

富营养化浅水湖泊生态修复中背角无齿蚌 (*Anodonta woodiana*) 对水质改善的影响*

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摘要: 滤水速率的快慢是决定滤食性河蚌对水质改善与否的关键, 但受蚌龄大小、食物多少和季节变化的影响。以背角无齿蚌 (*Anodonta woodiana*) 为研究对象, 设置幼龄蚌组、成年蚌组和无蚌对照组, 在惠州西湖生态修复后的清水态和未修复的富营养化水体同时进行中型系统原位实验, 测定了各处理组水层中氮、磷、总悬浮物 (TSS) 浓度和浮游藻类生物量 (用叶绿素 a (Chl.a) 浓度表示) 的季节变化, 以研究蚌龄、食物和季节变化对背角无齿蚌水质改善的影响。结果表明, 与对照组相比, 背角无齿蚌提高了清水态水体总磷 (TP) 和铵态氮浓度, 但对总氮 (TN)、TSS 和浮游藻类 Chl.a 浓度的影响不显著, 表明其不能有效改善清水态水体水质; 富营养化水体中, 背角无齿蚌虽对水中 TN 浓度影响不显著, 但显著降低了 TP 浓度、浮游藻类 Chl.a 浓度和 TSS 浓度; 表明背角无齿蚌可改善富营养化水体水质; 且富营养化水体中幼龄蚌的滤水速率显著高于成年蚌; 幼龄蚌的滤水速率春季最大 ($0.132 \pm 0.018 \text{ L}/(\text{g} \cdot \text{h})$), 夏季最小。因此, 在富营养化水体修复前期, 可通过放养本地滤食性河蚌, 如背角无齿蚌, 以改善水质, 春季放养幼龄蚌更佳, 为接下来的修复创造有利条件; 而在生态修复后期的清水态水体中, 单独的河蚌对水质改善效果不明显。本研究可为水生态系统保护和富营养化水体生态修复提供参考。

关键词: 滤食性河蚌; 底栖动物; 滤水速率; 营养盐代谢; 水质改善; 背角无齿蚌; 惠州西湖

Effects of *Anodonta woodiana* on water quality improvement in restoration of eutrophic shallow lakes

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Abstract: The filtration rate of filter-feeding mussels is crucial in improving the water quality. However, it is affected by mussel age, food concentration and season. A situ mesocosm experiment with young and adult mussels of *Anodonta woodiana* was set up in restored clear and eutrophic sub-lakes of Huizhou West Lake. Nutrients, total suspended solids (TSS) and biomass of phytoplankton as chlorophyll-a (Chl.a) were measured and their filtration rates were calculated in different treatments with seasons to study the effect of filter-feeding mussels on water quality in the restoration of eutrophic shallow lakes. Results showed that in clear water, the mussels increased the ammonium nitrogen and total phosphorus (TP), but did not change the concentrations of total nitrogen (TN), TSS, and Chl.a, which indicated that the mussels cannot improve the water quality in the clear water conditions. In eutrophic water conditions, though the mussels did not change the concentrations of TN, they decreased the concentrations of TSS, Chl.a and TP, which indicated that they can improve the water quality in eutrophic conditions. The filtration rate of young mussels was generally higher than that of adults. In addition, the filtration rate of the young mussels was the highest ($0.132 \pm 0.018 \text{ L}/(\text{g} \cdot \text{h})$) in spring, and lowest in summer. Thus, local mussels, such as *Anodonta woodiana*, can be set to improve water quality at early stages in restoring the degraded ecosystem due to eutrophication, especially in spring. However, mussels alone cannot improve wa-

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ter quality in clear water conditions during the late stages of restoration. The results of this study are important for management of aquatic ecosystems and restoration of eutrophic shallow lakes.

