

## The Effects of Intermittent Exposure to Suspended Solids and Turbulence on Three Species of Freshwater Mussels

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### ABSTRACT

*A laboratory experiment was performed to evaluate the effects of intermittent suspended solids exposure on the unionid clams *Quadrula pustulosa*, *Fusconaia cerina* and *Pleurobema beadleanum*. Intermittent impacts of this type are important effects of commercial navigation traffic in freshwater. Clams were cyclically exposed to turbulence alone or accompanied by 600-750 mg litre<sup>-1</sup> of suspended inorganic solids for 9 days. Clams exposed to suspended solids every 3 h reduced their metabolic rate but did not shift from the mainly protein based catabolism of controls. Feeding impairment was apparently compensated for by a reduction in metabolic demand. Conversely, clams exposed every 0.5 h to suspended solids shifted to virtually complete reliance on non-protein body stores as indicated by O:N values averaging 197.*

### INTRODUCTION

Increased levels of turbidity (suspended solids) and turbulence are a common result of Man's use of aquatic systems, particularly in dredging and navigation operations (Wilber, 1983). These increases in turbidity and turbulence often have deleterious impacts on aquatic organisms and their

role in disrupting aquatic communities has come under increasing scrutiny in recent years (Moore, 1977). It has also become apparent that there is considerable variation in response to increased turbidity among different groups of aquatic animals (Moore, 1977; Wilber, 1983).

Among the organisms most directly affected by increased levels of turbidity and turbulence are filter-feeders such as bivalves (Widdows *et al.*, 1979). These organisms are often the major primary consumers in many aquatic habitats (Russell-Hunter, 1983) and are frequently commercially important. Most of the impact work on turbidity effects has been carried out on marine bivalves (Wilber, 1983). However, the impact of navigation and dredging operations in freshwater on unionid mussels has become a concern in the United States. Most turbidity and turbulence studies have involved the continuous exposure of the test animals to constant turbidity or turbulence levels (Moore, 1977). Navigation impacts, however, are more likely to expose aquatic habitats intermittently to high turbidity and turbulence and for this reason the impact of navigation effects is often discounted.

The major effect of increased levels of turbulence and turbidity on bivalves is to reduce the rate and/or efficiency of feeding (Moore, 1977). Unfortunately, evaluating these parameters in the field to assess navigation and dredging impacts is very difficult. However, reduced feeding rates result in long-term physiological changes in poikilotherms which can be evaluated more easily in the field. Typically, starving or semi-starved poikilotherms show changes in metabolic rates (Barnes *et al.*, 1963; Bayne, 1973; Logan & Epifanio, 1978; Cappuzo & Lancaster, 1979; Dawirs, 1983; Page, 1983) and shifts to alternate catabolic substrates (Ansell & Sivadas, 1973; Bayne, 1973; Ikeda, 1977; Russell-Hunter *et al.*, 1983). Such shifts have been shown to be useful indicators of environmental stress in molluscs (Widdows, 1978; Bayne *et al.*, 1979, 1981).

This study reports on the physiological changes caused by the intermittent, cyclic exposure to turbidity and relative levels of turbulence in three species of freshwater mussels, *Quadrula pustulosa*, *Fusconaia cerina* and *Pleurobema beadleanum* (Mollusca: Bivalvia: Unionidae). Such information is needed to produce useful criteria for evaluating the impact of dredging and navigational operations on natural freshwater mussel populations.

## MATERIALS AND METHODS

*Quadrula pustulosa* (Lea), *Fusconaia cerina* (Conrad) and *Pleurobema beadleanum* (Lea) (Order Schizodonta: Family Unionidae) represent genera

that occur throughout the Mississippi River drainage and many other rivers that drain into the Gulf of Mexico. Clams used in our experiments were collected on 5 July 1983 from two adjacent riffles in the Tangipahoa River in southwestern Mississippi. On 5 July, the water at the site had a temperature of 21°C, calcium hardness of 3.2 mg litre<sup>-1</sup> Ca<sup>2+</sup>, pH of 6.8 and turbidity of 8.9 NTU. In general, the Tangipahoa is a clear, rapid-flowing river (Miller *et al.*, 1986). All clams were collected from gravelly sands at water depths ranging from 0.25 to 1.0 m. Approximately 200 individuals were collected and brought immediately to the laboratory.

