鞭毛藻来说砂壳纤毛虫类是少的,主要是网纹虫(*Favella* spp.)和少量拟铃虫(*Tintinnopsis* spp.)。A 站微型浮游动物总的细胞丰度是 770 ind./L。B 站的异养鞭毛藻没有检出,微型浮游动物主要是拟铃虫及少量的类铃虫(*Codonellopsis* spp.),另外还有一些桡足类的无节幼体(nauplii),其丰度比 A 站为低,是 620 ind./L。

2.3　调查站位浮游植物碳/叶绿素 a 浓度比率

根据上述方法获得调查站位 A 水体中浮游植物碳浓度为 244.32 μgC/L,B 站为 263.31 μgC/L,其碳/叶绿素 a 浓度比率分别为 27.15 和 88.66。浮游植物的碳/叶绿素 a 浓度比率范围在 0～200 之间,通常在 20～80 之间,生长迅速和活性高的群落其碳/叶绿素比率要低。本研究碳/叶绿素比率也显示了 A 站浮游植物的生长状况较 B 站的要好。

2.4　微型浮游动物的摄食压力

通过稀释法可以对微型浮游动物的摄食压力进行估算,其中浮游植物的现存量通常是用叶绿素 a 的浓度来表示的,主要是因为它的精确性高[24](*CV*<5%)。尽管多数的微型浮游动物摄食率稀释法研究是以

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叶绿素 a 浓度作为浮游植物生物量指标，但还有一些研究使用其它的指标来估算摄食压力，如显微镜计数浮游植物细胞[24]、HPLC 色素分析[42, 43]、流式细胞仪分析[27]等。本研究中叶绿素 a 分析的结果却不理想(图 4)，其 r^2 值很小(表 3)，其结果是无效的，原因可能是叶绿素测定常受外界的和测量过程的影响而不准确[44]，这种现象在一些研究中也出现过[24, 25, 28]。

表 2 研究站位的浮游植物种类组成

Table 2 The phytoplankton species founded at the studying stations

种类 Taxa	A 站 Station A	B 站 Station B	种类 Taxa	A 站 Station A	B 站 Station B
硅藻纲(Bacillariophyceae)			*Pseudo-nitzschia seriata*	+	+
Actinocyclus undulata		+	*Rhizosolenia clacar-avis*	+	
Amphiprora alata		+	*Rhizosolenia fragilissima*	+	+
Bacteriastrum varians	+		*Rhizosolenia gracillima*	+	+
Chaetoceros affinis	+	+	*Rhizosolenia hebetata*	+	+
Chaetoceros curvisetus	+	+	*Rhizosolenia robusta*		+
Chaetoceros danicus	+		*Rhizosolenia stolterfothii*	+	+
Chaetoceros divisus		+	*Rhizosolenia styliformis*	+	
Chaetoceros eibenii	+		*Skeletonema costatum*		+
Chaetoceros lorenzianus	+	+	*Streptotheca tamesis*		+
Coscinodiscus asteromphalus	+	+	*Thalassionema nitzschioides*	+	+
Coscinodiscus divisus		+	*Thalassiosira pacifica*		+
Coscinodiscus granii		+	*Thalassionema frauenfeldii*	+	+
Coscinodiscus lineatus	+	+	**蓝藻纲**(Cyanophyceae)		
Cyclotella stelligera		+	*Microcystis aeruginosa*		+
Cylindrotheca closterium	+	+	**甲藻纲**(Dinophyceae)		
Ditylum sol		+	*Ceratium furca*	+	+
Eucampia zodiacus		+	*Ceratium fusus*	+	+
Guinardia flaccida	+	+	*Ceratium macroceros*	+	
Lauderia annulata		+	*Diplopsalopsis orbilaria var. ovata*	+	
Leptocylindrus danicus		+	*Gyrodinium spirale*	+	
Leptocylindrus minimus	+	+	*Prorocentrum micans*	+	+
Melosira granulata		+	*Prorocentrum sigmoides*	+	+
Nitzschia lorenzianus		+	*Protoperidinium bipes*	+	
Odontella auriata		+	*Protoperidinium depressum*		+
Odontella mobiliensis		+	*Protoperidinium oceanicum*		+
Odontella regia		+	*Pyrophacus steinii*	+	+
Pleurosigma affinis		+	*Scrippsiella trochoidea*	+	
Pseudo-nitzschia delicatissima	+	+	**金藻纲**(Chyrsophyceae)		
Pseudo-nitzschia pungens	+	+	*Dictyocha fibula*	+	