Keywords: Filter-feeding mussel; benthic animal; filtration rate; nutrient metabolism; water quality improvement; *Anodonta woodiana*; Huizhou West Lake

生态修复成为改善富营养化水体水质的一种有效方法^[1]。底栖动物,特别是滤食性河蚌因其可滤食浮游植物、有机碎屑等悬浮颗粒^[2],被认为可增加水体透明度^[3-5],改善水质,已广泛应用。如 Hoser 等^[6]在荷兰的一些浅水湖泊的生态修复中运用了斑马贻贝(*Dreissena polymorpha*);在太湖蠡湖和上海金山城市沙滩人工潟湖水体的生态修复中也运用了滤食性河蚌^[7-8]。除滤食外,河蚌的呼吸、分泌、排泄等生理活动,也可显著增加水中营养盐浓度^[9]。滤食性河蚌可直接分泌释放出大量溶解性氮、磷营养盐^[9-10];也可通过粪便排泄等基本生理代谢活动释放营养盐^[10];还可在沉积物表层形成大量富含营养物质的假粪,更易分解而增加水层中的营养盐^[10-11];再者,其还能促进沉积物营养盐释放^[9,12],这些又被认为会恶化水质。如厦门筭筭湖因沙筛贝(*Mytilopsis sallei*)入侵,加剧了筭筭湖的富营养化^[13]。因此,滤水速率的快慢是滤食性河蚌对水质改善与否的关键。

滤食性河蚌的滤水速率快慢受蚌龄大小、食物多少与季节变化等因素的影响。如滤食性河蚌的滤水速率随浮游藻类浓度变化而不同,低藻浓度条件下滤食性贝类的滤水速率低下^[14];河蚌滤水速率与蚌龄的大小有关,小型河蚌的滤食活动更强^[15-16]。因此,了解蚌龄大小、食物多少以及季节变化对河蚌滤水速率的影响,对进一步认识河蚌能否改善水质以及富营养化水体生态修复中如何优化利用滤食性河蚌具有重要意义。

本研究以背角无齿蚌(*Anodonta woodiana*)为对象,采用野外原位实验的方法,开展清水态和富营养化条件下幼龄和成年背角无齿蚌滤食对水质改善效果的实验,测定不同处理组水中氮、磷、总悬浮物(TSS)浓度和浮游藻类生物量(用叶绿素 a(Chl.a)浓度表示)的季节变化,研究蚌龄大小、食物多少和季节变化等因素对滤水速率的影响,以期为湖泊生态系统保护和富营养化湖泊的修复提供参考。

1 材料与方法

1.1 实验材料

背角无齿蚌采自广东省惠州西湖。称重前用软毛刷刷掉蚌壳表面的附着生物,湖水洗净,用吸水纸去除蚌壳表面水分。实验用水取自广东省惠州西湖,用 13[#]浮游生物网滤除湖水中的大型浮游动物。

实验用桶为聚乙烯塑料材质,容积 120 L,具底,底部直径×上部直径×高≈45 cm×57 cm×61 cm。

1.2 实验方法

将实验用桶(固定于惠州西湖中)中注入 60 L 用 13[#]浮游生物网滤除浮游动物的惠州西湖湖水,分为幼龄蚌组、成年蚌组以及没有蚌的对照组,每组 4 次重复。幼龄蚌组每桶放置 1 只幼龄蚌(壳长=78.0±3.7 mm,鲜重=54.6±4.7 g);成年蚌组每桶放置 1 只成年蚌(壳长=110.1±1.6 mm,鲜重=136.3±8.4 g)。实验在春、夏、秋、冬季节选择晴朗天气分别在惠州西湖生态修复示范区的清水态水体和未修复的富营养化水体平湖进行,每次实验 10:00 开始,14:00 结束。

1.3 采样与分析

实验开始和结束时分别用 1000 ml 的聚乙烯塑料瓶采集水下 10~20 cm 处桶内水样和桶外湖泊水样,置于加冰的采集箱待测。该水样用于分析总氮(TN)、总磷(TP)、铵态氮(NH₄⁺-N)、总悬浮物(TSS)浓度和 Chl.a 浓度。Chl.a 浓度采用丙酮萃取分光光度法测定^[17];TN 浓度采用碱性过硫酸钾紫外分光光度法测定,TP 浓度采用钼酸铵分光光度法进行测定^[18];NH₄⁺-N 浓度采用纳氏试剂比色法进行测定^[19]。TSS 浓度采用 Whatman GF/C 纤维滤膜抽滤后 105℃烘干称重的方法^[20]进行测定。