On 6 July, the clams' shells were cleaned of aufwuchs and gradually introduced to aerated and dechlorinated Vicksburg city tap water (well source: 18 mg litre<sup>-1</sup> Ca<sup>2+</sup>) and maintained at 20°C. During both this laboratory acclimation period and subsequent experiments, clams were fed a suspension of Fleischmann's yeast. On 9 July, an identification number was scratched on the shell of each clam using a carbide scribe. The 52 *Q. pustulosa*, 68 *F. cerina* and 50 *P. beadleanum* were each then divided up into four groups of approximately equal number and size distribution.

Starting on 9 July (day 0), these four groups of each species were subjected to one of four treatments (at 20°C).

(i) Infrequent turbulence and suspended solids. Clams were exposed to suspended solids (average peak of 750 mg litre<sup>-1</sup>) created by low levels of turbulence maintained for 7 min every 3 h.

(ii) Infrequent turbulence. A control for the previous experimental treatment where the clams were exposed to low levels of turbulence, but not suspended solids, for 7 min every 3 h.

(iii) Frequent turbulence and suspended solids. Clams were exposed to suspended solids (average peak of 600 mg litre<sup>-1</sup>) created by low levels of turbulence maintained for 7 min every 0.5 h.

(iv) Frequent turbulence. A control for the third experimental treatment where the clams were exposed cyclically to low levels of turbulence but not suspended solids for 7 min every 0.5 h.

The four groups were exposed to their respective treatments in glass aquaria (25 × 51 × 20 cm) containing 30 litres of constantly, but gently, aerated water. Two tanks were used for each group to prevent crowding and to replicate each treatment. The turbulence necessary to cyclically suspend the solid material (Vortex diatomaceous earth) in each experimental tank was produced by two centrifugal water pumps (Aqualogy model 10-120). Each pump stayed on for 5 min and were 2 min out of phase with each other to keep diatomaceous earth from permanently settling on quiescent areas on the bottom of the tanks. On-off times for these pumps were controlled by an electronic timer. The diatomaceous earth was washed seven times before being added to the tanks to remove most of the very fine particles (not settled

in 30 min). Thus, solids to be resuspended consisted largely of intact diatom tests. Peak concentrations of suspended solids in samples from all tanks were monitored using a Bausch and Lomb model 710 spectrophotometer at a fixed wavelength (550 nm) so that diatomaceous earth cleared by clams could be determined by comparing sample absorption to an appropriate standard curve.

Following turbulence, the suspended solid concentrations in treatments (i) and (iii) reached their peak of 750 and 600 mg litre<sup>-1</sup>, respectively, and fell to 10% of that peak value within 15 min after the end of turbulence. Minimum suspended solids concentrations for treatments (i) and (iii) were 25 and 125 mg litre<sup>-1</sup>, respectively. The inability to get zero levels of suspended solids between successive episodes of turbulence is a general problem in turbidity studies (Moore, 1977). The peak suspended solids concentrations used in this study would be expected only in areas affected by dredging and navigation impacts (Wilbur, 1983; Robinson *et al.*, 1984).

To evaluate the maximum potential food ingestion rates of the 170 clams, their ability to clear yeast from a suspension of known concentration was evaluated at 20°C on day 4. Each clam was placed in 100 ml of water to which the equivalent of 8 mg of dry yeast was added volumetrically from a pre-mixed suspension. Clams were allowed to filter for 1 h. More yeast concentration was added if, during this hour, the concentration clearly dropped below half of the starting value. After 1 h, each clam was removed and returned to its respective tank. The final yeast concentrations were determined by measuring optical densities at 550 nm using the spectrophotometer. Reductions in concentrations relative to controls (yeast suspensions without clams) were easily converted to a food clearance rate (mg g<sup>-1</sup> h<sup>-1</sup>) using an empirical relationship of the optical density to yeast concentration. Obviously, feeding clams yeast suspensions in a closed chamber is not fully representative of natural conditions. Nevertheless, our measurements of food clearance rates provide relative estimates of the feeding state of the clams in the different treatments.