+**表示出现** +means presented

表 3 研究站位基于叶绿素 a 浓度估算的浮游植物生长率和微型浮游动物摄食压力*

Table 3 The phytoplankton growth rate and microzooplankton grazing pressure estimated by chlorophyll a concentration at the studying stations*

站位 Station	水深 Depth (m)	P_o (μg/L)	C_o (μgC/L)	r^2	μ (d^{-1})	g(d^{-1})	NGR (d^{-1})	$\%P_s$	$\%P_p$	I_c (μgC/(L·d))
A	2	9.0007	244.3690	0.2238	0.3205	0.6391	−0.3186	65.06501	172.2133	158.9987
B	2	2.97	263.3202	0.0565	0.3782	0.4881	−0.1099	56.37311	122.6423	148.4418

* P_o **为原始水样浮游植物现存量**；C_o **为原始水样浮游植物碳含量**；μ **为浮游植物内禀生长率**；g **为微型浮游动物摄食率**；NGR **为浮游植物净生长率**；$\%P_s$ **为对浮游植物现存量的摄食压力**；$\%P_p$ **为对浮游植物潜在初级生产力的摄食压力**；I_c **为对浮游植物碳的摄食率** P_o is the original chlorophyll a concentration; C_o is the original carbon content of phytoplankton; μ is instantaneous growth rate of phytoplankton; g is razing rate of microzooplankton; NGR is net growth rate of phytoplankton; $\%P_s$ is percentage of phytoplankton standing crop ingested by microzooplankton; $\%P_p$ is percentage of phytoplankton potential production ingested by microzooplankton; I_c is microzooplankton ingestion rate of phytoplankton carbon

万方数据

本研究中活体荧光值估算的微型浮游动物摄食压力结果是较好的,r^2 值为 0.6027 和 0.7062,如图 5 和表 4。研究结果表明香港牛尾海水域(A 站)的微型浮游动物摄食速率比龙鼓水道水域(B 站)低。牛尾海浮游植物的内禀生长率同龙鼓水道的相似,分别为 1.04 和 0.98 d^{-1},但浮游植物在牛尾海的净生长率是 0.33 d^{-1},而在龙鼓水道则出现了负增长,其净生长率是 −0.58 d^{-1},这与 2.1 节的分析结果是相一致的。微型浮游动物在牛尾海和龙鼓水道的摄食率分别为 0.71 和 1.56 d^{-1},在牛尾海的摄食压力分别占到了浮游植物现存量的 143.7%和初级生产力的 78.6%,而在龙鼓水道则高达 209.7%和 126.6%,在 A 和 B 站微型浮游动物对浮游植物碳的摄食率分别为 351 和 552 μgC/(L·d),龙鼓水道的微型浮游动物摄食压力要明显高于牛尾海。在 A 站浮游植物>5μm 的组分和<5μm 的组分分别占到总浮游植物叶绿素 a 浓度的 75.7%和 24.3%,而在 B 站则分别是 59.1%和 40.9%,这说明牛尾海水域的浮游植物从大小上来说不如龙鼓水道水域的更适合微型浮动物摄食。本研究结果显示,尽管香港牛尾海水域微型浮游动物异养鞭毛藻细胞丰度要高于龙鼓水道的砂壳纤毛虫,但由于纤毛虫的摄食压力要高于异养鞭毛藻,导致龙鼓水道的微型浮游动物摄食率超过牛尾海。同其它海区相比香港海域微型浮游动物的摄食压力是处于中等水平,如表 5。

