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CONTROL OF SUSPENDED SOLIDS AND PHYTOPLANKTON WITH FISHES AND A MUSSEL[1]

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ABSTRACT: Filtering efficiency of the fathead minnow (*Pimephales promelas*), gizzard shad (*Dorosoma cepedianum*), carp (*Cyprinus carpio*), and a freshwater mussel (*Elliptio complanata*) was measured in field and laboratory trials to assess the ability of each species to control phytoplankton and suspended solid densities. All fish species tested were ineffective filterers and generally increased, rather than suppressed, algal and suspended solid concentrations. Filtering efficiencies of fish varied between −354 and 84 percent, depending on the size, shape, abundance, palatability, composition, and resistance to digestion of the particles. Because of poor filtering abilities, unpredictable feeding habits, and sensitivity to stress, the fish species examined are not effective biological controls in waste lagoons. In contrast, the freshwater mussel *Elliptio* was a highly effective control organism, averaging 66 percent filtering efficiency over a wide size range of algal and suspended particles. Filtration efficiency was positively correlated with mussel density. *Elliptio* was efficient at filtering small particles, which are particularly difficult to remove. Mean filtration rates ranged from 53 to 134 ml/mussel/h depending on the algal species consumed and algal densities (range 50-180,000 cells/ml) and 3 mg/L/mussel/h on suspended solids (range 14 to 112 mg/L). Water clarification was facilitated by both direct consumption and pseudofeces deposition. *Elliptio* and probably other mussel species can effectively control algae and suspended solids in wastewater lagoons and eutrophic lakes, if environmental conditions, especially dissolved oxygen levels, are suitable (>5 mg/L) for their survival.
(KEY TERMS: aquatic ecosystems; waste/sewage treatment; water quality; filter feeding; freshwater mussels; fish; algal control.)

INTRODUCTION

Stocking filter-feeding aquatic organisms, primarily planktivorous fish, zooplankton, and freshwater mussels, has been proposed as an economical method for controlling nuisance algal populations in recreational lakes (Shapiro and Wright, 1984), waste stabilization lagoons (Henderson and Wert, 1976; Weigmann, 1982; Henderson, 1983), and aquaculture ponds (Cremer and Smitherman, 1980; Smith, 1985; Laws and Weisburd, 1990). Using aquatic organisms to suppress excessive phytoplankton abundances in ponds and lakes is increasingly being viewed as a more acceptable alternative to costly herbicides and their potentially undesirable ecological consequences (Tucker and Boyd, 1978; Weigmann, 1982; Shapiro and Wright, 1984; Carpenter *et al.*, 1985). However, experiments to effect biological control of algal densities directly through the introduction of filter-feeding organisms or indirectly by suppressing populations of zooplanktivorous fish have proved inconclusive.

In certain biomanipulation experiments, stocking ranid tadpoles in Michigan waste stabilization ponds (Weigmann, 1982) or phytoplanktivorous fish (Carpenter *et. al.*, 1985) has enhanced rather than depressed total algal biomass. Stimulation of phytoplankton abundance has been attributed to the following: the differential filtering ability of some fish species which allow them to consume large (netplankton), but not small (nannoplankton) algae (Drenner *et al.*, 1984; Smith, 1985; Laws and Weisburd, 1990); a decrease in herbivorous zooplankton as a result of predation by planktivorous fish (Brooks, 1968; Lynch and Shapiro, 1981; Hulbert and Mulla, 1986); and nutrient regeneration and cycling by tadpoles (Weigmann, 1982) or fish (Lamarra, 1975; Meyer *et al.*, 1983; Laws and Weisburd, 1990). Differences in species composition, quality, palatability, and digestibility of the phytoplankton community (Porter, 1977) and variable light and nutrient levels further

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complicate predictions of the impact of biological control organisms.