背角无齿蚌滤水速率计算公式为^[21]:

$$FR = V / (W \cdot t) [(\ln C_0 - \ln C_t) - (\ln C_0' - \ln C_t')] \quad (1)$$

式中,FR 为滤水速率(L/(g·h)),V 为实验桶中水的体积(L),W 为蚌的质量(g),t 为时间(h),C₀和 C_t分别为实验组实验开始和 t 时间悬浮有机物浓度(mg/L),C₀'和 C_t'分别为对照组实验开始和 t 时间悬浮有机物

浓度(mg/L).

1.4 数据统计分析

所有实验数据采用 SPSS 18.0 软件进行统计分析,各处理组随季节性变化的差异采用重复测量方差分析(RM-ANOVAs),组间差异采用单因素方差分析(One-way ANOVA). *表示与对照组差异显著($P<0.05$).

2 结果

2.1 营养盐

清水态水体中,除秋季的幼龄蚌组外,春、夏、秋、冬季各蚌处理组 TP 浓度均高于对照组($P<0.05$);但各季节的幼龄蚌组与成年蚌组间 TP 浓度差异不显著($P>0.05$). 富营养化水体中,幼龄蚌组的秋、冬季 TP 浓度显著低于对照组($P<0.05$);成年蚌组的春、冬季 TP 浓度也显著低于对照组($P<0.05$);其他季节各处理组组间差异不显著($P>0.05$)(图 1).

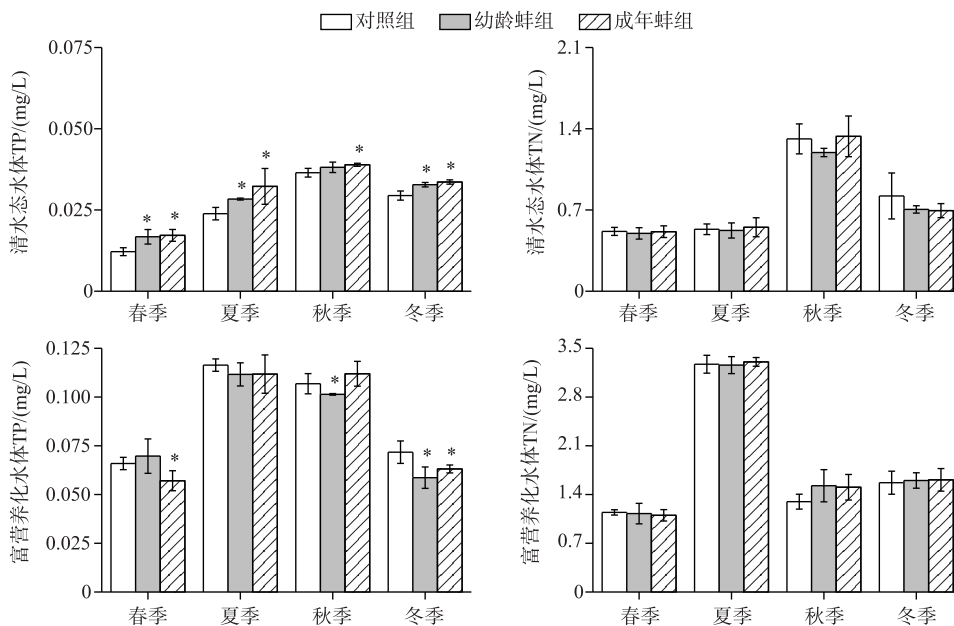


图 1 不同处理组 TP 和 TN 浓度

Fig.1 TP and TN concentrations in different treatments

不管在清水态水体还是富营养化水体中,各处理组 TN 浓度差异不显著($P>0.05$);但在清水态水体的春、秋季,成年蚌组 $\text{NH}_4^+\text{-N}$ 浓度显著高于对照组($P<0.05$);幼龄蚌组的 $\text{NH}_4^+\text{-N}$ 浓度在春季(0.18 ± 0.02 mg/L)也显著高于对照组(0.13 ± 0.01 mg/L)($P<0.05$)(图 2).

