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Filtration of Green Algae and Cyanobacteria by Freshwater Mussels in the Partitioned Aquaculture System

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Abstract.—The freshwater mussel *Elliptio complanata* was provided water containing green algae and cyanobacteria delivered from the Partitioned Aquaculture System (PAS) at eight flow rates to determine algal filtration rates as mg of particulate organic carbon (POC)/kg wet tissue weight per h. The dominant taxon in cyanobacterial waters was *Microcystis* while the dominant taxa in green algal waters were *Scenedesmus* and *Ankistrodesmus*. The cell counts of *Scenedesmus* and *Ankistrodesmus* were the only algal taxa that were significantly different between the incoming water and water filtered by mussels. Filtration rates of POC obtained from green algal water were significantly greater than from cyanobacteria-dominated waters at all flow rates. A significant increase in mean filtration rate was observed as flow rates increased. The filtration rate of green algae increased as POC concentration increased, peaking at 28 mg C/L. A maximum filtration rate was not observed with cyanobacterial waters.

Catfish production from the Partitioned Aquaculture System (PAS) is 2–3 times that of traditional earthen ponds (Brune and Wang 1998; Schwartz 1998). The PAS is based on the concept of managing algal standing crop productivity at desired levels to increase fish production (Smith 1988; Smith and Piedrahita 1988; Drapcho 1993). Fish farmers consider excessive algal growth an undesirable result of nutrient input from feeding and fish waste (Brune 1995). One consequence of undesirable algal blooms is off-flavor in fish flesh making them unmarketable (Sevrin-Reyssac and Pletikosic 1990; Brune 1995). Cyanobacterial (blue-green algal) species have been associated with these types of water management problems such as off flavor; but unfortunately, fish farmers generally do not notice the presence of cyanobacteria until they start to accumulate on the water surface (Sevrin-Reyssac and Pletikosic 1990).

Conover (1976) suggested phytoplankton communities could be maintained by balancing algal production and consumption by filter feeders. Several non-native filter-feeding species including silver carp, tilapia, and the Asiatic clam *Corbicula fluminea* have been added to aquaculture ponds to increase fish production and crop algal production (Smith 1985; Burke et al. 1986; Buttner 1986); however, non-native species may be prohibited by law or require time-consuming licensing and expensive escape precautions for use in aquaculture. To avoid this problem a native freshwater mussel *Elliptio complanata* was selected as a filter-feeding candidate for use in the PAS. In comparison to gizzard shad, fathead minnows, and common carp, *E. complanata* was more effective in reducing suspended solids in laboratory and field experiments (Helfrich et al. 1995). Starkey (1999) indicated *E. complanata* survived well and influenced the algal community in the PAS. *E. complanata* is also a ubiquitous abundant mussel whose glochidia do not infect catfish (Watters 1994).

PAS water contains several taxa of both green algae and cyanobacteria. The dominant green algae *Scenedesmus* spp. occurred in July while the dominant cyanobacterium, *Merismopedia* sp. was observed in a short unstable period in late August (Brune 1995). Fish farmers usually encoun-

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ter cyanobacterial blooms in the late summer months as water temperatures warm (Sevrin-Reyssac and Pletikosic 1990). The objective of this study was to determine filtration rates of *E. complanata* over the course of the production cycle when green algae and cyanobacteria were dominant in the PAS.

Materials and Methods

E. complanata collected from Big Garvin Creek, South Carolina, for algal filtration determinations were held in the Partitioned Aquaculture System (PAS) at Calhoun Field Station, Clemson University. Prior to stocking experimental chambers, algal rich water from the PAS was passed through the chambers for 24 h. A similar number and size of mussels were stocked at 1.22 kg wet tissue weight in each of the eight chambers. A ninth chamber without mussels was used as an experimental blank (control). The tissue biomass of *E. complanata* was estimated from the relationship: tissue wet weight (g) = 1.8806 + 0.2626 whole animal weight (g); $r^2 = 0.94$; $N = 110$ (Starkey 1999). Mussels were placed off the bottom to avoid suspension of feces and pseudofeces. Mussels were held in the chamber for 72 h before returning to a holding area in the PAS.