Initial research to improve water quality and clarity focused largely on the potential of exotic filter-feeding fish such as silver carp *Hypophthalmichthys molitrix*, bighead carp *Aristichtys nobilis*, and tilapia *Tilapia* sp. (Young *et al.*, 1983; Wilson *et al.*, 1984; Burke *et al.*, 1986; Leventer, 1987) or on molluscan species such as the Asiatic clam *Corbicula fluminea* and the zebra mussel *Dreissena polymorpha* (Buttner and Heidinger, 1981; Buttner, 1986; Reeders *et al.*, 1993). However, fisheries management agencies recognize the potential adverse ecological and economic impacts of non-native species, and so they legally constrain their introduction (Taylor *et al.*, 1984; Courtenay, 1992). The production of sterile hybrids and polyploids of these species is possible, but not always economical, and their food habits may differ from diploid, parental strains (Young *et al.*, 1983).

The purpose of this study was to assess the ability of North American freshwater fishes and a mussel species to effectively filter a wide range of naturally-occurring phytoplankton species and suspended solids of different abundances and sizes in laboratory and field trials in wastewater lagoons. The species used included: gizzard shad (*Dorosoma cepedianum*); fathead minnow (*Pimephales promelas*); Israeli carp, a genetic variant of the common carp (*Cyprinus carpio*); and a freshwater mussel, the eastern elliptio (*Elliptio complanata*). The overall objective was to assess the potential use of these species for algal control and water-quality management in eutrophic systems.

METHODS

The fish species selected as biological control agents in this study, although not obligate phytoplanktivores, do consume algae and suspended solids. Their consumption depends primarily on environmental conditions and sizes of suspended particles (Drenner *et al.*, 1986; Mummert and Drenner, 1986). Gizzard shad were collected by electrofishing in the Kanahwa River, Winfield, West Virginia (WV). Fathead minnows and common carp were purchased from a commercial hatchery in WV. Fish were held on artificial diets for several weeks in recirculating systems at the Department of Fisheries and Wildlife Sciences' Aquaculture Center, Virginia Tech, Blacksburg, Virginia (VA), prior to testing. *Elliptio* is a large-bodied (30-125 mm, 0.6-15 g), widely distributed, and locally abundant unionid species with a high filtration rate (Patterson, 1984). Those used in this study were collected from the James River, Scottsville, VA.

Laboratory filtering trials were conducted during July-October 1987 in eight 40-L glass aquaria holding 10 L of whole water samples containing natural phytoplankton communities collected from a hypereutrophic pond (municipal wastewater), Montgomery County, VA. Water samples were screened through a 30µ filter to exclude large zooplankton. Water temperature was maintained between 21 to 22°C. Light was provided by florescent lamps on a 14-h light:10-h dark cycle. Phytoplankton cells were kept in suspension by continuous aeration. Shell length (sl) and wet weight (ww) of *Elliptio* and total length (tl) of fish was measured. *Elliptio* (98 mm sl, 92 g ww), fathead minnows (50 mm tl, 1 g wet weight), and gizzard shad (30-125 mm tl 8 g ww) were stocked at densities averaging 2.5, 3.3, and 1.7 per L, respectively, during the four, five, and six trials held for each species, respectively, and held under test conditions for 24 h. Carp were unavailable for the laboratory trials and gizzard shad were not used in the field tests.

Field trials were conducted during October 1987 in sixteen 19-L plastic enclosures, which contained 7 L wastewater pond effluent and were suspended 4 cm below the surface in a municipal wastewater treatment pond at the New Castle wastewater treatment facility, Craig County, VA. The relatively high nutrient levels in the pond stimulated a continuous algal bloom. Dissolved oxygen in the pond was supplied by submerged aerators, operated automatically for at least 15 min/h. Phytoplankton and solids were kept in suspension and available to fish and mussels by continuous aeration in the enclosure similar to the laboratory trials. *Elliptio* (101 mm sl, 118 g), fathead minnows (63 mm tl, 3 g), and common carp (166 mm tl, 79 g) were stocked into enclosures at random at densities of 1.1, 8.6, and 0.4 per L, respectively, each with four replicates, and permitted to filter for 60 h.

