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海州湾贝类养殖海域浮游植物粒径结构特征及其与环境因子的关系*

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摘要　为了解海州湾贝类养殖海域浮游植物的粒径结构及影响因素，于 2023 年 3、7、9、10 和 12 月对海州湾的贝类养殖区(一区和二区)和非养殖区(航道区和空白区)浮游植物的叶绿素 *a* (Chl-*a*)浓度、粒径结构及环境因子进行了调查研究。结果显示，3 月和 12 月，调查海域各区域的 Chl-*a* 浓度无显著差异，其平均值分别为(1.98±0.61) μg/L 和(3.69±1.55) μg/L；7 月和 10 月，一区 Chl-*a* 浓度的平均值分别达到了(9.80±2.04) μg/L 和(12.34±6.27) μg/L，显著高于其他区域($P<0.05$)；9 月，二区 Chl-*a* 浓度(1.47~1.94 μg/L)显著低于非养殖区($P<0.01$)。从粒径结构来看，3 月和 7 月，微型浮游植物和小型浮游植物占据主要优势地位；9 月、10 月和 12 月，调查海域以小型浮游植物为主，占比分别为 58.43%、75.87%和 89.01%。双因素方差分析表明，微微型浮游植物的贡献率受月份因素影响显著($P<0.001$)，微型和小型浮游植物的贡献率受月份、月份和区域交互作用影响显著($P<0.05$)。RDA 排序结果显示，一区粒径结构受 N/Si 的影响显著，二区受总氮和 N/P 影响显著，航道区受铵盐的影响显著，空白区受溶解无机氮的影响显著($P<0.05$)。总体来讲，调查海域浮游植物的 Chl-*a* 浓度主要受到陆源输入营养盐和温度的影响，其中二区浮游植物在 9 月受贝类滤食的影响较明显。4 个区域的浮游植物粒径结构的改变主要是由季节变化引起，这说明海州湾贝类养殖的密度适宜，未对浮游植物的 Chl-*a* 浓度和粒径结构产生很大的影响。

关键词　浮游植物；粒级结构；贝类养殖；营养盐
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2022 年,我国海水养殖年产量达到 2 275.7 万 t,其中海水贝类养殖年产量达到 1 569.6 万 t,同比增加 2.85% (农业农村部渔业渔政管理局等, 2023)。我国海水养殖贝类多为双壳滤食性贝类,浮游植物作为养殖贝类的主要饵料生物,是评估贝类养殖容量的重要指标(张继红等, 2016)。浮游植物根据其粒径大小可以

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分为微微型浮游植物(picophytoplankton, <2 μm)、微型浮游植物(nanophytoplankton, 2~20 μm)和小型浮游植物(microphytoplankton, 20~200 μm) (Sieburth *et al*, 1978)。其中，微微型浮游植物虽然能为海域提供近半成的初级生产力(Letscher *et al*, 2023; 黄邦钦等, 2002)，但由于滤食性贝类对微微型浮游植物的截留率极低(Ward *et al*, 2004; Gianasi *et al*, 2023)，采用浮游植物的现存总量进行养殖容量评估会使评估结果过高。因此，研究目标海域浮游植物的粒径组成结构和时空分布特征，能够提高贝类养殖容量评估的准确性，为海水贝类养殖提供科学指导。

确定浮游植物粒径结构的方法包括分级叶绿素法(Agirbas *et al*, 2015)、遥感技术监测法(Lamont *et al*, 2018)和原位颗粒成像法(Fragoso *et al*, 2019)等。分级叶绿素法技术成熟，可对大量样品进行快速检测，我国的研究学者采用分级叶绿素法对桑沟湾(李凤雪等, 2020)、獐子岛(蒋增杰等, 2015)、长江口(宋书群等, 2008)、东海和南黄海(邓春梅等, 2008)等多海域的浮游植物粒径分布进行了调查，因而本研究也选择采用该方法对各粒级浮游植物的 Chl-*a* 浓度进行检测。海州湾位于苏北鲁南，东临黄海，是我国典型的紫贻贝(*Mytilus edulis*)养殖基地(刘明坤等, 2022)，该地紫贻贝的养殖模式为延绳筏式养殖。牡蛎是我国养殖最多的贝类，相较于传统的二倍体牡蛎，三倍体牡蛎具有更高的生长速率和更庞大的体型，被认为是优良的养殖品种(刘纪皎，2020)。当前海州湾三倍体长牡蛎(*Crassostrea gigas*)的主要养殖方式为购买半成体长牡蛎，随后在养殖海域内利用吊笼筏式养殖的模式进行育肥。两种贝类的养殖周期均为“夏播春收”——每年 7 月投入贝苗或半成体贝，12 月开始陆续收获成体贝，直至翌年的 4 月结束。大规模的贝类养殖活动可能会导致浮游植物数量和群落结构发生改变(Tan *et al*, 2024; Zhu *et al*, 2023)。目前，海州湾贝类养殖区浮游植物丰度和粒径变化的相关研究尚未见报道。本研究于 2023 年对海州湾贝类养殖区及附近海域的浮游植物和环境因子开展季度调查，通过分级叶绿素法研究各季度浮游植物粒径组成结构及其与环境因子的关系，探索贝类养殖和环境因子对浮游植物粒径结构的影响，同时为贝类养殖容量评估和科学指导养殖规划提供依据。

1 材料与方法

1.1 调查站位及样品采集

调查海域如图 1 所示，为 4 个区域，包含 11 个站位，分别为一区($1^{\#}$~$3^{\#}$站位)、航道区($4^{\#}$~$6^{\#}$站位)、二区($7^{\#}$~$9^{\#}$站位)和空白区($10^{\#}$和 $11^{\#}$站位)。其中，一区和二区为贝类养殖区，航道区和空白区为非养殖区。分别于 2023 年 3、7、9、10 和 12 月展开了 5 个航次的生态环境综合调查。用便携式水质分析仪(YSI 公司, Professional Plus, 美国)现场测定各站位的表层水温、pH、盐度和溶解氧，用透明度盘测定各站位的透明度。用有机玻璃采水器采集各站位的表层水，水样于 4 ℃条件下保存，以备测定浮游植物的 Chl-*a* 浓度和海水营养盐浓度。