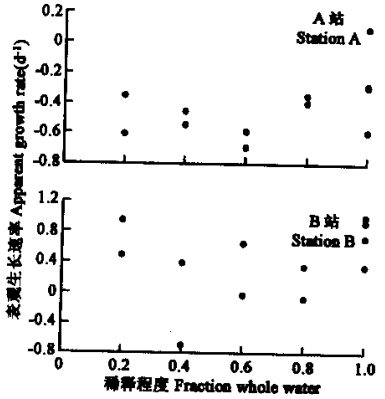

图 4　香港水域稀释法实验叶绿素 a 浓度表观生长速率与稀释程度的分析(A 站:牛尾海;B 站:龙鼓水道)

Fig. 4　Analyses of dilution experiments of apparent growth rate determined by measurement of chlorophyll a and fraction of whole water in the Hong Kong waters (A. the Port Shelter; B. Urmston Rcad)

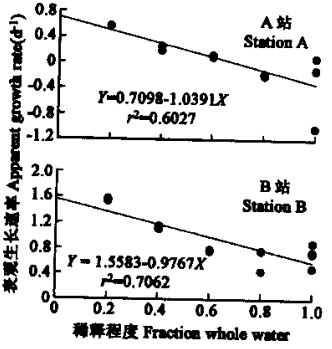

图 5　香港水域稀释法实验活体荧光表观生长速率与稀释程度的回归分析(A 站:牛尾海;B 站:龙鼓水道)

Fig. 5　Regression analyses of dilution experiments of apparent growth rate determined by measurement of in vivo fluorescence and fraction of whole water in the Hong Kong waters (A. the Port Shelter; B. Urmston Rcad)

表 4　研究站位基于活体荧光值估算的浮游植物生长率和微型浮游动物摄食压力*

Table 4　The phytoplankton growth rate and microzooplankton grazing pressure estimated by *in vivo* fluorescence at the studying stations*

站位 Station	水深 Depth (m)	P_o (μg/L)	C_o (μgC/L)	r^2	μ (d^{-1})	g(d^{-1})	NGR (d^{-1})	$\%P_s$	$\%P_p$	I_c (μgC/(L·d))
A	2	1.920	244.3690	0.6027	1.0391	0.7098	0.3293	143.6677	78.64998	351.0794
B	2	0.452	263.3202	0.7062	0.9767	1.5583	−0.5816	209.6675	126.6354	552.0968

* 项目符号同表 3　Same meaning as in table 3

2.5　黑暗和长培养时间下的稀释法实验

在进行稀释法估算微型浮游动物摄食率时,是有几点假设的:(1)现场浮游生物的生长是呈指数关系的,也就是尽管在很短的时间内生长率会有波动,但在一天的培养时间内它的平均值是指数关系的;(2)浮游植物生长率是非密度制约的,也就是浮游植物生长不会受营养盐的限制;(3)微型浮游动物对浮游植物的摄食率也是非密度制约的,在不同的稀释度下微型浮游动物摄食率不会发生变化[32, 56]。不同的海区其环

境条件和微型浮游动物群落组成是不一样的，对以上 3 种假设的符合程度也是不一样的，为检测黑暗和不同培养时间下对浮游植物生长和微型浮游动物的影响，所以本研究进行了黑暗长时间培养情况下的稀释法实验(表 6 和图 6)。

表 5 不同海区稀释法培养实验获得的微型浮游动物对浮游植物初级生产力的摄食压力(%)

Table 5 Comparison of microzooplankton grazing pressure (%) on primary productivity determined by dilution method in world wide