2.2 总悬浮物、浮游藻类生物量

清水态水体中,幼龄蚌组和成年蚌组水中 TSS 浓度和 Chl.a 浓度与对照组相比差异均不显著($P>0.05$);富营养化水体中,春、冬季的幼龄蚌组和成年蚌组水体 TSS 浓度均低于对照组($P<0.05$),但幼龄蚌组与成年蚌组之间的差异不显著($P>0.05$);春季对照组 TSS 浓度为 10.74 ± 1.54 mg/L,幼龄蚌组为 7.92 ± 0.73 mg/L,成年蚌组为 8.16 ± 0.95 mg/L;冬季对照组 TSS 浓度为 16.11 ± 0.51 mg/L,幼龄蚌组为 12.80 ± 1.37 mg/L,成年蚌组为 12.82 ± 1.08 mg/L. 夏、秋两季蚌处理组与对照组之间差异不显著($P>0.05$)(图 3).

富营养化水体中,夏、秋和冬季幼龄蚌组浮游藻类 Chl.a 浓度分别为 31.14 ± 1.78 、 41.9 ± 0.34 和 10.73 ± 0.58 $\mu\text{g/L}$,分别低于对照组的 38.91 ± 3.29 、 50.03 ± 5.54 和 18.85 ± 1.50 $\mu\text{g/L}$ 和成年蚌组的 40.08 ± 5.39 、 45.24 ± 1.23 和 21.97 ± 4.59 $\mu\text{g/L}$ ($P<0.05$),但春季幼龄蚌组与对照组差异不显著($P>0.05$);成年蚌组与对照组间差

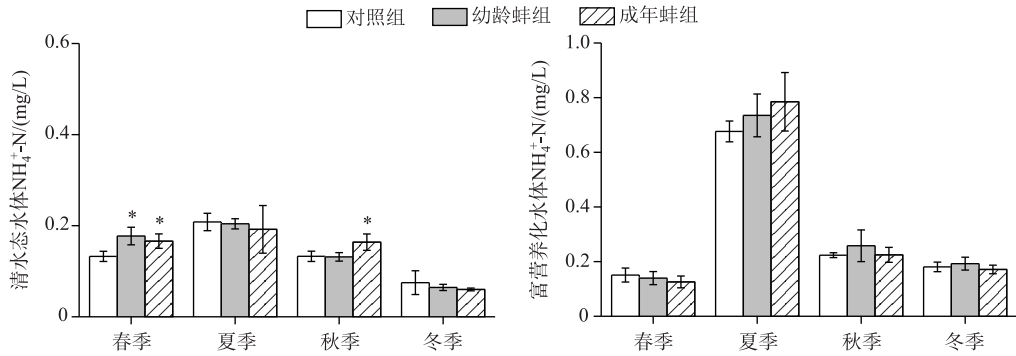


图 2 不同处理组 NH₄⁺-N 浓度

Fig.2 Ammonium nitrogen concentrations in different treatments

异各季节均不显著 ($P>0.05$); 浮游藻类 Chl.a 浓度随季节变换差异显著 (RM-ANOVAs, $P<0.05$), 夏、秋季显著高于春、冬季 ($P<0.05$) (图 3).