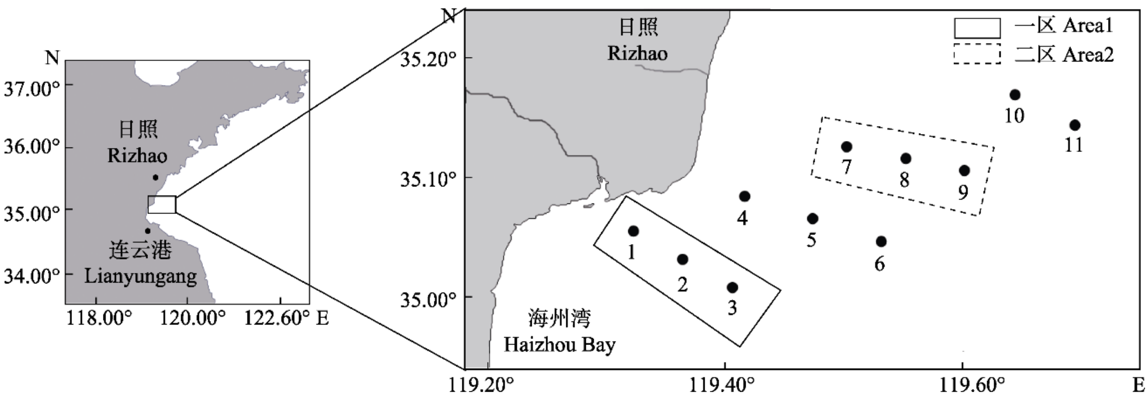


图 1 海州湾海域调查站位

Fig.1 Investigation stations in Haizhou Bay

1.2 样品分析方法

采用孔径为 20、2 和 0.2 μm 的玻璃纤维滤膜依次过滤 500 mL 的重复水样，被 20 μm 孔径滤膜截留的属于小型浮游植物(micro Chl-*a*)，被 2 μm 孔径滤膜截留的属于微型浮游植物(nano Chl-*a*)，被 0.2 μm 孔径滤膜截留的属于微微型浮游植物(pico Chl-*a*)。采用孔径为 0.45 μm 的玻璃纤维滤膜过滤另外的 500 mL 水样用于总叶绿素的测定。所有滤膜用锡纸包裹后于 –20 ℃冷冻保存，带回实验室后在低温避光的条件下，用 90%的丙酮萃取 24 h，离心后使用美国 Turner-

Designs Trilogy 荧光仪测定各粒级浮游植物的 Chl-*a* 浓度(Agawin *et al*, 2000)。使用全自动营养盐分析仪(QuAAtro 型, Seal, 德国)测定水体中总磷(TP)、总氮(TN)、磷酸盐(PO_4^{3-}-P)、硅酸盐(SiO_3^{2-}-Si)、硝酸盐(NO_3^--N)、亚硝酸盐(NO_2^--N)和铵盐(NH_4^+-N)的浓度。溶解无机氮(DIN)的浓度为 NO_3^--N、NO_2^--N 和 NH_4^+-N 浓度之和(孙怡茹等, 2024)。