To evaluate levels of metabolic activity of the clams, individual oxygen uptake rates were monitored from days 5–8 with Clark-type polarographic oxygen electrodes using a Yellow Springs Instrument model 5302 respirometer. Water in the respirometer was stirred by a magnet gently spinning below a mesh screen supported by a stainless steel annulus. Clams were placed on the screen above the magnet. Approximately 50 ml of water without yeast or suspended inorganic solids was used in the respirometer. In all cases oxygen uptake rates were measured on clams with their siphons opened normally. Uptake rates were monitored from 90% to 65% air saturation in water at 20°C. Clams generally spent 20 to 30 min in the respirometer chamber. A few clams were too large to fit in the respirometer.

Thus, oxygen uptake rates were not measured on nine *Q. pustulosa* and ten *F. cerina* from all treatments.

To detect major shifts in catabolic substrates (proteins versus carbohydrates and fats), the total nitrogen (ammonia plus urea) excretion rate for each clam was assessed on day 9. Clams were placed individually in 50 or 100 ml of water, depending on the clam's size, for 1 h. At the end of the hour the clams were removed and 3 mg of Fisher U-21 urease was added for every 50 ml of water. Total ammonia excreted as ammonia or urea was then determined using an Orion model 95-10 ammonia probe coupled to an Orion model 407 A/L specific ion meter, following methods described in Russell-Hunter *et al.* (1983). All of the N excretion rates were done during a 1-h period on day 9 because N excretion is typically more labile than O<sub>2</sub> uptake rates (Bayne, 1973; Russell-Hunter *et al.*, 1983; Aldridge, 1983; Aldridge *et al.*, 1986) and, hence, this procedure results in reliable O:N ratios for comparing treatment effects.

Individual clams were never kept out of their treatment tanks for more than 90 min during any one of the three physiological rate determinations. On day 10, all clams were killed by shucking the flesh from the shells. Prior to weighing the soft tissues were dried to constant weight for 2 days at 75°C.

## RESULTS

We made three paired comparisons of treatments. First we assessed the effect of the periodicity of two levels of physical disturbance (turbulence) by comparing the physiological condition of clams in the infrequent versus the frequent turbulence treatments (ii) and (iv). In the other two comparisons we evaluated the combined effects of suspended solids and turbulence exposure by comparing treatments (i) and (ii) as well as (iii) and (iv). No differences between replicate aquaria were seen ( $p > 0.10$ , two-tailed *t*-test).

While acknowledging that there is no zero level control for assessing turbulence effects, a comparison of treatments (ii) and (iv) is useful in assessing the relative effects on clams of varying the time interval between brief periods of turbulence (Table 1). All three species responded to more frequent turbulence by lowering nitrogen excretion rates and hence increasing O:N. Values for O:N were derived from each pair of rate determinations made on an individual clam. The O:N ratio provides an assessment of the relative contribution of protein to total catabolism (Corner *et al.*, 1975; Ikeda, 1977; Widdows, 1978; Russell-Hunter *et al.*, 1983; Bayne & Newell, 1983). Protein-based catabolism is indicated by O:N values less than 30 (Bayne & Widdows, 1978). Infrequent exposure to turbulence had no major effect on the clams. All three species yielded O:N values

TABLE 1  
Tissue Dry Weights (TDW), Food Clearance Rates (FCR), Oxygen Uptake Rates ( $\text{VO}_2$ ), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Infrequent Turbulence and Those Exposed to Frequent Turbulence

