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Effect of yellow loess on clearance rate in seven species of benthic, filter-feeding invertebrates

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Abstract

Attempts have been made, especially in Asia, to displace harmful algal blooms (HABs) by spraying 'china clay' and 'loess' over affected coastal waters. The impact of this technique on benthic communities and processes is not known. We examined the effects of yellow loess on clearance rates of the benthic, filter-feeding invertebrates, *Crassostrea virginica* (Gmelin 1791), *C. gigas* (Thunberg 1793), *Mytilus edulis* (Linnaeus 1758), *M. trossulus* (Gould 1850), *Argopecten irradians* (Lamarck 1819), and *Crepidula fornicata* (Linnaeus 1758). An *Obelia* species of hydroid was also studied and the percent time open was analysed. Depletion rates were measured using a range of loess concentrations suspended in culture with unicellular algae (*Rhodomonas lens*) in 0.45 μm filtered seawater. The effects of loess on clearance rates and behaviour were species-specific. *C. virginica* was not impacted until clay concentrations reached 1.0 g L^{-1}, while *A. irradians* showed a significant decrease at 0.01 g L^{-1}. *M. edulis* showed a significant decrease in clearance rates at the 1 and 10 g L^{-1} concentrations. For hydroids, the percent time open was significantly lower than the control at 0.01, 0.1, and 10 g L^{-1}. We clearly demonstrate that loess has a significant negative impact on filter-feeding invertebrates. The use of clay as a strategy for mitigation of HABs should be approached with extreme caution. While the control of active blooms may eventually be possible, it may not necessarily be an environmentally advisable or responsible approach to dealing with HABs.

Keywords: harmful algal blooms, mitigation, loess, clay, filter-feeding, scallop, mussel, oyster

Introduction

Harmful algal blooms (HABs) are a common and recurring threat to coastal regions worldwide and in some areas are annual occurrences (Shumway 1990; Hallegraeff 1993; van Dolah 2000). The economic impacts of these HABs can be extreme, averaging \$49 million in the United States alone (see Anderson, Kaoru & White 2000 and references therein). Currently, HABs cannot be prevented or controlled, and management is the only recourse. Management options include reducing the incidence and extent of the blooms, stopping or containing the bloom, and mitigation (minimizing impacts on human health, ecosystems, and fisheries) (Boesch, Anderson, Horner, Shumway, Tester & Whitledge 1997; CENR 2000; Anderson, Andersen, Bricelj, Cullen & Rensel 2001).

Efforts to prevent HABs focus on reducing inputs of pollutants to coastal waters (Burkholder & Glasgow Jr 1997; NRC 2000; Anderson *et al.* 2001) and discussions abound on other possible strategies, including siting of aquaculture facilities, modifying water circulation, and restricting species introductions (Boesch *et al.* 1997; CENR 2000). Numerous efforts have been undertaken to control blooms directly, including chemicals, flocculents and biological control agents; however, the proposed means of chemical and biological control have been fraught with logistical and environmental difficulties (see review by Perez & Martin 1999). Rounsefell & Evans (1958) tested the large-scale dispersion of copper sulphate using crop-dusting airplanes in Florida. While the copper sulphate was successful in eliminating the red tide organism, it was not species-specific and killed other co-occurring algae and organisms. Biological control has focused on parasites, bacteria, viruses and other algae (see studies by Cosper and co-workers, Milligan & Cosper 1994; review by Anderson *et al.* 2001), but again the biological and environmental implications are not clearly understood and this arena still needs much research before it can be considered for field applications.

In theory, the most promising means of control to date is the use of flocculents, specifically clay and loess. Loess, an unstratified, usually brownish to yellow loamy deposit found in North America, Europe, and Asia and deposited by the wind, is the actual material used in some Asian countries to mitigate HABs in the vicinity of aquaculture sites. These particles, when added to seawater, adsorb inorganic and organic particles, including algae and other particles to form a floc that falls to the sediment surface. These substances have been used effectively in China (Yu, Zou & Ma 1994a–c), Japan (Shirota 1989), and Korea (Na, Choi & Chun 1996; Choi, Kim, Lee, Yun, Kim & Lee 1998; Choi, Lee, Yun, Lee & Bae 1999; Bae, Kim, Kim, Cho & Yun 2000; Yu, Sun & Zou 2001) to remove HAB species from waters surrounding fish culture facilities. In recent laboratory studies, Sengco, Li, Tugend, Kulis & Anderson (2001) have reported on the removal of HAB species using clay (see below).

In practice, the mitigation procedure involves spraying fine particulate mineral suspensions over the surface of coastal waters affected by HABs. The particles adsorb onto the surface of algal cells, promoting coagulation and/or cell lysis and sink to the bottom (Yu *et al.* 1994a–c). The low cost and effectiveness of removing algae from the water column make this seem a promising solution.

There are, however, several potential risks associated with the use of clay or other particulates to remove harmful algae from the water column, including the potential release of toxins during the flocculation process and the impact of the sedimented cells and clay on benthic organisms (CENR 2000). The impacts can be especially detrimental to filter-feeding species, whose feeding apparati can become saturated or clogged, thus incapacitating the animals and not only depriving them of food, but also rendering them incapable of moving oxygenated seawater through their systems. Further, the accumulated biomass deposited by the clay may cause oxygen depletion in the bottom waters. Thus, the consequences of this activity are potentially highly detrimental in coastal areas where the spatial and temporal relationships between the benthos and the water column are intimately coupled, and especially in areas where flow rates are low.