Water was delivered to each chamber at one of eight known flow rates (0.1, 0.2, 0.6, 1.0, 1.5, 2.0, 2.5, and 3.0 L/min) by short-time pulse additions controlled by individual solenoid valves and electric timers. One flow rate was randomly selected from the eight flow rates for the experimental blank. Flow rates were verified by taking repeated timed measurements with a graduated cylinder. Standpipes in each chamber controlled water volume at 127 L and an airstone was used to maintain a mixed water column. Between experiments each chamber and the water delivery system were thoroughly cleaned.

Water temperature was recorded at 2–4 h intervals from 1700 to 2300 whereas dissolved oxygen, pH and nitrite-nitrogen were measured once every 24 h during each 72-h experiment. Dissolved oxygen and temperature values were measured with a YSI probe (Model 58, YSI Incorporated Yellow Springs, Ohio, USA). Nitrite-nitrogen using a spectrophotometer (APHA et al. 1989) and pH values were measured using a Hach test kit (Model FF-1A, HACH Company, Loveland, Colorado, USA).

Samples of incoming water and water from the chamber (outgoing water) were taken from each chamber. These samples were taken from 0700 to 2300 every 4 h until two tank detention times were achieved and every 2 h thereafter over the 72-h experimental period. Optical light transmission values of the water samples were then obtained at 750 nm with the spectrophotometer (APHA et al. 1989). For each experiment, a standard curve was prepared by regressing transmission values against analytically determined particulate organic carbon (POC) values of known dilutions of PAS water used in trials. The POC in water was determined using a Total Organic Analyzer (DC-190, Rosemount Dohrman, Cincinnati, Ohio, USA). A regression for each experiment was determined between the analytically determined POC values and transmission values. The relationships ($N = 7$) were linear with coefficient of determinations (r^2) from 0.90 to 0.96.

The filtration rate of POC as dry weight was estimated for each timed water sample using the following equation:

$$\text{filtration rate (mg C/h)} = C_i - C_o * FR;$$

where C_i is the concentration of POC in the incoming water, C_o is the POC concentration from the outgoing water, and FR is the controlled flow rate. The net change between the incoming and outgoing water in the blank was used to represent incidental settling and was used to correct filtration rates for each experiment. Filtration rates were then divided by the tissue-wet weight of the mussels to estimate specific filtration rates (mg C/kg wet tissue per h).

Water samples from four PAS units were examined and classified as either cyanobacteria-dominated or green algae-dominated water when the abundance of either taxa exceeded 60% of the total cells in duplicate hemocytometer counts. Water source for an experiment was then selected depending on the algal bloom in order to compare filtration rates between green algal and cyanobacterial waters. Since filtering experiments with green algal and cyanobacterial waters could not be run simultaneously, experiments were run when PAS water met prescribed algal conditions. Experiments for each type of algal bloom were repeated a minimum of three times within a 23–27 C range from 12 June to 13 September 1999. Comparisons of filtration rates between algal blooms were restricted to those values recorded after the incoming water equaled twice the chamber volume (two turnovers).

Abundance of algal taxa in the incoming and outgoing water was estimated for one 72-h experiment each with green algal and cyanobacterial waters. Three 70-mL samples of incoming and outgoing water were taken at the same flow rate (0.2 L/min) and time for the green algal and cyanobacterial experiments. Algae were identified to genus using Prescott (1961), and duplicate samples were counted with a hemocytometer.