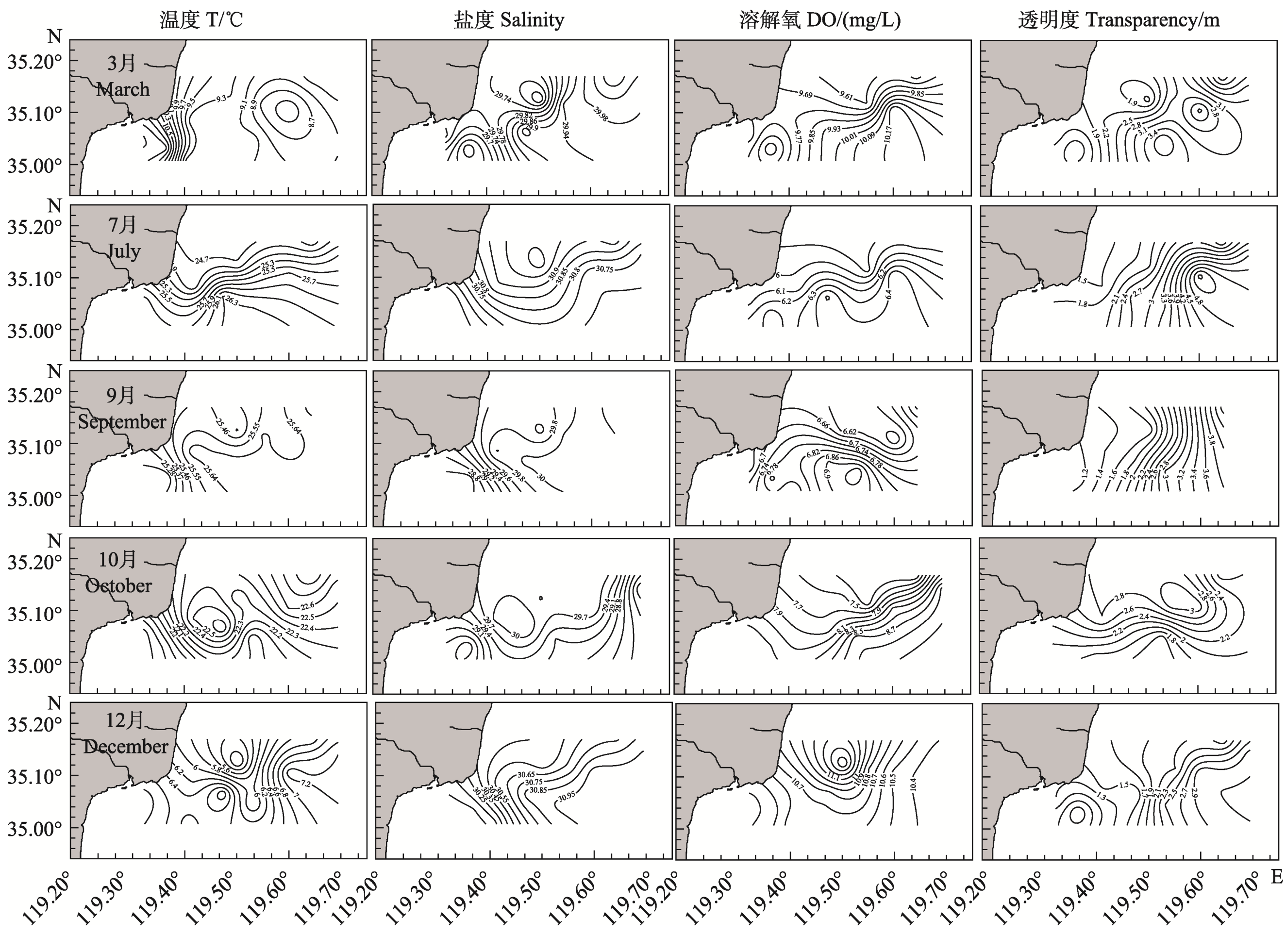
1.3　数据处理与统计分析

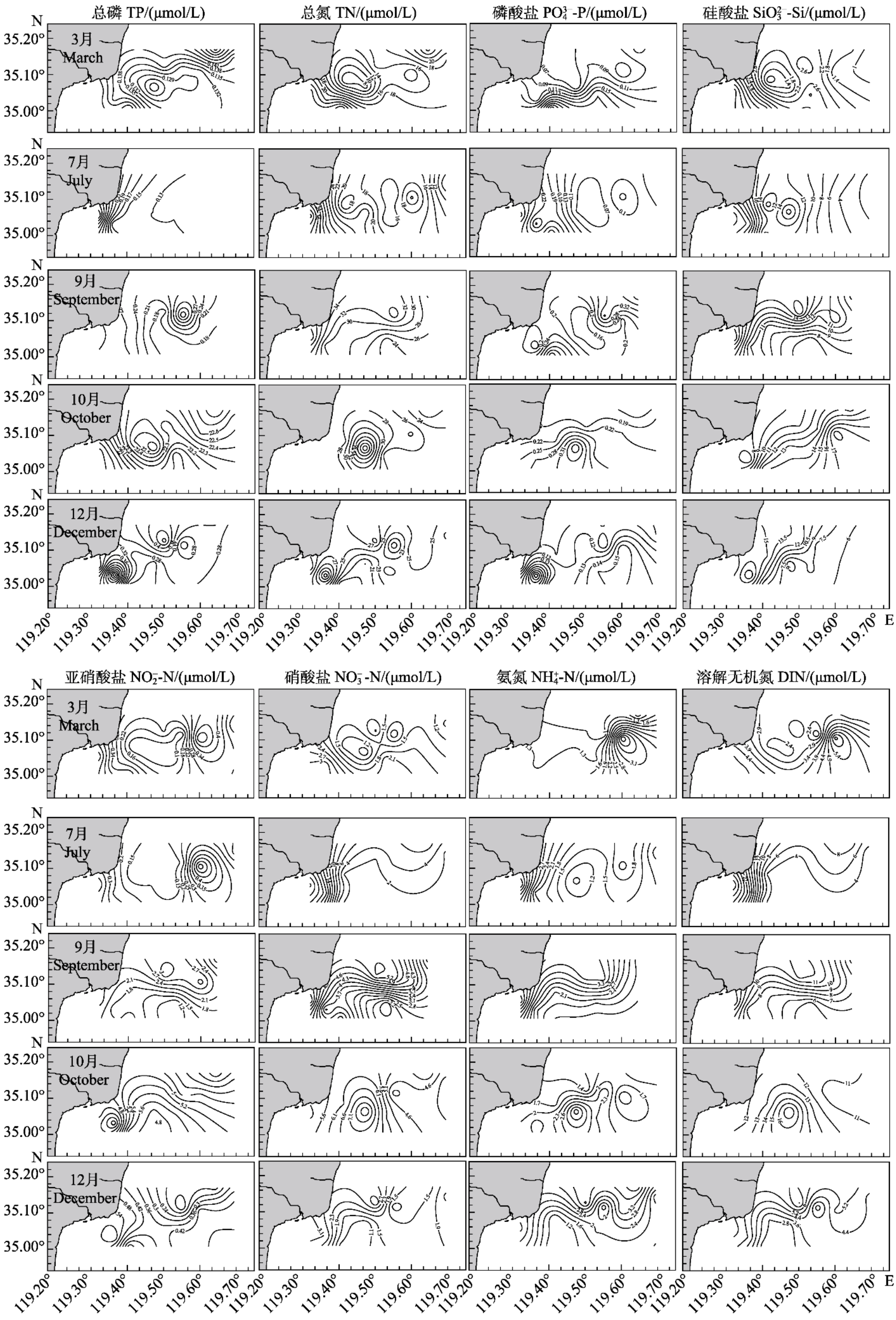
环境因子和浮游植物的等值线图由 Golden software Surfer 15 绘制。实验数据采用 SPSS 26 进行正态性检验, 符合正态分布的数据采用单因素方差分析(one-way ANOVA), 不符合正态分布的数据采用秩和检验(Wilcoxon rank-sum test)(卢亚芳等, 2017); 双因素方差分析(two-way ANOVA)月份和区域因素对浮游植物的影响, 设置显著性水平为 $P<0.05$ (刘毅等, 2017)。应用 Canoco 5 对浮游植物和环境因子数据进行去趋势对应分析(detrended correspondence analysis, DCA), 若第一轴特征值大于 4.0, 则选择典型相关分析(canonical correlation analysis, CCA); 若小于 3.0, 则选择冗余分析(redundancy analysis, RDA); 若在 3.0~4.0 之间, 则 CCA 或 RDA 均可(Hill *et al*, 1980)。本研究的 DCA 结果均小于 3, 因此, 选择线性模型 RDA 进行排序分析, RDA 排序图中箭头间夹角的 COS 值表示各因子间的相关系数。

2　结果与分析

2.1　调查海域环境参数

调查海域海表环境参数的时空分布情况见图 2, 9 月由于大风天气, 11[#]站位未取得环境数据。各环境因子的月份差异显著($P<0.01$)。温度(T)的年变化范围为 4.98~26.32 ℃, 7 月温度最高, 12 月温度最低; 3、9 和 10 月的数据显示, 一区的温度与其他区有显著差异($P<0.05$)。盐度(S)的年变化范围为 27.34~31.02, 7 月和 12 月的盐度较高, 10 月最低; 3、9 和 12 月, 一区的盐度显著小于其他区域($P<0.05$), 7 月和 10 月盐度的分布呈北高南低的趋势。溶解氧(DO)在 7、9




总磷 TP/(μmol/L)
总氮 TN/(μmol/L)
磷酸盐 PO_4^{3-}-P/(μmol/L)
硅酸盐 SiO_3^{2-}-Si/(μmol/L)
亚硝酸盐 NO_2^--N/(μmol/L)
硝酸盐 NO_3^--N/(μmol/L)
氨氮 NH_4^+-N/(μmol/L)
溶解无机氮 DIN/(μmol/L)
3月
March
7月
July
9月
September
10月
October
12月
December
N
35.20°
35.10°
35.00°
119.20°
119.30°
119.40°
119.50°
119.60°
119.70°
E