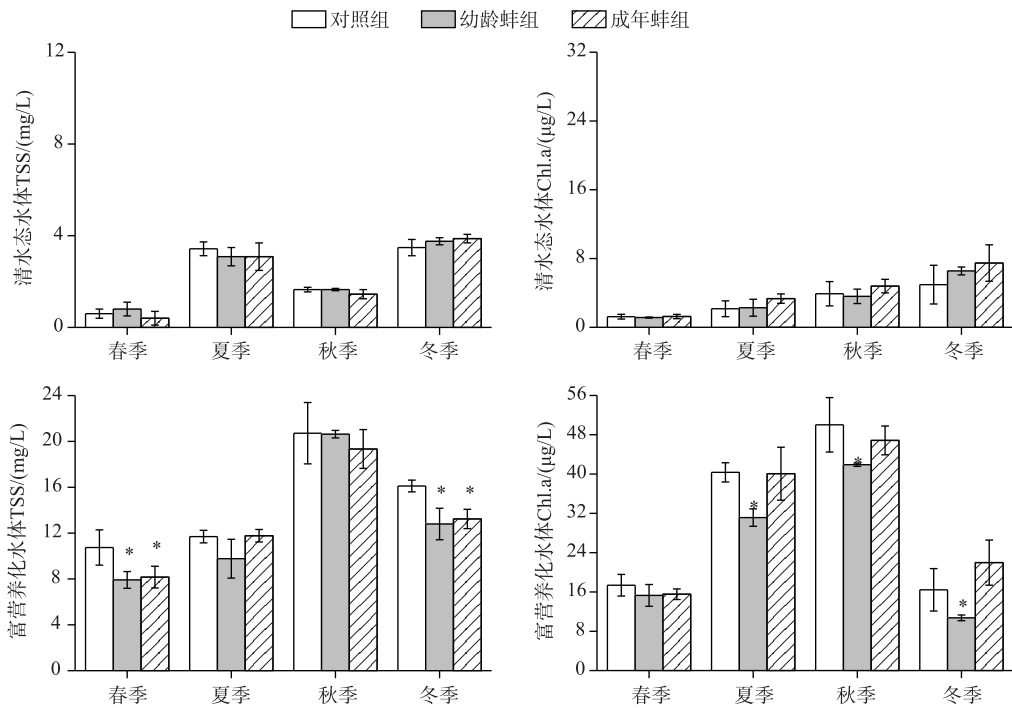


图 3 不同处理组 TSS 和 Chl.a 浓度

Fig.3 TSS and Chl.a concentrations in different treatments

2.3 滤水速率

富营养化水体中, 幼龄蚌组与成年蚌组的滤水速率随季节变化差异显著 (RM-ANOVAs, $P<0.05$), 其中, 春季最大, 冬季次之, 夏季最小. 幼龄蚌组的滤水速率春季为 $0.132 \pm 0.018 \text{ L}/(\text{g} \cdot \text{h})$, 冬季为 $0.109 \pm 0 \text{ L}/(\text{g} \cdot \text{h})$; 成年蚌组的滤水速率春季为 $0.035 \pm 0.003 \text{ L}/(\text{g} \cdot \text{h})$, 冬季为 $0.019 \pm 0.004 \text{ L}/(\text{g} \cdot \text{h})$; 幼龄蚌组的滤水速率显著高于成年蚌组 ($P<0.05$). 夏季幼龄蚌组和成年蚌组的滤水速率均低.

而在清水态水体中, 水层中悬浮颗粒物和浮游藻类浓度低, 且与对照组相比差异不显著, 各处理组背角无齿蚌的滤水速率几乎为 0.