A single tailed *t*-test was used to determine differences in algal taxa between incoming and outgoing samples of green algal and cyanobacterial waters. Filtration rate data were analyzed with ANOVA using the general linear model with 72-h experiments as replicates for flow rate, algal taxa and their interaction. Similarly, ANOVA was used to detect differences in water quality values among flow rates and algal taxa experiments. Prior to performing statistical analysis on filtration rates versus POC levels, means were calculated for filtration rates and POC levels (flow rates) for each experiment. A second order polynomial regression model was used to estimate the response of filtration rates to increasing POC levels. The parameters of the regression equations for filtration rates in green algal and cyanobacterial waters were compared using analysis of covariance (Graybill and Iyer 1994). Alpha level was set at 0.05.

Results

Water quality in the experimental chambers was statistically similar among the eight flow rates and algal taxa experiments. Mean (± SE) dissolved oxygen was 10.2 ± 0.08 mg/L (8.2–11.5), pH 7.5 ± 0.05 (7.1–9.3), and nitrite-nitrogen 0.11 ± 0.08 mg/L (0.00–0.35). Water temperature during the cyanobacterial experiments were slightly warmer 25.1 ± 0.29 C (24–27) than with green algal water 24.5 ± 1.50 C (23–27).

The green algal water source used in the filter experiments contained eight green algae taxa constituting 73% of algal abundance, whereas the two cyanobacterial taxa present constituted 14%, and diatoms 13%. In contrast, cyanobacterial water source was composed of three cyanobacteria taxa making up 70% of the algae, eight green taxa constituted 23%, and 7% were diatoms.

The outgoing green algal water representing the mussel-filtered water contained significantly fewer *Scenedesmus* than the incoming water (Table 1). Also significantly fewer *Scenedesmus* and *Ankistrodesmus* were observed in outgoing cyanobacterial water. No difference, however, was detected in the abundance estimates of the cyanobacteria, either in *Microcystis* or *Merismopedia* between the incoming and outgoing green algal and cyanobacterial water sources.

Mussel filtration rate of POC was significantly affected by flow rate, algal taxa, and their interaction (Table 2). Filtration rates of POC from green algal water were significantly greater than those from cyanobacterial water at all the flow rates except 0.1 L/min. An increase in filtration rate was observed as flow rate increased up to 2.5 L/min while a further increase to 3.0 L/min resulted in a significant decrease in filtration rate (Table 2).

The coefficient of determination (R^2) for

TABLE 1. *Mean (± SE) algal counts (log_{10} cells/mL) of incoming and outgoing green algal and cyanobacterial water. Those taxa means within rows of green algal and cyanobacterial water followed by a different letter are significantly different by* t*-tests.*

Taxa	Green algal water			Cyanobacterial water		
	N	In	Out	*N*	In	Out
Scenedesmus spp.	6	4.86 ± 0.01 a	3.92 ± 0.072 b	6	3.52 ± 0.72 a	1.88 ± 0.67 b
Ankistrodesmus spp.	6	3.56 ± 0.09	3.23 ± 0.07	6	3.82 ± 0.78 a	2.27 ± 0.81 b
Golenkinia sp.	6	3.17 ± 0.02	2.93 ± 0.05	6	—	—
Planktosphaeria sp.	6	2.62 ± 0.07	2.37 ± 0.05	6	—	—
Coelastrum sp.	6	—	—	6	3.84 ± 0.79	3.47 ± 0.71
Microcystis sp.	6	2.68 ± 0.11	2.55 ± 0.11	6	4.26 ± 0.87	4.31 ± 0.88
Merismopedia sp.	6	—	—	6	3.64 ± 0.75	2.35 ± 0.83
Diatoms	6	2.45 ± 0.05	2.26 ± 0.03	6	3.69 ± 0.75	3.38 ± 0.69

the quadratic relationship between POC levels of green algal and cyanobacterial waters and filtration rates was 0.82 and 0.52, respectively (Fig. 1). The intercepts and parameter coefficients describing filtration rates were significantly different between the two water supplies. Filtration rate of POC by mussels provided green algal water peaked at 511 mg C/kg wet tissue per h at 28 mg C/L. The data from the cyanobacterial experiments does not permit a similar conclusion; however, it is anticipated filtration rate would peak at a lower POC level.