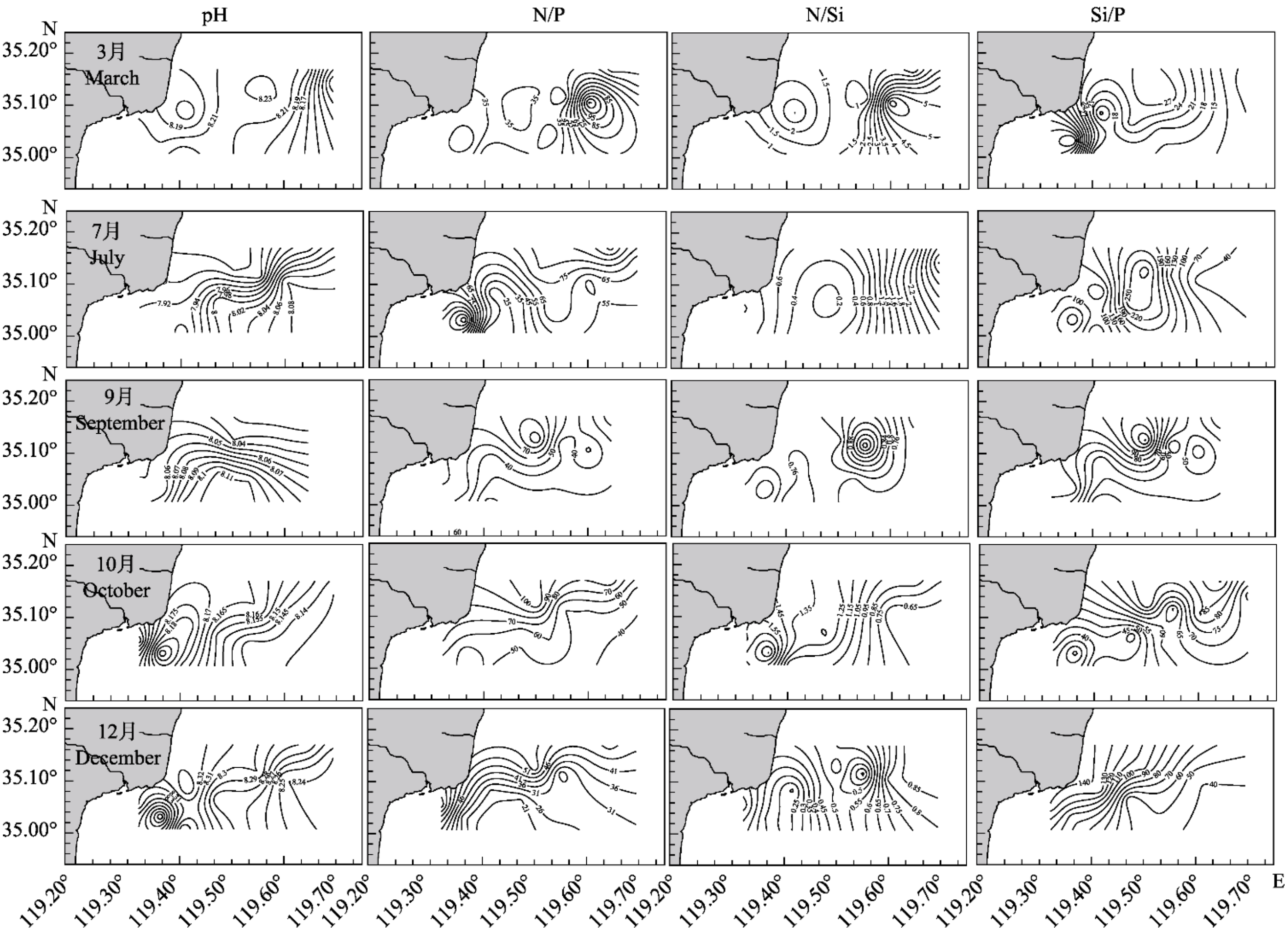


图 2　海州湾调查海域理化因子的时空分布

Fig.2　Spatial and temporal distribution of physicochemical factors in the investigated area of Haizhou Bay

和 10 月的浓度显著小于 3 月和 12 月($P<0.01$)；溶解氧的浓度在 3、7、9 和 10 月的分布呈由北向南逐渐增高的趋势，在 12 月呈由北向南逐渐降低的趋势，9 月 2 个养殖区的溶解氧浓度显著小于航道区($P<0.01$)。10 月二区的透明度显著大于其他区域($P<0.05$)，其他月份均为空白区的透明度较大，其分布主要呈由西向东递增的趋势。

总磷、总氮、磷酸盐和硅酸盐的年变化范围分别为 0.12~0.72 μmol/L、6.02~44.06 μmol/L、0.04~0.43 μmol/L 和 0.65~30.86 μmol/L，其浓度在 3 月最低；4 种营养盐在 7 月主要分布于近岸海域，其浓度呈由西向东递减的趋势，一区的浓度显著高于其他区域($P<0.05$)；在 9 月和 12 月，2 个养殖区是 4 种营养盐浓度的高值区。硝酸盐、亚硝酸盐、铵盐和溶解无机氮的年变化范围分别为 0.64~36.39 μmol/L、0.04~5.69 μmol/L、0.56~4.99 μmol/L 和 1.49~41.61 μmol/L，4 种营养盐在9月和10月的浓度显著高于3月和12月($P<0.05$)；3、7、9 和 12 月，4 种营养盐在一区和二区形成一大一小 2 个高值区。pH 年变化范围为 7.88~8.34，每个月份区域间差异不显著。N/P 在 3 月的二区比值最大，其他月份在海域的西北部较大；N/Si 在 10 月呈现由西向东逐渐递减的趋势，其他月份正相反；Si/P 的分布主要呈由西北向东南递减的趋势。

2.2　海州湾贝类养殖海域各粒级浮游植物的分布特征

海州湾贝类养殖海域各粒级浮游植物的 Chl-*a* 浓度平面分布见图 3。总 Chl-*a* 浓度的年变化范围为 0.86~18.49 μg/L，月份差异显著($P<0.05$)；pico Chl-*a*、nano Chl-*a* 和 micro Chl-*a* 浓度的年变化范围分别为 0~0.90、0.13~6.12 和 0.35~15.30 μg/L，月份差异显著($P<0.01$)。3 月，pico Chl-*a* 分布均匀，nano Chl-*a* 分布呈从北向南依次递减的趋势，micro Chl-*a* 主要分布于西部海域，总 Chl-*a* 在一区和二区的浓度显著高于空白区($P<0.05$)。7 月，各粒级浮游植物均呈由西向东依次递减的趋势，pico Chl-*a*、nano Chl-*a* 和总 Chl-*a* 在一区的浓度显著高于其他 3 个区域($P<0.05$)，micro Chl-*a* 在一区的浓度显著高于航道区($P<0.05$)。9 月，pico Chl-*a* 在一区和二区存在 2 个浓度低值区；nano