Filtering efficiency was calculated as the percent difference between pre- and post-filtering concentrations of phytoplankton cells or suspended solids over the experimental period (adjusted for changes in the controls). Filtration rate (mean volume of water cleared of suspended particles per unit of time) was calculated by differences in cell concentrations through time. To determine filtering rates, aquaria in the laboratory were filled with pond wastewater containing dense levels of suspended solids (>50 mg/L) and algal populations (>100,000 cells/ml) and were stocked at densities of either eight mussels (104 mm sl, 123 g) per aquaria or no mussels (reference enclosures). Water samples (100 ml) for plankton and solids analyses were collected at 0, 2, 4, 8, 16, and 24 h after stocking. Dense blooms of bluegreens were enumerated by counting colonies rather than individual cells. Regression analysis was used to calculate filtering rates.

The influence of three mussel stocking densities (0.6, 1.1, and 1.7 mussels/L) on suspended solids and algal populations was examined in three consecutive 24-h laboratory and four 24-h field trials. In the laboratory, duplicate aquaria filled with wastewater suspensions were randomly assigned one of the three mussel densities or were unstocked as references. In the field trials, triplicate enclosures were randomly stocked with one of the three mussel densities or kept as unstocked controls.

Mussels were held through winter in two rectangular cages (55 x 55 x 60 cm) anchored at 1 m depth in the New Castle wastewater facility from July 1988 to June 1989. Annual growth and survival of mussels was monitored on October 20, 1988, and again on June 28, 1989. Ninety-two mussels were individually measured (SL), wet-weighed (nearest g), and marked by gluing a numbered plastic tag on the shell. Growth was determined by the increase in shell length and body weight over the 11 months.

One-way analysis of variance (ANOVA) model and Duncan's multiple range test were used to test for differences through time in algae and suspended solids concentrations between unstocked reference and stocked treatment aquaria in laboratory and field tests. Analysis of variance was calculated on pooled data to test differences in algae and suspended solid levels through time as a function of mussel stocking densities. Regression analysis was used to calculate mussel filtering rates through time, and t-tests were used to compare regression coefficients between the stocked and unstocked aquaria. The threshold for detecting statistical significance was $p < 0.05$ for all tests.

RESULTS

Filtering Efficiency

E. complanata was particularly effective in reducing total suspended solids, which consisted largely of phytoplankton cells, in laboratory trials (Table 1). Filtering efficiency of *Elliptio* at initial suspended solids levels of 112 mg/L averaged 66 percent (range 58-76 percent). Accompanying increases in water clarity and the deposition of pseudofeces were readily apparent in aquaria stocked with mussels during the 24-h trials. In contrast to *Elliptio,* fathead minnows and gizzard shad increased suspended solids concentrations by an average of 4 percent (range 2-12 percent) and 45 percent (11-70 percent), respectively, within a 24-h period.

Results in the field trials were consistent with those obtained in the laboratory. *Elliptio* substantially reduced suspended solids by 121 percent relative to the control enclosures in the New Castle wastewater treatment pond. This was nearly twice the filtering efficiency exhibited by mussels in the laboratory.

Fathead minnows, gizzard shad, and carp were ineffective filterers, and enhanced suspended solids concentrations with efficiencies from –4 to –354 percent in most lab and field trials (Tables 1, 2). Changes in algal densities and solids in most stocked aquaria were not significantly different ($p > 0.05$) from those in the reference aquaria. The only notable reduction in phytoplankton occurred in field enclosures stocked with carp when the algal community was almost a monoculture of *Chlorella* (Table 2).

TABLE 1. Mean Net (adjusted for controls) Filtering Efficiency (percent) and Standard Deviation (sd) of the Freshwater Mussel *Elliptio* and Two Fish Species on Suspended Solids (SS) in 24 h Laboratory and 60 h Field Trials. Asterisk denotes significantly different ($p < 0.05$) filtering efficiency from controls.

Species	Mean Density (filterer/L)	Pre-Filter SS (mg/L)	Post-Filter SS (mg/L)	Net Filtering Efficiency Percent (sd)
		Lab		
Elliptio	3.4	112 (2)	62 (26)	66 (5)*
Minnow	0.5	117 (43)	162 (83)	–4 (3)
Shad	1.4	84 (19)	112 (29)	–45 (14)*
		Field		
Elliptio	1.1	15 (2)	14 (1)	121 (5)*
Minnow	8.6	16 (2)	92 (9)	–354 (42)*
Carp	0.4	15 (1)	62 (17)	–210 (16)

TABLE 2. Mean Net (adjusted for controls) Filtering Efficiency (percent) and Standard Deviation (sd) of *Elliptio* and Two Fish Species on the Three Dominant Phytoplankton Taxa in Laboratory and Field (chlorophyta only) Trials.