Discussion

The taxonomic make-up of the PAS algal community had a profound effect on *E. complanata* filtration rate. For example, the mean filtration rates of *E. complanata* in green algal water were significantly greater than in cyanobacterial water at 7 of the 8 flow rates, and significant decreases in algal abundance, via mussel filtering activity, were observed with only green algal taxa *Scenedesmus* and *Ankistrodemus* (Tables 1, 2). The size of *Scenedesmus* (1–4 cell stacks, 3–10 μm diameter and 7–12 μm long) and *Ankistrodesmus* (crescent shaped, 3–10 μm diameter) was similar to the size of lake seston (3.17–5.04 μm diameter) filtered at a maximum rate by *E. complanata* (Paterson 1986). *E. complanata* effectively reduced *Chlorella* (a sphere 6–12 μm diameter), a similar-sized algae in a sewage lagoon algal community (Helfrich et al. 1995).

TABLE 2. *Filtration rates of particulate organic carbon (mg C/kg wet tissue per h) of green algal and cyanobacterial waters within the temperature range of 23–27 C. Those means not sharing lowercase letters within rows and uppercase letters within a column are significantly different.*[1]

Flow rate (L/min)	Green algal water mean ± SE	Cyanobacterial water mean ± SE	Total mean ± SE
0.1	57.5 ± 3.6 a	15.3 ± 0.5 a	39.4 ± 8.7 A
0.2	99.8 ± 11.2 a	17.9 ± 0.2 b	64.7 ± 17.6 A
0.6	159.7 ± 13.4 a	43.1 ± 1.0 b	109.7 ± 24.6 B
1.0	214.0 ± 3.9 a	60.1 ± 0.9 b	148.0 ± 31.2 B
1.5	258.5 ± 6.4 a	104.4 ± 33.7 b	192.5 ± 33.8 C
2.0	323.8 ± 43.9 a	71.8 ± 0.6 b	215.8 ± 56.0 CD
2.5	514.2 ± 36.1 a	127.7 ± 37.8 b	348.5 ± 81.7 E
3.0	412.0 ± 8.9 a	54.7 ± 1.0 b	260.2 ± 71.8 D
Total	307.0 ± 33.3 a	80.9 ± 13.3 b	

[1] $F_{\text{flow rate}} = 42.04$, df = 7, $P = 0.0001$; $F_{\text{taxa}} = 338.27$, df = 1, $P = 0.0001$; $F_{\text{flow rate} \times \text{taxa}} = 18.64$, df = 7, $P = 0.0001$.

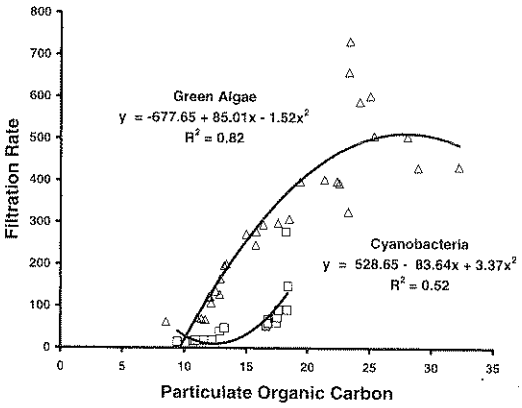

FIGURE 1. *Mean filtration rates (mg C/kg wet tissue per h) versus mean particulate organic carbon levels (mg C/L) from experiments using green algal (triangles) and cyanobacterial (boxes) water.*

Microcystis, the most abundant cyanobacterium in the PAS samples, was not filtered by *E. complanata* (Table 1). Zebra mussels, *Dreissena polymorpha* filtered *Microcystis aeruginosa* as single cells (4 μm diameter) over larger green algal taxa (Baker et al. 1998) but were ineffective in controlling large, gelatinous colonies of *Microcystis* (Lavrentyev et al. 1995). Although *Microcystis* may occur as single cells, it was usually encountered as the 40–50 μm diameter colonies with mucus envelope in PAS units (S. Davis, Clemson University, personal communication). In addition to the large size of colonial *Microcystis,* toxic metabolites may be produced by some cyanobacteria, limiting their utilization by mussels (Buttner and Heidinger 1981). Both chemical and physical aspects of *Microcystis* may have affected filtration by *E. complanata* in this study.