Chl-*a* 主要分布于非养殖区，其在航道区的浓度显著高于一区和二区(P<0.05)；micro Chl-*a* 多分布于西南部近岸区域；总 Chl-*a* 在一区和航道区的浓度显著高于二区(P<0.05)。10 月，一区各粒级浮游植物的 Chl-*a* 浓度显著的高于其他区域(P<0.05)，各粒级浮游植物的 Chl-*a* 浓度基本呈由西向东依次递减的趋势。12 月，pico Chl-*a* 和 nano Chl-*a* 的分布较为均匀，micro Chl-*a* 和总 Chl-*a* 浓度在西北部最高。

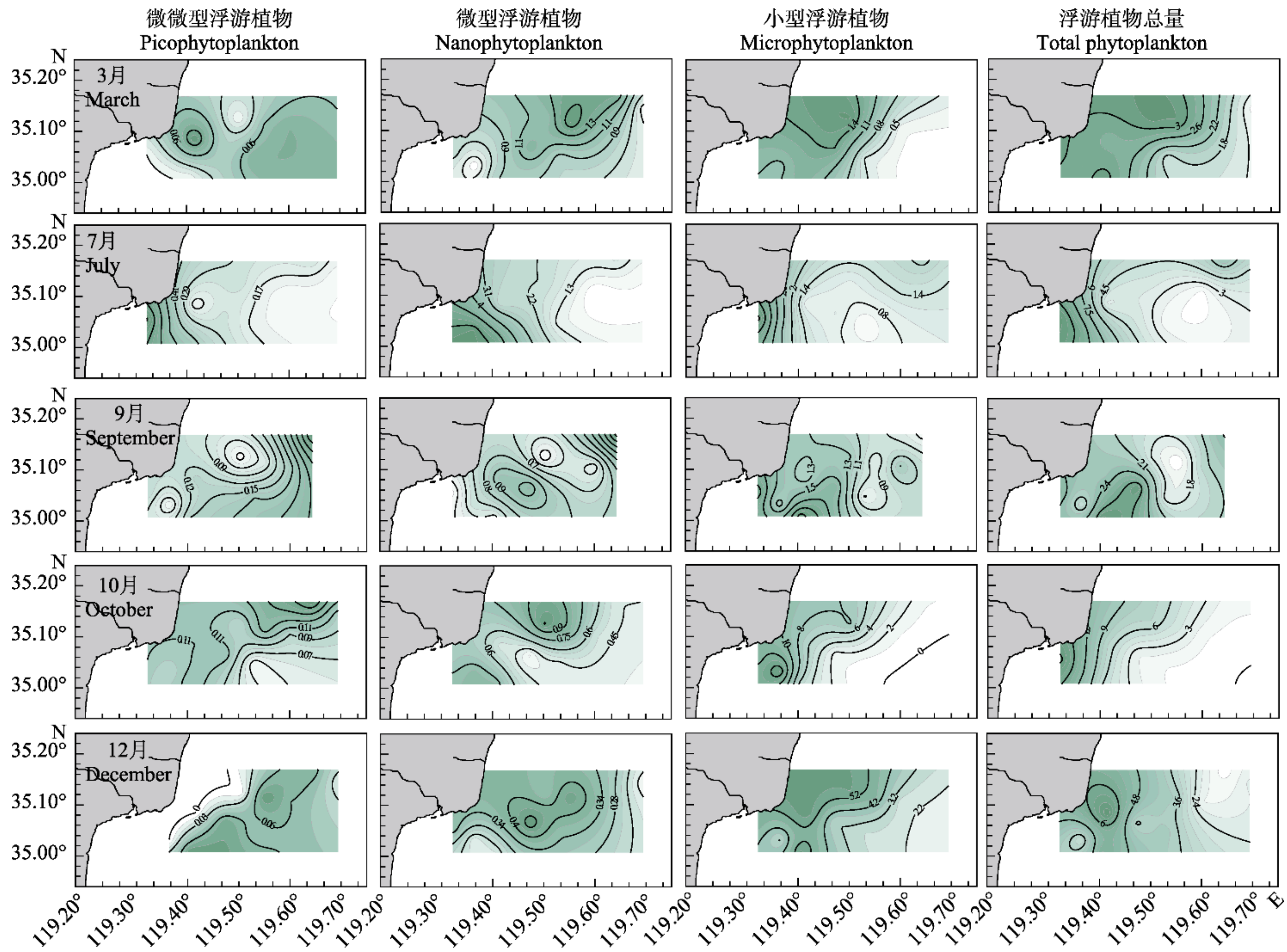


图 3 海州湾调查海域各粒级浮游植物的时空分布

Fig.3 Spatial and temporal distribution of phytoplankton in the investigated area of Haizhou Bay

2.3 海州湾贝类养殖海域各粒级浮游植物的贡献率

海州湾贝类养殖海域各粒级浮游植物的 Chl-*a* 浓度和贡献率见图 4。3 月，一区和航道区中 micro Chl-*a* 占据优势地位，二区和空白区 nano Chl-*a* 占比更高，pico Chl-*a* 在 4 个区域贡献都极低。7 月，一区和航道区的 nano Chl-*a* 占据优势地位，二区和空白区则是 micro Chl-*a* 占比更高，pico Chl-*a* 的贡献率相比春季有所上升，在 4 个区域中分布均匀。9 月，一区、航道区和二区是 micro Chl-*a* 占据优势地位，空白区中 nano Chl-*a* 占比更高，pico Chl-*a* 在航道区的贡献率(7.16%)比一区(3.80%)和二区(4.71%)更大，在空白区的 S10 站位更是达到了 14.88%。10 月，micro Chl-*a* 成为 4 个区域的优势粒径植物，在 2 个养殖区的贡献率大于 2 个非养殖区。12 月，micro Chl-*a* 的贡献率进一步升高，在 4 个区域中平均占比为 89.01%。

应用双因素方差分析月份和区域因素对各粒级浮游植物贡献率的影响(表 1)。结果表明，浮游植物的粒径结构受到了月份因素的显著影响(P<0.001)，微型浮游植物和小型浮游植物受到了区域和月份交互作用的显著影响(P<0.01)。

2.4 海州湾贝类养殖海域各粒径浮游植物与环境因子的关系

各粒级浮游植物与环境因子的 RDA 分析结果见图 5，图中红色空箭头表示环境因子，黑色实箭头表示浮游植物。一区、二区、航道区和空白区的排序图前两轴分别解释了 79.31%、86.94%、88.35%和 99.09%