	Mean Net Filtering Efficiency (percent)			
Species	**Anacystis (Lab)**	**Oscillatoria (Lab)**	**Chlorophyta (Lab)**	**Chlorophyta (Field)**
Elliptio	64 (23)	37 (27)	56 (26)	307 (15)
Minnow	–3 (7)	10 (6)	0	–20 (15)
Shad/Carp	–9 (7)	–21 (8)	–12 (4)	84 (36)

Selective Filtration

As expected, phytoplankton cells of the three major taxa comprised the majority of the suspended solids in samples from the hypereutrophic ponds (Table 2). In the laboratory trials, *Anacystis* (Cyanophyceae), a colonial bluegreen (30-250 μm/colony) comprised of small cells enclosed in a gelatinous matrix, was the dominant taxa, consisting of 48 to 93 percent of the total cell counts (averaging 3 million cells/ml). Other minor taxa included the filamentous bluegreen *Oscillatoria* (< 12 percent of cells) and a diversity of small (6-30 μm) Chlorophyceae (green algae), including *Scenedesmus, Ankistrodesmus, Chlorella, Closterium,* and *Phacus* (< 5 percent of cells).

The composition of the algal community, cell densities, and the suspended solids loads in the New Castle Sewage Treatment Plant pond during the field trials were considerably different from that in the laboratory trials (Table 2). In the field trials, the pond algal community was dominated by *Chlorella,* small (6-12 μm) spherical cells representative of stabilization ponds at this season (Dinges, 1982). The mean initial concentrations of algae (178,000 cells/ml) and suspended solids (15 mg/L) were substantially lower than those of 400,000 cells/ml and 75 mg/L in most laboratory trials.

Elliptio consistently reduced all algal taxa present in both laboratory and field trials (Table 2). Filtering efficiencies varied considerably depending on the algal taxa, averaging 64, 37, and 56 percent in the laboratory for *Anacystis, Oscillatoria,* and *Chlorella,* respectively, and as much as 307 percent for green algae in the field trials. The mussel *Elliptio* filtered small *Chlorella* cells and removed the larger *Oscillatoria* cells less effectively. Filtration efficiency for the fish species tested was low, except in one instance when carp in the field trials were effective (84 percent efficiency) in reducing Chlorophyceae populations.

Effect of Mussel Density

Filtering efficiency of *Elliptio* was directly related but not proportional to filtering intensity (density of mussels stocked). In the laboratory trials, the highest filtering efficiencies (> 50 percent) consistently occurred at the high stocking density, 1.7 mussels/L, whereas the lowest efficiencies corresponded to the low stocking density, 0.5 mussels/L (Table 3). However, filtering efficiency per mussel was not directly proportional to stocking density; tripling the number of mussels stocked resulted in only a doubling of filtering efficiencies. Filtering efficiency of *Elliptio* was similar for both *Anacystis* and Chlorophyceae cells over all three stocking densities, and equivalent to previous laboratory filtering trials (Table 2) at medium filtering intensity (1.1 mussel/L).

TABLE 3. Mean Filtering Efficiencies (percent) and Standard Deviation (sd) of Three Mussel Densities (0.6, 1.1, 1.7 mussels/L) on Suspended Solids (mg/L) and Dominant Phytoplankton Taxa in Laboratory and Field Trials.

	Mussel Stocking (filtering densities)		
	Low (0.6/L)	**Medium (1.1/L)**	**High (1.7/L)**
Laboratory Trials			
Suspended Solids (mg/L)	37[a] (6)	51[ab] (3)	58[b] (6)
Anacystis (cells x 10^4)	28[a] (4)	40[a] (4)	54[b] (3)
Chlorophyta (cells x 10^4)	28[a] (9)	41[a] (8)	54[b] (7)
Field Trials			
Suspended Solids (mg/L)	47[a] (8)	49[a] (12)	61[a] (8)
Chlorophyta (cells x 10^4)	57[a] (4)	83[b] (3)	92[b] (2)

[a,b]In-row superscripts with the same letter are not significantly different ($p > 0.05$).