Species	Physiology monitor		Treatment		Student's <i>t</i> -test		
	Infrequent	Frequent	df	<i>t</i>	Significance		
<i>Quadrula pustulosa</i>	TDW (g)	1.05 ± 0.23	1.13 ± 0.44	22	1.35	NS	
	FCR (mg yeast g <sup>-1</sup> h <sup>-1</sup> )	7.86 ± 5.63	8.93 ± 7.00	24	0.43	NS	
	$\text{VO}_2$ (μmol O <sub>2</sub> g <sup>-1</sup> h <sup>-1</sup> )	18.20 ± 5.75	15.52 ± 4.16	20	1.25	NS	
	NE (μmol N g <sup>-1</sup> h <sup>-1</sup> )	2.61 ± 0.78	1.66 ± 0.61	24	3.46	<i>p</i> < 0.01	
	O:N	14.00 ± 4.38	17.22 ± 4.22	20	1.76	NS	
<i>Fusconaia cerina</i>	TDW	0.98 ± 0.37	1.02 ± 0.36	32	0.33	NS	
	FCR	11.56 ± 8.80	8.00 ± 3.59	32	1.54	NS	
	$\text{VO}_2$	16.82 ± 5.62	14.81 ± 3.86	27	1.13	NS	
	NE	2.41 ± 1.18	1.49 ± 0.80	32	2.63	<i>p</i> < 0.05	
	O:N	13.86 ± 4.04	32.42 ± 38.67	27	1.79	NS	
<i>Pleurobema beadleum</i>	TDW	0.36 ± 0.07	0.36 ± 0.09	28	0.16	NS	
	FCR	7.92 ± 8.83	9.71 ± 7.99	28	0.59	NS	
	$\text{VO}_2$	20.81 ± 6.41	22.02 ± 9.80	28	0.13	NS	
	NE	3.96 ± 1.11	2.17 ± 1.85	28	3.16	<i>p</i> < 0.01	
	O:N	11.30 ± 4.73	62.34 ± 92.78	28	2.05	<i>p</i> < 0.05	

NS, not significant at at least *p* > 0.05 level.

TABLE 2

Tissue Dry Weights (TDW), Filter Clearance Rates (FCR), Oxygen Uptake Rates ( $\text{VO}_2$ ), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Infrequent Turbidity and Those Exposed to Infrequent Turbidity Plus Turbidity

Species	Physiology monitor	Treatment		Student's <i>t</i> -test		
		Turbulence	Turbulence plus turbidity	df	<i>t</i>	Significance
<i>Quadrula pustulosa</i>	TDW	1.05 ± 0.23	1.19 ± 0.44	24	1.00	NS
	FCR (mg yeast g <sup>-1</sup> h <sup>-1</sup> )	7.86 ± 5.63	3.35 ± 1.74	24	2.76	<i>p</i> < 0.05
	$\text{VO}_2$ (μmol O <sub>2</sub> g <sup>-1</sup> h <sup>-1</sup> )	18.20 ± 5.75	12.48 ± 4.75	20	2.10	<i>p</i> < 0.05
	NE (μmol N g <sup>-1</sup> h <sup>-1</sup> )	2.61 ± 0.78	1.51 ± 0.38	24	4.54	<i>p</i> < 0.001
	O:N	14.00 ± 4.38	16.34 ± 6.42	20	1.00	NS
<i>Fusconaia cerina</i>	TDW	0.98 ± 0.37	0.99 ± 0.29	32	0.06	NS
	FCR	11.56 ± 8.80	5.07 ± 3.51	32	2.82	<i>p</i> < 0.01
	$\text{VO}_2$	16.82 ± 5.62	13.55 ± 4.69	27	1.71	NS
	NE	2.41 ± 1.18	1.73 ± 0.75	32	1.99	NS
	O:N	13.86 ± 4.05	19.40 ± 11.86	27	1.66	NS
<i>Pleurobema beadleianum</i>	TDW	0.36 ± 0.07	0.36 ± 0.06	26	0.12	NS
	FCR	7.92 ± 8.83	3.18 ± 1.49	26	2.18	<i>p</i> < 0.05
	$\text{VO}_2$	20.81 ± 6.41	12.15 ± 6.43	26	3.44	<i>p</i> < 0.01
	NE	3.96 ± 1.11	2.37 ± 1.06	26	3.90	<i>p</i> < 0.001
	O:N	11.30 ± 4.73	15.21 ± 15.87	26	0.88	NS

NS, not significant at at least *p* > 0.05 level.