图 4　海州湾调查海域不同粒径浮游植物的 Chl-*a* 浓度和占比

Fig.4　The concentration and proportion of Chl-*a* in phytoplankton of different grain sizes in the investigated area of Haizhou Bay

的物种变化。应用蒙特–卡洛置换检验方法对海水环境因子进行预筛选(表 2)，一区的 N/Si，二区的 N/P 和总氮，航道区铵盐和空白区的溶解无机氮对各粒径浮游植物影响显著($P < 0.05$)。RDA 排序图显示，一区的 micro Chl-*a* 与 N/Si 呈显著正相关；二区中，pico Chl-*a* 与总氮呈显著负相关，nano Chl-*a* 与 N/P 呈显著正相关；航道区，3 个粒级浮游植物的 Chl-*a* 浓度均与铵盐呈显著负相关；空白区中 micro Chl-*a* 与 DIN 呈正相关。RDA 排序结果表明，浮游植物粒径结构对环境因子的响应存在季节性差异。

3 讨论

海州湾位于黄海中南部的温带海域，浮游植物群落结构和多样性的季节差异明显。5 次调查取样发现，海州湾调查海域的叶绿素浓度在 7 月和 10 月最高，在 3 月最低，这与 Gao 等(2022)的研究结果相似。通常情况下，不同粒级浮游植物的叶绿素浓度变化受温度、盐度、营养盐浓度、海流和潮汐等多种环境因子的影响(Farias *et al*, 2022; Liang *et al*, 2019; Smayda *et al*, 2001)。Moisan 等(2010)指出，微微型浮游植物对温度有高敏感性。本研究发现，pico Chl-*a* 在 7 月达到一年中的最大值，一区和空白区的 RDA 排序图亦显示，温度升高能促进微微型浮游植物的生长。有研究指出，硝酸盐的供给比光照因素对 pico Chl-*a* 的影响更大(Berube *et al*, 2016)，獐子岛海域的研究表明，pico Chl-*a* 与 DIN 浓度呈显著正相关(李苏恒等, 2022)，这些研究结果印证了 pico Chl-*a* 受各类营养盐调控。本研究调查发现，多个月份的微微型浮游植物在空白区的浓度大于其他区域，其原因可能是空白区的营养盐浓度较低，小粒径的微微型浮游植物比大粒径的浮游植物吸收营养盐的效率更高(Pulina *et al*, 2018)。7 月和 10 月，nano Chl-*a* 和 micro Chl-*a* 的分布呈现西部沿岸浓度高、东部海区浓度低的趋势，这与文斐等(2012)对黄海海域的研究结果相符。海区内营养盐的含量及分布情况可能受到了陆源输入的影响，在河口丰富的海区，硅酸盐和 DIN 等多种营养盐主要受控于河流输入的季节性变化(Liu *et al*, 2005)。由于海州湾一区附近有绣针河、竹子河等多条入海河流，地表径流带来了丰富的营养盐，从而促进了一区浮游植物的生长，使一区各粒级浮游植物的 Chl-*a* 浓度显著高于

表 1 双因素方差分析结果

Tab.1 The results of two-way ANOVA

响应变量 Response variable	自变量 Independent variables	自由度 Degree of freedom	均方 Mean Sq.	*F* value	*P* value
微微型浮游植物 Picophytoplankton	区域 Area	3	0.01	1.67	0.192
	月份 Month	4	0.18	25.15	<0.001***
	区域×月份 Area×Month	12	0.00	0.57	0.845
微型浮游植物 Nanophytoplankton	区域 Area	3	0.02	2.01	0.130
	月份 Month	4	0.36	32.44	<0.001***
	区域×月份 Area×Month	12	0.03	2.62	0.013*
小型浮游植物 Microphytoplankton	区域 Area	3	0.05	2.80	0.055
	月份 Month	4	0.95	56.63	<0.001***
	区域×月份 Area×Month	12	0.04	2.17	0.038*

注：*：显著相关(P<0.05)；***：极显著相关(P<0.001)。下同。

Notes: *: Significant at 0.05 level (P<0.05); ***: Highly significant at 0.001 level (P<0.001). The same below.

表 2 蒙特–卡洛置换检验结果

Tab.2 Results of Mont-Carlo replacement test

调查区域 Investigated area	环境因子 Environmental factor	解释比和贡献比 Explains and contribution/%	pseudo-*F*	*P*
一区 Area 1	N/Si	44.3	7.2	0.01*
二区 Area 2	N/P	22.1	5.8	0.03*
	TN	11.4	4.5	0.04*
航道区 Channel area	NH_4^+-N	27.8	5.8	0.04*
空白区 Reference area	DIN	11.9	30	0.02*