In the field, filtering efficiencies of *Elliptio* also were density dependent and generally higher than in the laboratory trials. Filtering efficiency on green algae at the high and intermediate mussel stocking densities was exceptional, exceeding 80 percent. Differences between laboratory and field filtering efficiencies probably reflected the relatively lower total cell concentrations in the field (14 cells/ml) versus those in the laboratory (109 cells/ml), greater volumes in the field (10.5 L) versus the lab (7L), differences in the phytoplankton community composition between the laboratory (84 percent bluegreens, 16 percent greens) and field (100 percent greens), and variations in environmental conditions.

Mussel Filtration Rates

Net (adjusted for controls) suspended solids reduction by *Elliptio* over 24 h in laboratory trials was 47 percent, but most (>50 percent) of the decline occurred during the first 8 h (Figure 1). Mean filtration rate was high initially, averaging 2.6 mg/L/h in the first 2 h, but declined through time, averaging only 1.1 mg/L/h in the last hour of the 24-h trial. The following regression equations characterized the time-dependant reductions by mussels: (1) suspended solids, (2) *Anacystis* cells, and (3) *Scenedesmus* cells.

(1) ln Suspended Solids = –0.042 T + 3.912
($r^2 = 0.91$)

(2) ln *Anacystis* cells = –0.043 T + 11.332
($r^2 = 0.83$)

(3) ln *Scenedesmus* cells = –0.056 T + 10.998
($r^2 = 0.67$)

Anacystis concentrations at initial densities near 100,000 cells/ml were reduced through the 24-h trial by 46 percent, but most (50 percent) of the reduction occurred during the first 4 h (Figure 1). The mean filtration (clearing) rate for *Anacystis* was 54 ml/h in the first 2 h and declined thereafter.

Scenedesmus populations at initial densities near 82,000 cells/ml were reduced over the 24 h trial by 55 percent, but the majority (50 percent) of the filtration occurred during the first 4 h (Figure 1). The mean filtration rate for a near monoculture of *Scenedesmus* was 134 ml/h in the first 2 h and declined through time.

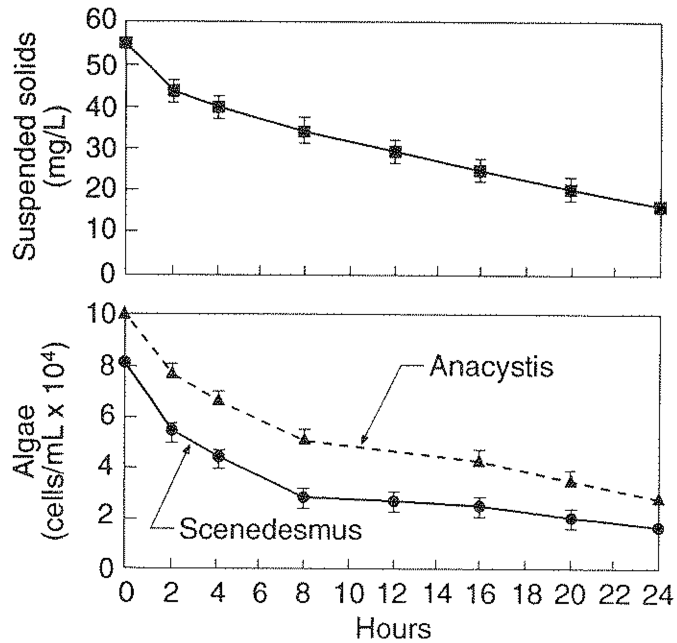

Figure 1. Mussel Filtration Rate as a Function of Mean Suspended Solids and Algae Cells (*Anacystis* and *Scenedesmus*) in Laboratory Trials over 24 h.

Survival and Growth

Survival rates of *Elliptio* during July 1988 to June 1989 in the wastewater treatment pond averaged 80 percent (range 65 to 95 percent). Mortality was the greatest during the winter months when surface water temperatures approached 9°C and phytoplankton population densities were minimal. Mortality did not appear size-specific, and the mussels were similar in size.