TABLE 3  
Tissue Dry Weights (TDW), Filter Clearance Rates (FCR), Oxygen Uptake Rates ( $\dot{V}O_2$ ), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Frequent Turbulence and Those Exposed to Frequent Turbulence Plus Turbidity

Species	Physiological monitor	Treatment		Student's <i>t</i> -test		
		Turbulence	Turbulence plus turbidity	df	<i>t</i>	Significance
<i>Quadrula pustulosa</i>	TDW (g)	1.13 ± 0.44	1.10 ± 0.27	24	0.17	NS
	FCR (mg yeast g <sup>-1</sup> h <sup>-1</sup> )	8.93 ± 7.00	2.36 ± 2.19	24	3.23	<i>p</i> < 0.01
	$\dot{V}O_2$ (μmol O <sub>2</sub> g <sup>-1</sup> h <sup>-1</sup> )	15.52 ± 4.16	13.41 ± 3.75	19	1.22	NS
	NE (μmol N g <sup>-1</sup> h <sup>-1</sup> )	1.66 ± 0.61	0.11 ± 0.07	24	9.09	<i>p</i> < 0.001
	O:N	17.22 ± 4.22	233.50 ± 69.04	18	9.95	<i>p</i> < 0.001
<i>Fusconaita cerina</i>	TDW	1.02 ± 0.36	0.97 ± 0.30	32	0.41	NS
	FCR	8.03 ± 3.59	5.12 ± 4.37	32	2.10	<i>p</i> < 0.05
	$\dot{V}O_2$	14.81 ± 3.86	15.80 ± 3.73	24	0.71	NS
	NE	1.49 ± 0.80	0.24 ± 0.31	32	6.01	<i>p</i> < 0.001
	O:N	32.42 ± 38.67	216.78 ± 112.91	24	6.05	<i>p</i> < 0.001
<i>Pleurobema beadleianum</i>	TDW	0.36 ± 0.09	0.33 ± 0.07	29	0.76	NS
	FCR	9.71 ± 7.99	3.34 ± 2.74	29	2.93	<i>p</i> < 0.05
	$\dot{V}O_2$	22.02 ± 9.80	16.64 ± 4.78	29	1.92	NS
	NE	2.17 ± 1.85	0.23 ± 0.11	29	4.05	<i>p</i> < 0.001
	O:N	62.34 ± 92.78	149.19 ± 50.50	28	6.88	<i>p</i> < 0.001

NS, not significant at at least *p* > 0.05 level.



averaging 13, that reflected their ability to base their metabolism on near total reliance on the proteinaceous food ration of yeast. Clams frequently exposed to turbulence showed significantly higher values of O:N. However, only for *P. beadleanum* was this increase (from 11 to 62) substantial enough to indicate that catabolism had become predominantly based on non-proteinaceous body stores.

The effects of infrequent exposure to elevated suspended solids were evaluated by comparing them to the effects of infrequent exposure to turbulence alone. When exposed infrequently to suspended solids and turbulence (treatment (i)), all three species showed significant and substantial reductions in food clearance rates. In addition *Q. pustulosa* and *P. beadleanum* showed reduced oxygen uptake and nitrogen excretion rates (Table 2). However, shifts in O:N were not observed.

The additive effects of suspended solids and turbulence exposure were more severe when coupled with more frequent turbidity exposure (treatment (iii)). *Q. pustulosa*, *F. cerina* and *P. beadleanum* all made significant reductions in food clearance and nitrogen excretion rates (Table 3). Dramatic shifts in O:N were made by all of the clams exposed to frequent turbidity to the extent that their catabolism had become entirely based on non-proteinaceous body stores as indicated by O:N ratios in excess of 145.