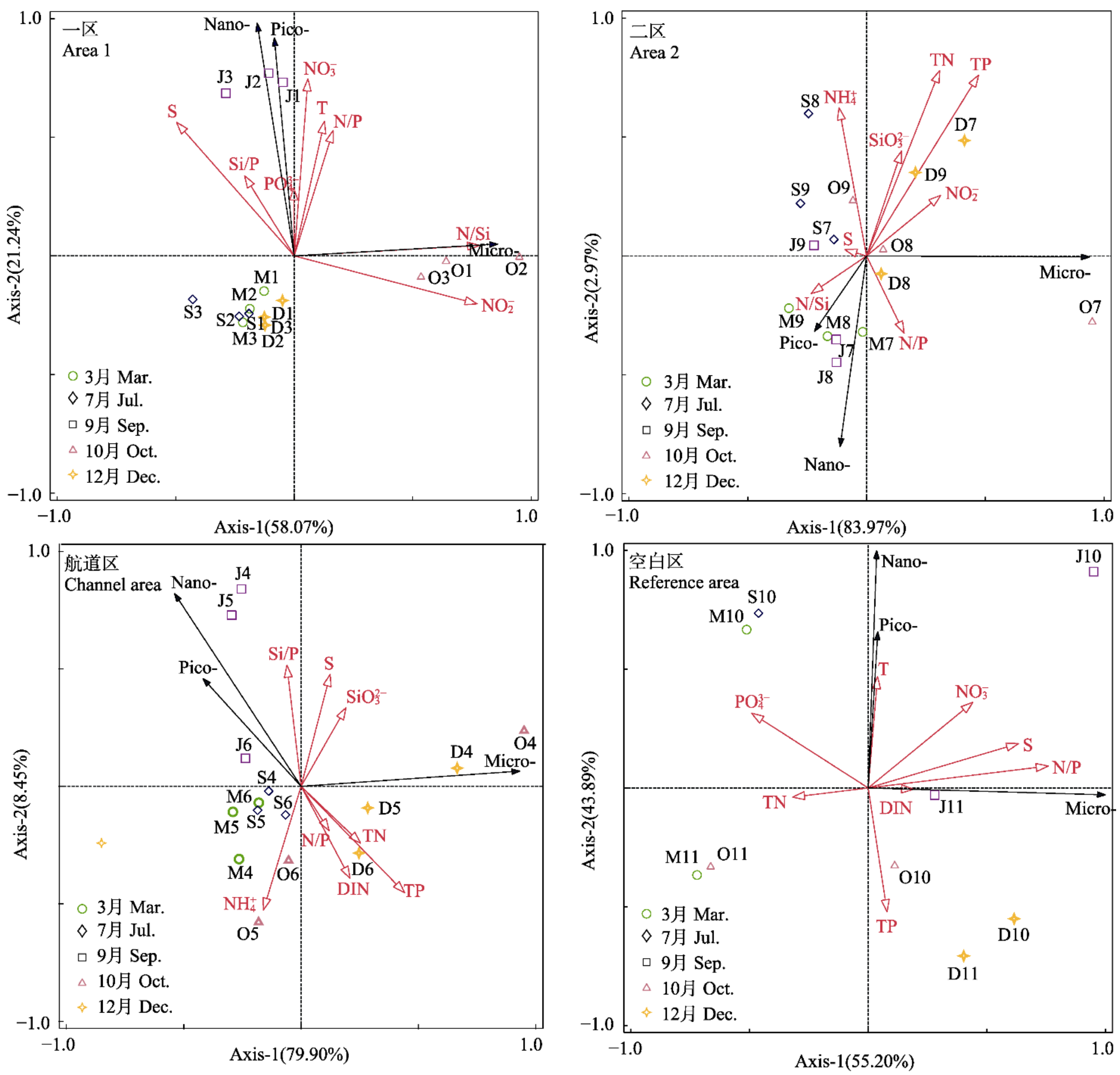


图 5　海州湾调查海域不同粒径浮游植物与主要环境因子的冗余分析

Fig.5　RDA analysis of size-fractionated Chl-*a* and main environmental factors of phytoplankton in the investigated area of Haizhou Bay

其他区域。营养盐作为浮游植物生长所需要的基本要素，其浓度的高低通常能够影响浮游植物的丰度和分布(Kim *et al*, 2022)。根据营养盐相对限制法计算氮、磷和硅之间的比例关系(Justić *et al*, 1995)，当 N/Si<1 且 N/P<10 时，N 是相对限制性元素；当 Si/P>22 且 N/P>22 时，P 是相对限制性元素；而当 Si/P<10 且 N/Si>1 时，则 Si 是相对限制性元素。据此评估，P 的相对限制广泛存在于调查海域，3、7、9、10 和 12 月存在 P 相对限制的站位分别有 4、8、8、11 和 9 个，磷酸盐是影响海州湾浮游植物生长的主要环境因子。在贝类养殖海域，浮游植物生物量通常受到海域生态环境和养殖活动的共同影响(苏家齐等，2018)。养殖活动的影响主要包括贝类对浮游植物的摄食压力和贝类代谢产生营养盐的影响(齐占会等, 2021)。在贝类养殖密度比较高的情况下，贝类滤食会对浮游植物的生物量有下行控制作用，导致浮游植物的 Chl-*a* 浓度降低(Butts *et al*, 2022；仇菲等, 2025)。例如，在挪威西南海岸的贻贝养殖场，海域的 Chl-*a* 浓度在贻贝养殖期内降低了 15%~40% (Strohmeier *et al*, 2008)，浙江枸杞岛的贻贝养殖区也发现类似现象 (关莹莹等, 2022)。对于营养盐贫瘠的海域，贝类排泄会加快营养盐的周转速度(Gaertner-Mazouni *et al*, 2012；徐东会等，2017)，从而刺激浮游植物生物量的提升(潘玉龙等, 2019)。本研究发现，在 9 月，尽管二区的营养

盐浓度显著高于非养殖区，但是，浮游植物的 Chl-*a* 浓度分别比航道区和空白区低 36.9%和 55.6%，因此推测，9 月二区的贝类摄食压力较大，可能是控制浮游植物生物量的主要原因。

本研究中，3 月和 7 月养殖活动对浮游植物粒径结构的影响较小，其粒径结构主要受营养盐和温度的影响；9、10 和 12 月，养殖活动持续进行，整个海区小型浮游植物的占比逐渐增加。在福建省的贝类养殖区，浮游植物的优势类群从微型向小型和微微型转变，主要是由环境条件的季节性变化引起(Mo *et al*, 2023)；在大亚湾海域，温度升高和河流营养盐的输入导致浮游植物粒级小型化(谢福武等, 2018; 向晨晖等, 2021)；吴文广等(2018a、b)研究发现，獐子岛虾夷扇贝(*Patinopecten yessoensis*)养殖区海域 nano Chl-*a* 的占比从秋季的 72.3%降低到冬季的 47.3%，而 micro Chl-*a* 从 23.77%增加到 52.97%，这与本研究的结果相似。综上所述，浮游植物粒径结构的改变是一个复杂的过程，可能是水温和营养盐浓度的降低，使小型浮游植物具有更强的竞争力，因此，9—12 月其占比增加。除环境因素外，滤食性贝类摄食的能力和选择性也会影响浮游植物的粒径结构(Trottet *et al*, 2008)。贝类通常对粒径较大颗粒的保留率较高(Møhlenberg *et al*, 1978)，因此，贝类对浮游植物的摄食选择性通常使浮游植物的粒径小型化(Jiang *et al*, 2016; 柴正晴等, 2022)。本研究发现，养殖区内并未出现浮游植物小型化的趋势，反而在 9、10 和 12 月，养殖区内小型浮游植物的占比要高于非养殖区。除颗粒大小外，浮游植物的形状、营养物质含量和细胞运动性等因素都可能影响滤食性贝类的摄食选择性(Ward *et al*, 2004)。例如，肖雪艳等(2022)通过围隔实验发现，虾夷扇贝对柔弱拟菱形藻(*Pseudo-nitzschia delicatissima*)和双菱藻(*Surirella* sp.)有较大的滤除效应，但对菱形藻(*Nitzschia* spp.)和针杆藻(*Synedra* spp.)影响不大；Tan 等(2017)调查发现，在马来西亚的自然海域中，角毛藻(*Chaetoceros* spp.)是浮游植物的优势种，但检测贻贝胃含物发现甲藻(*Prorocentrum* spp.)和圆筛藻(*Coscinodiscus* spp.)占比最大，而角毛藻的占比很小。由于海洋养殖生态系统的复杂性和多变性，浮游植物粒径结构的改变可能是养殖活动和多种环境因素共同作用引起的，这些控制因素相互作用，共同决定了浮游植物在时空尺度上的粒径结构。由于微微型浮游植物难以被贝类的摄食器官捕获(Cranford *et al*, 2008)，因此，普遍观点认为微微型浮游植物对于养殖贝类的营养价值不高。但近年来也有科学家提出不同的观点，Richard 等(2022)通过实验发现，平均体重为 21.4 g 的贻贝能够大大减少一种微微型浮游植物(*Picochlorum*)的丰度，Huang 等(2023)通过高通量测序发现泥蚶(*Tegillarca granosa*)胃含物中存在高多样性的微微型浮游植物，其中，*Ostreococcus* (6.12%~67.88%)和 *Picochlorum* (4.07%~35.33%)的含量最高。本研究未发现微微型浮游植物在养殖区与非养殖区之间存在显著差异，但贝类可以通过摄食微型浮游动物对其产生间接影响，因此，微微型浮游植物在贝类养殖海域生态系统中的作用不容忽视，未来还需进一步关注。