Mean growth rate of mussels (mean sl 103 mm) was 0.5 g/day during the summer and 0.3 g/day in the fall, then declining to negative growth (weight loss) over winter. Mean individual weight loss over winter was 15 percent body weight (range 5 to 24 percent).

Survival of fish during holding, transportation, and the field and laboratory filtering trials was generally high, except for that of gizzard shad (60 percent), which was substantially lower than that of fathead minnows (96 percent) and carp (95 percent).

DISCUSSION

Compared to the freshwater mussel, *Elliptio complanata,* the three native fish species tested in this study were less effective as biological controls of phytoplankton and suspended solids. Although fathead minnows have been reported to consume some (<25 percent) algae (Coyle, 1930; Isaak, 1961), zooplankton were their primary prey in this study and another (Held and Peterka, 1974). Our results show that fathead minnows have little or no direct effect on suspended solids and can even stimulate (>64 percent) solid levels (Hall and Shelton, 1983), as in our study (>345 percent). Similarly, the potential of gizzard shad to filter-feed on suspended matter is overrated. Our results verify those of Drenner *et al.* (1984), Drenner *et al.* (1986), Mummert and Drenner (1986), and Threlkeld *et al.* (1987) in that gizzard shad are ineffective filterers, particularly on small algae (<100 μm), which are characteristic of eutrophic, wastewater systems. Carp consume some green algae (Jester, 1974) and did reduce *Chlorella* concentrations in our field trials, but total algal and suspended solids concentrations significantly increased in the presence of carp in our study and others (Orgeron, 1976), perhaps because of accelerated recycling of nutrients by fish through excretion or physical resuspension of benthic detritus (Lamarra, 1975; Drenner *et al.,* 1986).

Exotic species such as the silver carp and *Tilapia* species are more effective filterers (Dinges, 1982; Spataru *et al.,* 1982; Henderson, 1983; Leventer, 1987) than the native fish we selected, but their importation is restricted by most state fisheries agencies. Moreover, fish alone may not provide reliable control in wastewater stabilization ponds because phytoplankton species in hypereutropic systems are frequently too small (nanoplankton) to filter effectively or too large (filamentous or colonial) and unpalatable because of their noxious chemical defenses or gelatinous sheaths. Fish may stimulate rather than suppress algal growth by preying on zooplankton grazers, excreting soluble nutrients into the water column, or resuspending nutrient-rich bottom sediments.

The highly efficient filtering ability of *Elliptio* on suspended particles of various species, sizes, and shapes and over a diversity of environmental conditions suggests that this species and probably other freshwater mussels are good candidates for biological controls capable of regulating suspended solids and phytoplankton densities in eutrophic lakes, ponds, and wastewater systems. Although freshwater mussels have received little attention as effluent clarifiers in wastewater lagoons and recreational lakes, we and others (Jorgensen, 1975; Morton, 1983; Kryger and Riisgard, 1988) have demonstrated that they can consume a diversity of algal species and particle sizes.

In our study, biological control of suspended solids and algae by *Elliptio* was accomplished by two mechanisms. Suspended particles were either (a) accepted as food items, consumed and digested; or (b) collected, packaged, and expelled as pseudofeces. Both processes removed suspended materials, facilitated clarification, and enhanced biodeposition. The sum of both processes was calculated as filtering efficiency; no attempt was made to quantify the impact of consumption and deposition independently. Substantial pseudofeces production was evident in certain of the laboratory trials, particularly those with dense concentrations of large particle sizes. Corresponding observations (Kirby-Smith, 1972; Winter, 1978; Morton, 1983; Patterson, 1984; Anderson *et. al.,* 1994) suggest that an excess of large particles may interfere with the particle-sorting ability of bivalves, depress filtration and consumption, but increase biodeposition. Although water clarification via biodeposition may be temporarily enhanced, nutritional stress to mussels may ultimately result in diminished clarification.