海区 Region	$\%P_p(d^{-1})$	引用文献 Citation
东北太平洋亚北极区①	18～77	[45]
东北太平洋亚北极区	5～158	[46]
东北太平洋亚北极区	16～45	[47]
太平洋赤道区②	55～83	[3]
太平洋赤道区	70～133	[48]
东北大西洋③	39～115	[14]
东北大西洋	37～100	[16]
东北大西洋	81～100	[17]
东北大西洋	50～88	[15]
南大西洋④	0～78	[49]
南大西洋	0～60	[19]
别林斯高晋海⑤	21～271	[18]
阿拉伯海⑥	67	[50]
阿拉伯海	4～60	[43]
南极普里兹湾⑦	34～100	[29]
诺瓦斯克提亚，哈利法克斯港⑧	40～100	[51]
马里兰切萨皮克湾⑨	35～243	[52]
墨西哥湾⑩	30	[53]
纽芬兰鲁及湾⑪	64～118	[24]
法国比斯开湾⑫	73～136	[25]
旧金山湾⑬	44～722	[54]
加拿大北部琼斯海峡⑭	40～114	[11]
加拿大北部巴芬湾⑮	37～88	[11]
华盛顿沿岸⑯	17～52	[31]
新西兰沿岸⑰	20～194	[55]
渤海⑱	85～319	[28]
香港东部水域⑲	79	本研究 This study
香港西部水域⑳	127	本研究

① NE subarctic Pacific ②Equatorial Pacific ③ Northeast Atlantic ④ South Atlantic ⑤ Bellingshausen Sea ⑥ Arabian Sea ⑦ Prydz Bay, Antarctic ⑧ Halifax Harbour, NS ⑨ Chesapeake Bay, Maryland ⑩ Gulf of Mexico ⑪ Logy Bay, Newfoundland ⑫ Biscay Bay, France ⑬ San Francisco Bay ⑭ Jones Sound, NWT ⑮ Baffin Bay, NWT ⑯ Washington coast ⑰ NZ coast ⑱ Bohai Sea, China ⑲ East of Hong Kong water ⑳ West of Hong Kong water

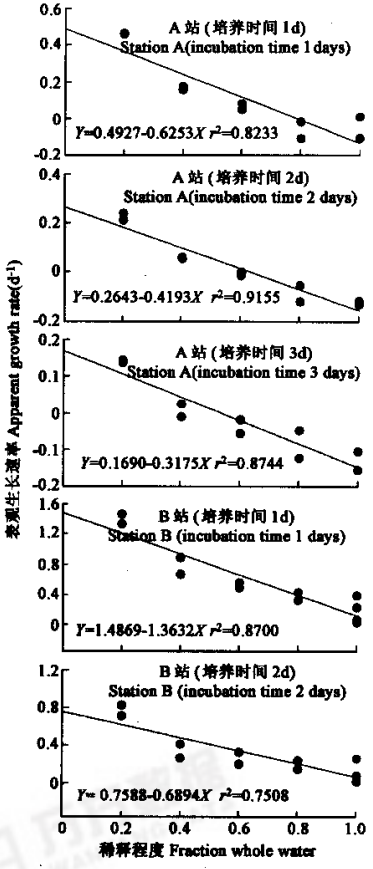

图 6 黑暗中稀释法实验活体荧光表观生长速率与稀释程度的回归分析(A 站：牛尾海；B 站：龙鼓水道)

Fig. 6 Regression analyses of dilution experiments of apparent growth rate determined by measurement of in vivo fluorescence and fraction of whole water under darkness (A. the Port Shelter; B. Urmston Road)

从表 6 可知：r^2 值 A 站较 B 站好而且都比有光条件下(表 4)要好，说明其结果是可信的。浮游植物生长率 k 随培养时间加长而降低，说明黑暗情况下浮游植物群落趋向死亡。B 站的 k 要大于有光情况下的 μ，说明在黑暗条件下 B 站浮游植物仍然有生长的趋势，这和 Caron 等[57]的结果是相似的，而 A 站的浮游植物于黑暗中则更易在微型浮游动物摄食以外的因素下死亡。从表 1 中可以看出 B 站的营养盐从浓度上是不缺乏的，所以在黑暗下浮游植物不会立刻停止生长，细胞还会利用体内的营养盐进行光合作用暗反应，