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Distribution of Size-Fractionated Phytoplankton and Their Relationships with Environmental Variables in Bivalves Mariculture Areas of Haizhou Bay

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Abstract The mariculture industry has rapidly developed in recent decades owing to population growth and the increasing demand for seafood. Phytoplankton is an important indicator for assessing the carrying capacity of bivalve mariculture as well as a limiting factor for large-scale and high-density bivalve cultivation. Phytoplankton can be categorized by size into picophytoplankton (<2 μm), nanophytoplankton (2–20 μm), and microphytoplankton (20–200 μm). Considering that the retention rate of picophytoplankton by filter-feeding bivalves is very low, using the total amount of phytoplankton available for aquaculture capacity assessment would result in an overestimation. Therefore, understanding the particle size composition and spatiotemporal distribution characteristics of phytoplankton in the target sea area can improve the accuracy of assessing bivalve culture capacity and provide scientific guidance for marine bivalve aquaculture. Blue mussel *Mytilus edulis* and triploid oyster *Crassostrea gigas* are the most common bivalve species in Haizhou Bay, a typical bivalve mariculture area in China. This study aimed to understand the size-fractionated phytoplankton and its

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environmental influencing factors, including water temperature, salinity, dissolved oxygen, pH, total nitrogen, total phosphorus, phosphate, silicate, nitrate, nitrite, ammonia nitrogen, dissolved inorganic nitrogen, N/P, N/Si and Si/P, both in bivalve mariculture areas (Area 1 and 2) and non-mariculture areas (channel and reference areas). Phytoplankton biomass was investigated in March, July, September, October, and December 2023 by measuring Chl-*a* of size-fractionated phytoplankton. Two-way variance and redundancy analyses were used to analyze the effects of environmental factors on size-fractionated phytoplankton. (1) The annual variation range of total Chl-*a* concentration in the investigated area was 0.86–18.49 μg/L, and the seasonal difference was significant (P < 0.05). The annual ranges of pico Chl-*a*, nano Chl-*a*, and micro Chl-*a* concentrations were 0–0.90, 0.13–6.12, and 0.35–15.30 μg/L, respectively, with significant seasonal differences (P<0.01). However, no significant differences were observed in the concentrations of Chl-*a* in March (1.98±0.61 μg/L) and December (3.69±1.55 μg/L). In July and October, the average concentrations of Chl-*a* in Area 1 were (9.80±2.04) μg/L and (12.34±6.27) μg/L, respectively, which was much higher than those in other areas (P<0.05). This may be due to the higher nutrient concentration in the coastal waters. In September, the Chl-*a* concentration in Area 2 (1.47–1.94 μg/L) was significantly lower than in the non-bivalve mariculture areas (P<0.01). Simultaneously, the nitrate and nitrite concentrations in Area 2 were significantly higher than in the other areas. This period marked the rapid growth of bivalves and was presumed to be caused by bivalve feeding and excretion. (2) Phytoplankton communities exhibit notable spatiotemporal variation. In March, the phytoplankton communities of Area 1 and the channel area were dominated by microphytoplankton, whereas Area 2 and the reference area were dominated by nanophytoplankton. In July, nanophytoplankton dominated in Area 1 and the channel area, whereas microphytoplankton dominated in Area 2 and the reference area. In September, microphytoplankton dominated Area 1, Area 2, and channel area, whereas nanophytoplankton dominated the reference area. The proportion of picophytoplankton in the reference area was significantly higher than that in other areas (P<0.05). In October, the contribution rate of microphytoplankton increased gradually in all areas, and the value added in bivalve mariculture areas was significantly higher than that in the non-bivalve mariculture areas (P<0.05). In December, no significant difference was observed in the contribution rate of particle size in different areas, but the contribution rate of microphytoplankton continued to increase across different areas, with an average value of 89.01%. The contribution rate of picophytoplankton was mainly affected by seasonal factors (P<0.001), whereas the contribution rate of nanophytoplankton and microphytoplankton was significantly affected by seasonal and seasonal and regional interactions (P<0.05). (3) Seasonal and regional differences exist in the response of the particle size structure of phytoplankton to environmental factors in the survey areas. The redundancy analysis showed that the first two axes explained 79.31%, 86.94%, 88.35%, and 99.09% of the species variation in Area 1, Area 2, channel area, and reference area, respectively. Seasonal and regional differences influenced the response of the particle size structure of phytoplankton to environmental factors in the four areas. A significant negative correlation was observed between nanophytoplankton and N/Si in Area 1. In Area 2, picophytoplankton was significantly negatively correlated with total nitrogen, and nanophytoplankton was significantly positively correlated with N/P. In the channel area, the phytoplankton of three sizes were significantly negatively correlated with ammonia nitrogen. Microphytoplankton was positively correlated with DIN in the reference area (P<0.05). Consequently, nutrient salts mainly regulated the Chl-*a* concentration of phytoplankton in Area 1, whereas the effects of nutrient salts and cultured bivalve influenced the Chl-*a* concentration of phytoplankton in Area 2. For the entire survey area, seasonal changes in environmental conditions are the main cause of phytoplankton particle size structure variation. In addition, the presence of seasonal and regional interactions in nanophytoplankton and microphytoplankton suggests that bivalve farming may also affect the size-fractionated phytoplankton.

Key words Phytoplankton; Size fraction; Bivalve culture; Nutrients