## DISCUSSION

In our study, exposure of three species of unionid mussels to infrequent (once every 3 h) and frequent turbidity (once every 0.5 h) at levels of 750 and 600 mg litre<sup>-1</sup>, respectively, caused reduced filter clearance rates. Frequent exposure to turbidity resulted in reduced nitrogenous excretion rates in all three species and larger O:N ratios. The response to infrequent exposure to turbidity was more variable with only *Quadrula pustulosa* and *Pleurobema beadleanum* showing major responses. Both reduced oxygen uptake and nitrogenous excretion rates in tandem. The fact that the animals exposed to turbidity infrequently showed no shift in catabolic substances (O:N ratio) suggests that they were less seriously affected than mussels exposed frequently to turbidity.

Our findings of reduced filter clearance rates of food particles by freshwater mussels exposed intermittently to relatively high concentrations of suspended solids are supported by work on the bivalves *Crassostrea virginica* (Loosanoff & Tommers, 1948), *Mytilus edulis* (Widdows *et al.*, 1979), and *Spisula solidissima* (Robinson *et al.*, 1984) as well as in the filter feeding gastropod *Crepidula fornicata* (Johnson, 1971). Work by both

Widdows *et al.* (1979) and Robinson *et al.* (1984) indicates that concentrations of inorganic suspended solids as low as  $100 \text{ mg litre}^{-1}$  can have a major impact on food clearance rates in *M. edulis* and *S. solidissima*. That such reductions in food clearance rates are ultimately translated into reductions in growth rates is seen in the suspended solids research on *Mercenaria mercenaria* (Pratt & Campbell, 1956; Bricelj *et al.*, 1984) although not over the very brief, 10-day period of the present study.

Less work has been done with filter feeders on the effects that suspended solids have on other aspects of their physiological energetics (e.g. oxygen uptake and nitrogenous excretion). However, it appears that imposed starvation or semistarvation is the major impact of high levels of suspended solids and, indeed, other environmental stresses on filter-feeders. Generally, the long-term response of most poikilotherms to reduced food availability is to lower metabolic rates (Bayne, 1973; Bayne *et al.*, 1979; Russell-Hunter *et al.*, 1983) and to shift to alternative catabolic substrates (Russell-Hunter & Eversole, 1976; Widdows, 1978; Bayne *et al.*, 1979). Lower oxygen uptake rates are universally an indicator of lower metabolic rates in aerobic organisms (Prosser, 1973).

Much more variable are the types of shifts seen in the use of alternative catabolic substrates. In some organisms, such as overwintering *Mytilus edulis*, starvation stress shifts the animal from its normal catabolic energy sources of carbohydrates and lipids (high O:N ratios) to a more proteinaceous catabolism (low O:N ratios) (Widdows, 1978). In our studies on freshwater mussels, however, the clams exposed to frequent turbidity and turbulence shift from the control catabolism heavily based on protein (O:N < 20) to a catabolism presumably based on stored carbohydrates and lipids (O:N > 100) which would ordinarily be used in reproduction or overwintering. Summer O:N ratios for unionids in nature are normally less than 50 (D. E. Buckley, pers. comm.) as are summer O:N ratios for other freshwater molluscs (Aldridge, 1985). Such a diversity of responses emphasizes the need for using appropriate controls in assessing the effects of environmental perturbations on the physiological energetics of different types of organisms (Bayne *et al.*, 1981).

In summary, the intermittent exposure of freshwater mussels to high levels of suspended solids ( $600$  to  $750 \text{ mg litre}^{-1}$ ) significantly altered their physiological energetics as assessed by filter clearance, oxygen uptake and nitrogenous excretion rates and also caused shifts in the catabolic substrates being used, as indicated by O:N ratios. Such assessments of physiological energetic responses to intermittent turbidity should be useful in evaluating and managing the ecological consequences of navigation and dredging activities on freshwater mussels.

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