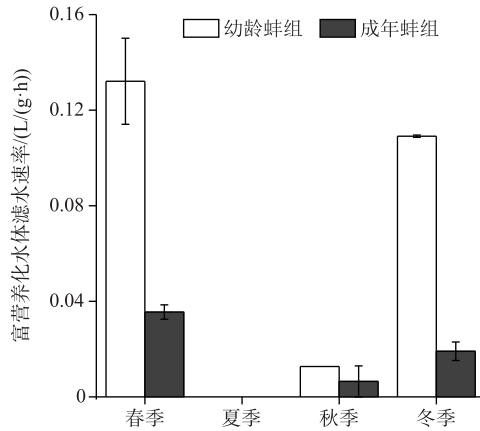


图4 富营养化水体背角无齿蚌滤水速率

Fig.4 Filtration rates of mussels in eutrophic water conditions

3 结论与讨论

3.1 背角无齿蚌对不同营养状态水体水质的影响

本研究显示,富营养化水体中,春、冬两季幼龄蚌组和成年蚌组 TSS 浓度均低于对照组,且夏、秋、冬季幼龄蚌组浮游藻类 Chl.a 浓度也低于对照组,表明背角无齿蚌降低了 TSS 浓度和浮游藻类密度.另外,富营养化水体中,幼龄蚌组的 TP 浓度在秋、冬季低于对照组;成年蚌组的 TP 浓度在春、冬季也低于对照组,表明背角无齿蚌降低了富营养化水体中 TP 浓度.水中 TSS 浓度、浮游藻类 Chl.a 浓度和 TP 浓度的降低,不仅有利于改善水质,也有利于提高水体透明度,从而改善浅水水体底部光照条件,为底栖植物(沉水植物和底栖藻类)的生长进一步创造条件.

滤食性贝类不仅能通过滤食作用改善水质,还可通过分泌、排泄等生理活动释放营养盐^[22-23].本研究显

示清水态水体中,除秋季的幼龄蚌组外,春、夏、秋、冬季各蚌处理组 TP 浓度均高于对照组;春、秋季,成年蚌组 $\text{NH}_4^+\text{-N}$ 浓度高于对照组;幼龄蚌组的 $\text{NH}_4^+\text{-N}$ 浓度也在春季高于对照组,这表明背角无齿蚌提高了清水态水体中营养盐浓度.另在清水态水体中,幼龄蚌组和成年蚌组 TSS 浓度和浮游藻类 Chl.a 浓度与对照组相比差异不显著,表明清水态水体中背角无齿蚌对 TSS 浓度和浮游藻类 Chl.a 浓度影响效果不明显.已有研究表明蚌类滤食活动因悬浮颗粒浓度而变化,食物浓度低会导致滤食活动弱,甚至停止^[24].本研究中清水态水体背角无齿蚌对 TSS 浓度和浮游藻类 Chl.a 浓度影响效果不明显,可能是由于其浓度低所致.

3.2 背角无齿蚌滤水速率的季节变化

温度是季节变化中最重要的生态因子之一.温度变化也影响到背角无齿蚌的滤水速率.本研究表明,富营养化水体中背角无齿蚌滤水速率春季最大,冬季次之,夏季最小,这可能是实验期间夏、秋季较高水温(分别为 32.9~35.4 和 28.4~29.7℃)降低了背角无齿蚌的滤水速率,而春季和冬季水温分别为 22.7~24.7 和 20.9~22.3℃.有研究显示高温可降低滤食性河蚌的滤水速率,如斑马贻贝的滤水速率在 20~24℃ 时比 28~32℃ 高^[25-26];当温度超出适宜的范围时,会降低摄食器官的活力,从而导致滤水速率的下降^[27].

3.3 蚌龄大小对水质的影响

不同蚌龄背角无齿蚌的滤水速率有较大差别^[2,15-16].本研究显示富营养化水体中,春、冬两季幼龄蚌组的滤水速率显著高于成年蚌组.吴庆龙等^[16]的研究也表明体重小的幼龄蚌滤水速率显著高于体重大的成年蚌.本研究富营养化水体中,幼龄蚌组浮游藻类 Chl.a 浓度显著低于成年蚌组,也表明幼龄蚌组滤水速率高于成年蚌组.

综上,富营养化水体中,背角无齿蚌在春、冬季节滤水速率高,可降低 TSS、浮游藻类 Chl.a 和 TP 浓度,从而改善水质,且幼龄蚌组的滤水速率高于成年蚌组;因此,在富营养化水体的修复前期,可放养本地滤食性河蚌,在春季放养幼龄蚌更佳,以改善水质,提高水体透明度,为接下来的修复创造条件.在清水态水体中,背角无齿蚌滤水速率低,对水质改善效果不明显,反而提高水体 TP、 $\text{NH}_4^+\text{-N}$ 等浓度.因此,在生态修复后期的清水态水体中单独的滤食性河蚌对水质改善效果不明显.

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