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但 A 站的浮游植物在黑暗下会较快地停止生长。这就提示今后进行 A 站位附近海域浮游动物摄食研究时,可以用直接培养法[58]。尽管培养 1d 的结果同有光情况下是相接近的,微型浮游动物的摄食率在黑暗下都有所下降,而且随时间的加长下降更多。实验结果说明对于研究海域微型浮游动物摄食率稀释法实验应在有光的条件下 1d 之内完成。

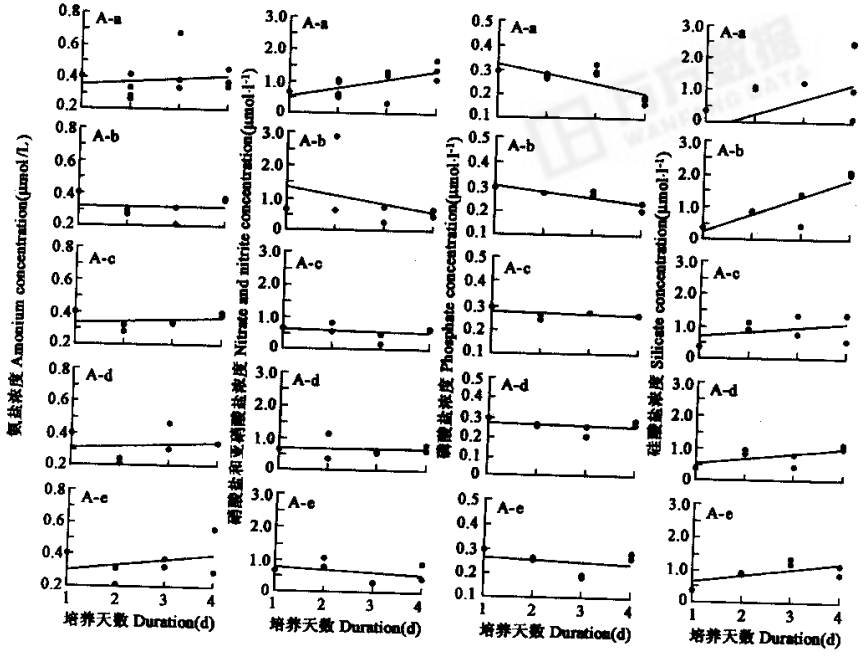
在 Landry[32]的标准操作和一些研究中[26, 42, 57]都提及要在实验组中添加营养盐以弥补营养盐限制造成的浮游植物的非指数式增长。对黑暗培养下营养盐浓度的分析(图 7)如下:B 站不同稀释处理组相同营养盐的变化趋势都相似,而 A 站就有些差异特别是氮盐,说明微型浮游动物的摄食率在 B 站不受稀释程度的影响,但在 A 站就要受影响。这可能是 A 和 B 站微型浮游动物的群落组成不同,砂壳纤毛虫较异养鞭毛藻不易受稀释程度的影响。氨盐要优先于硝酸盐为浮游植物吸收利用,在 B 站 5 个稀释处理都出现氨盐吸收情况,而在 A 站氨盐浓度变化不大。硝酸盐和亚硝酸盐,在 A 站变化也不大,在 B 站却有上升的趋势,这是由于细菌的矿化和硝化作用结果,也从一个侧面反映了黑暗情况下此站位微型浮游动物对细菌摄食压力的减弱。磷酸盐可以被浮游植物过量吸收入细胞内作为储备之需,小细胞的浮游植物对磷酸盐吸收更快,同时细菌也有吸收磷酸盐的现象[59]。磷酸盐在 A 和 B 站都有下降的趋势,但 B 站更明显些,说明 B 站浮游植物生长比 A 站更需要磷酸盐。硅酸盐在 A 站有略微增加趋势,表明 A 站硅藻生长完全受到抑制,而 B 站由于硅酸盐浓度较大,基本上看不出变化来。总之实验结果说明在 A 站进行稀释法培养时可以不添加营养盐,而在 B 站尽管周围水体中营养盐不缺乏,但仍需要添加营养盐。