Efficient filtration appears to be a function of particle size and density (Morton, 1983) and probably other environmental and chemical characteristics, such as water temperature, dissolved oxygen concentration, and turbidity (Alexander *et al.,* 1994). Increased clarification in our field experiments may be attributed to lower food densities (eight times less dense) dominated by small, single-cell *Chlorella* which may be more manageable and palatable than the large (50 to 250 μm) gelatinous-sheathed, *Anacystis* colonies. Toxic metabolites produced by some bluegreens, including *Anacystis,* can inhibit invertebrate filtration (Porter, 1977) and diminish the mussels' utilization (Buttner and Heidinger, 1981). Clearly, mussel filtration is affected by the quality and the quantity of the food particles available, but despite suboptimal sizes, densities, and species present in the wastewater tested, filtering efficiency of *Elliptio* was high, averaging 37 to 300 percent.

Filtration Rates

Estimated filtration rates (mean volume of water cleared of suspended particles per unit of time) of freshwater mussels are highly variable, reflecting differences in environmental conditions and experimental methods, particularly the densities, sizes, and species of suspended cells and mussels. High variability in filtration rate is frequently evident even within single experiments (Ward and Aiiello, 1973; Lauritsen, 1986a, b). Several authors have reported discontinuous daily and seasonal filtration (Walz, 1978; Benedens and Hinz, 1980) and differential acclimation (Mayzaud and Poulet, 1978) to influence filtration rates.

Maximum filtration rates of native mussels are nearly comparable to those of exotic species such as the zebra mussel *Dreissena* or the Asiatic clam *Corbicula,* which are frequently suggested as biological controls for suspended algae. High filtering rates of 150-580 ml/mussel/h (Gusseman, 1978), 357-632 ml/mussel/h (Patterson and Cameron, 1985), and 300 ml/mussel/h (Lewandowski and Stanczykowska, 1975) reported for large unionid mussels are close to those of 347 ml/mussel/h (Buttner and Heidinger, 1981), 587-770 and 278-782 ml/mussel/h (Lauritsen, 1986a, b) estimated for *Corbicula,* and the 40-75 ml/mussel/h (Reeders *et al.,* 1989) and 286 ml/mussel/h (Kryger and Riisgard, 1988) calculated for *Dreissena.* It is important to note that, in contrast to native mussels, *Corbicula* and *Dreissena* can aggregate in high densities, and more effectively filter smaller phytoplankton.

Mean filtration rates of 53-134 ml/mussel/h estimated for *E. complanata* in this study were similar to values reported for *Elliptio* and other species. Patterson (1984, 1986) estimated that the maximum filtration rate for *Elliptio* on food particles at optimum densities (<9,000 cells/ml) and size (3-4 μm) was 400 ml/g (dry weight mussel tissue)/h, but decreased to 12-70 ml/g/h at proportionally small increases in particle sizes (>10 μm) and concentrations (13,000 cells/ml). In comparison, filtration rates for *Elliptio* in our study were equivalent at 21-53 ml/g (dry weight mussel tissue)/h on small algal cells (>10 μm in size) and densities (> 80,000 live cells/ml). Although enhanced filtration rates for *Elliptio* may be expected under less eutrophic conditions than the primary sewage lagoon waters used in the laboratory experiments, our estimated filtration rates are probably representative of the filtering capacity of this species in wastewater suspensions that are rich in suspended solids (>55 mg/L) and relatively large algae. Enhanced filtration rates may be expected in typical lake waters with reduced densities of small, readily consumable algal cells.

A complicating factor in calculating filtering efficiencies and rates is estimating the relative amount of particle consumption to pseudofeces production and the potential for particle resuspension. Because we did not distinguish between consumption and deposition, and because resuspension of deposited pseudofeces was likely (under the vigorous aeration necessary in aquaria), our filtering efficiencies and rates probably are underestimates.

Another problem in accurately estimating filtering efficiencies and rates is the relationship between food particle density and mussel filtering intensity. In this study and another (Coughlan, 1969), suspended particles subjected to filtering by mussels declined logarithmically through time. Absolute reductions were greatest during the first few hours. Subsequent declines result presumably because constant filtering rates cause lower particle densities which, in turn, mediate reduced filtering intensity. Filtering efficiencies and rates, then, are subject to variation, depending on particle density, the duration of the filtering trial, and filtering consistency. Cyclic and discontinuous filtering by mussels can strongly bias filtering efficiency estimates.