Filtration rate estimates vary widely among freshwater bivalve species. Based on calculations of data from Cahoon and Owen (1996), the maximum filtration rates were 2.74 and 1.48 mg C/kg wet tissue per h for *C. fluminea* and *E. waccamawnesis,* respectively. However, these species were exposed to extremely low seston concentrations (calculated as 0.07–1.5 mg C/L) of Lake Waccamaw, North Carolina, water. At higher calculated seston concentrations (1–20 mg C/L), *C. fluminea* filtration rates ranged from 233 to 270 mg C/kg wet tissue per h (Way et al. 1990). In comparison, the calculated mean filtration rate for the small clam *Sphaerium striatinum* was 55 mg C/kg wet tissue per h at 20 mg C/L (Hornbach et al. 1984). At a comparable concentration for green algal PAS water (i.e., 20 mg C/L), the filtration rate was 415 mg C/kg wet tissue per h for *E. complanata.* Some of the variation among filtration rate estimates may be explained by cell concentration and the algal taxa available to the bivalves while other variation is perhaps species specific. For example at sample POC concentrations of 20 mg C/L of green algal PAS water, *Pyganodon cataracta, E. icterina,* and *C. fluminea* had mean filtration rates of 380, 430, and 735 mg C/kg wet tissue per h, respectively (K. Stuart, Clemson University, unpublished data).

Filtration rate defined as mg C/kg tissue per h is a function of the volume of water filtered per time or filtration rate (mL/h) and cell concentration (mg C/L) (Foster-Smith 1975; Walz 1978). As cell concentrations increase, filtration rate is constant up to a concentration where a maximum amount of food is ingested (Foster-Smith 1975; Walz 1978; Winter 1978); then filtration rate decreases in such a manner that the ingestion rate remains constant (Winter 1978). Further increases in cell concentration results in pseudofeces production and eventually a reduction in both filtration and ingestion rates (Winter 1978). As a consequence of the above relationships, filtration rate of a filter feeder should decrease with further increasing cell concentration. This was the pattern exhibited by the filtration rate of *E. complanata* as POC concentrations reached 28 mg C/L and higher concentrations (Fig. 1).

The maximum green algal filtration rate of 511 mg C/kg wet tissue per h for *E. complanata* at 28 mg C/L is the equivalent to a daily feed rate of 2.5% dry weight/wet body weight. Nile tilapia *Orechromis nilo-*

ticus filtered 3.4% dry weight/wet body weight per day from green algae PAS water over a similar temperature range (Turker et al. 2000). The highest average filtration rate (128 mg C/kg wet tissue per h at 2.5 L/min) for *E. complanata* with cyanobacteria PAS water was only equivalent to 0.5% dry weight/wet body weight per day. At 26 C Nile tilapia fed at a daily rate of 1.7% from water dominated by the cyanobacterial species *M. aeruginosa* (Dempster et al. 1995). One of the advantages to using tilapia as a filter feeder is its ability to filter cyanobacteria; however, tilapia do not survive below 15 C (Whitfield and Blaber 1976). In addition to effectively filtering green algae, *E. complanata* continues filtering algae at lower water temperatures than tilapia (Stuart et al., in press). This fact and that other mussel species may be more effective in controlling cyanobacteria (Helfrich et al. 1995) suggests that freshwater mussels represent potential candidates for biological controls of algal bloom in aquaculture settings.

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