表 6　黑暗情况下不同培养时间基于活体荧光值估算的浮游植物生长率和微型浮游动物摄食压力

Table 6　The phytoplankton growth rate and microzooplankton grazing pressure estimated by *in vivo* fluorescence under dark at different experimental duration

站位 Station	培养时间 Experimental duration (d)	r^2	k(d^{-1})*	g (d^{-1})	NGR (d^{-1})
A	1	0.8233	0.6253	0.4927	0.1326
	2	0.9155	0.4193	0.2643	0.1550
	3	0.8744	0.3175	0.1690	0.1485
B	1	0.8700	1.3632	1.4869	−0.1237
	2	0.7509	0.6894	0.7588	−0.0694

* $k=\mu-m$,m 为除微型浮游动物摄食以外的浮游植物死亡率(包括病毒和细菌伤害、自溶等) m is the rate of mortality of the phytoplankton assemblage as a consequence of viral and bacterial lysis or autolysis



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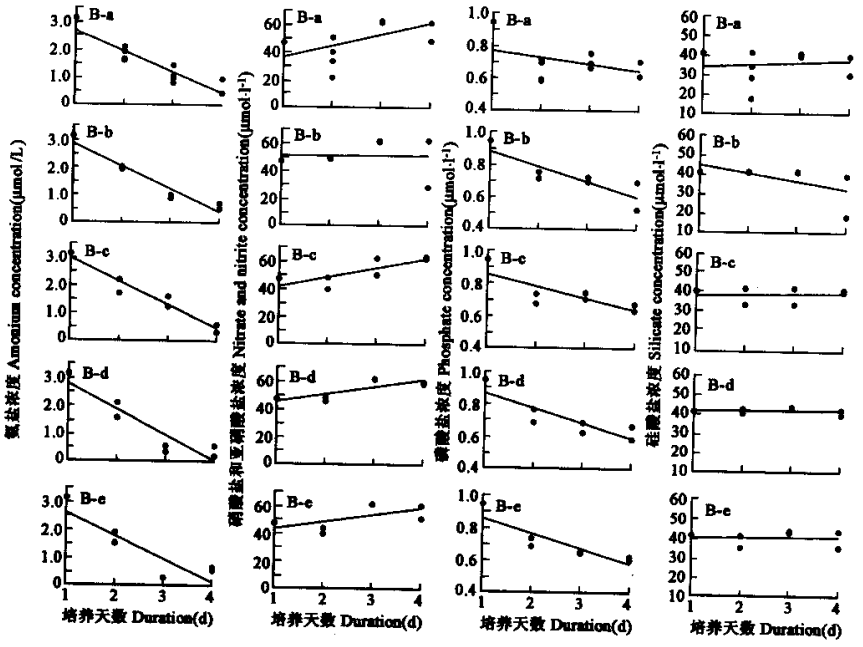

图 7 黑暗长时间稀释法实验各处理组营养盐浓度的变化比较

Fig. 7 Comparison of nutrient concentrations in all treatments of dilution experiment under dark and long time incubation

A. A **站** Station A; B. B **站** Station B; a. **稀释度** 0% 0% fraction diluted water; b. **稀释度** 20% 20% fraction diluted water; c. **稀释度** 40% 40% fraction diluted water; d. **稀释度** 60% 60% fraction diluted water; e. **稀释度** 80% 80% fraction diluted water

3 结论

对于香港东西部水域两典型站位微型浮游动物摄食压力的初步研究表明,在夏季牛尾海水域微型浮游动物主要类群是异养鞭毛藻,龙鼓水道主要是砂壳纤毛虫类。龙鼓水道的微型浮游动物摄食压力要大于牛尾海水域。牛尾海水域浮游植物因自上而下控制较小更易形成赤潮,需要相对加大监测力度。研究站位微型浮游动物的摄食同世界其他海区相比处于中等水平。需要进一步在香港更多水域和不同季节进行此类研究,同时也可结合其它方法进行比较。中国在此方面的研究还需要进一步加强[56, 60, 61]。

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