Management Implications

Our results suggest that *E. complanata,* and probably other species of native freshwater mussels, are efficient filterers that can be stocked in wastewater lagoons and eutrophic lakes to control phytoplankton and suspended solids loads. Although a wide variety of environmental and species-specific (size-specific) characteristics of both mussels and their food items affects filtering capacities and rates, we found that even under suboptimal conditions, mussels filter phytoplankton and suspended solids at relatively high rates, promoting clarification and offering an alternative to applying herbicides, such as copper sulfate, which can be toxic to invertebrates and, notably, to juvenile mussels at low concentrations (Jacobson *et al.,* 1993).

In eutrophic lakes and wastewater lagoons subject to wide fluctuations in oxygen, ammonia, and other critical parameters, basic physiological requirements of freshwater mussels must be satisfied. Although the critical oxygen threshold for freshwater mussels is relatively low (Fuller, 1974; Lewis, 1984), anoxic conditions that prevail in the benthic portion of wastewater lagoons and eutrophic lakes are not suitable for sustaining mussels. Supplemental aeration to maintain dissolved oxygen levels >4 mg/L and suspending mussels in floating cages near the surface were necessary strategies to minimize diel or seasonal oxygen depletion and promote mussel survival, which averaged 80 percent during the year in the wastewater pond. Sublethal effects of ammonia on mussel filtration have not been examined, but high concentrations of unionized ammonia are characteristic of eutrophic ponds, and levels lethal to freshwater bivalves range from 0.24 mg/L (Goudreau, 1988) to 1.29 mg/L (West, 1985). Relatively high pH and water temperatures common in wastewater lagoons further increase the availability of toxic unionized ammonia (Emerson *et al.,* 1975).

Mussel stocking densities used in this study were relatively high for natural populations, averaging 31, 63, and 93 mussels/m^2, respectively, in the three treatment levels in the lab trials, and 75, 151, and 226 mussels/m^2 in the field trials. Natural densities of *Elliptio* range from 0.1 mussels/m^2 (Strayer *et al.*, 1981) to 60 mussels/m^2 (Fisher and Tevesz, 1976).

Increasing densities of *Elliptio* facilitated clarification in both laboratory and field trials, although particle removal expressed on a per mussel basis declined with increasing numbers of filterers. This suggests that individual filtration efficiency may be inhibited by increasing mussel densities beyond some optimal number per volume. At high mussel densities, increased competition, depressed oxygen levels, or other environmental conditions may result in reduced filtering. Alternatively, density-dependent filtration may confer some physiological advantage. Patterson (1983) observed a decline in oxygen consumption as *Elliptio* densities in a respirometer increased, and speculated that increased water pumping enhanced respiration and decreased metabolic costs in aggregated distributions.

Despite many sources of variability, we conservatively estimate a stocking density of 100,000 to 300,000 mussels/pond, suspended in the photic zone and filtering within the ranges (53-134 ml/mussel/h) measured in this study, would provide adequate biological control to meet effluent discharge standards (suspended solid load <30 mg/L) at the New Castle Wastewater Treatment Plant during the critical summer period. This assumes an average filtration rate of 2.4 L/mussel/d clearing the upper 7.6 cm in depth in a one surface-acre pond (volume 308,370 L) and a maximum loading rate of 379,000 L/d. Phytoplankton production in eutrophic ponds generally is limited to the upper few centimeters of surface waters because of light attenuation and the self-shading of algal blooms.

Beneficial characteristics of mussels as biological controls in eutrophic waters include their relatively high filtration rates on small phytoplankton and solids, efficient water clarification either by direct consumption or pseudofeces deposition, tolerance of wide variations in water quality, and ease in transportation and stocking, adaptability to suspended cage culture, and longevity. A greater understanding of the feeding preferences and performance of different species and sizes of freshwater mussels under varying physicochemical conditions is essential before they can be successfully stocked as reliable biological controls in wastewater systems and eutrophic lakes nationwide.

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