Not all impacts of clay on benthic organisms have been shown to be negative. Shirota (1989) showed that some benthic organisms, e.g. sea cucumbers, actually benefitted from the clay-organic floc as a food source. It has also been demonstrated that at very low concentrations, clay may enhance particle digestion by some filter-feeding molluscs (Cranford & Gordon 1992; Cranford 1995).

Yu *et al.* (1994a, b) and Yu & Zou (2000) demonstrated that the efficiency of removal of algal cells from the water column by clay is affected by the type of clay, pH, algal cell type and the relative concentrations of clay and algal cells. They utilized concentrations of clay ranging from 1 to 10 $g\,L^{-1}$ in laboratory experiments. Other investigators have demonstrated the effective removal of algal cells using clay concentrations $>1\,g\,L^{-1}$ (Archambault, Bricelj, Grant & Anderson 2000). Rensel, Anderson & Connell (2000) reported that *Heterosigma* can be removed from the water column by clay and estimated that a typical farm would require an annual clay application of $\approx$ 40 kg per farm and noted that this amount pales in comparison to the estimated six million metric tons of sediment, including clay, entering Puget Sound each year from natural sources. In a more recent study, Rensell *et al.* (2003), in the most comprehensive field testing of clay to date, report rapid and highly efficient removal (84%) with very low levels of clay application (300 $g\,m^{-2}$ of surface area, equivalent to $\approx 0.12\,g\,L^{-1}$ inside each mesocosm tested).

Specific loading applications under field conditions are highly variable and difficult to quantify. In many instances, the material is simply dispersed from a barge using a fire hose to spray it onto the surface of surrounding waters. In one estimate, 100–400 g of clay per m^2 was applied to a bloom of *Cochlodinium* in Korea (Choi pers. comm.) and the Japanese Fisheries Agency (1982) spread 110–140 g of clay per m^2 ($=\sim 390$–$500\,g\,L^{-1}$) on a bloom of the same species. This same group demonstrated high levels of cell removal ($\sim$79–100%) by clay (7.5 $g\,L^{-1}$) for a number of algal species (*Mesodinium rubrum*, *Prorocentrum sigmoidis*, *Alexandrium catenella*, *Gymnodinium* T-65, *Heterosigma akashiwo*, *Gyrodinium instriatum*, *Prorocentrum micans*, *P. triestinum*, *Scrippsiella trochoidea*). Clay concentrations of 1.3–2.2 $g\,L^{-1}$ effectively removed *Chattonella marina*, and concentrations of 6–13 $g\,L^{-1}$ were effective on the larger species, *C. antiqua*. Most recently, Kim (1998) (see also Kim 2000) reported 74%, 98%, and 99% removal of *Cochlodinium polykrikoides* blooms after 30 min with 2, 6, and 10 $g\,L^{-1}$, respectively, and only 41%, 64%, and 88%

removal by yellow loess. The removal of red tide organisms reached 100% at 6.4 $g\,L^{-1}$ of loess. Sengco *et al*. (2001; pers. comm.) have carried out the most detailed studies to date on the ability of clay minerals to remove algal species from suspension. They have demonstrated clearly in laboratory studies that several of these minerals, often at very low concentrations, are efficient at removing HAB species from suspension. Their studies did not, however, address the issue of sedimentation of the materials or impacts on benthic fauna.

While flocculation and sedimentation of bloom organisms appear to be a viable, low-cost means of removing harmful algal species from the water column, it is important to consider the potential impacts on the integrated ecosystem before any mitigation strategy is employed. In the case of clay and other particulates, it is imperative to consider the effect of sediment deposition and associated flocs of harmful algae on benthic fauna. The present study was undertaken to elucidate the potential impacts of particulate-algal residue on the ability of seven species of benthic, filter-feeding organisms to remove algal cells from suspension. Yellow loess, supplied by an aquaculture facility in Korea, was used in laboratory experiments to simulate actual field conditions.

Materials and methods

Seven benthic suspension feeding organisms [eastern oyster, *Crassostrea virginica* (Gmelin 1791), Pacific oyster, *C. gigas* (Thunberg 1793), foolish mussel, *Mytilus trossulus* (Gould 1850), blue mussel, *M. edulis* (Linnaeus 1758), bay scallop, *Argopecten irradians* (Lamarck 1819), common Atlantic slippersnail, *Crepidula fornicata* (Linnaeus 1758), and an *Obelia* species of hydroid] were initially subjected to five concentrations of loess ranging from 0.01 to 10 $g\,L^{-1}$. All experiments were carried out at 14–18 °C and 28–32‰ salinity. These preliminary experiments using pure suspensions of loess showed little to no feeding in all animals. In subsequent experiments, 2.5×10^4 cells mL^{-1} of the unicellular alga, *Rhodomonas lens*, were added to each treatment to stimulate feeding. Experiments were conducted at the University of Connecticut (Avery Point, CT, USA) in the summer of 1999; University of Washington (Friday Harbor Laboratory, San Juan Island, WA, USA) in the summer of 2000; and Southampton College of Long Island University (NY, USA) in the fall of 2000.

Hydroids, *Obelia* sp., were collected daily from floating docks (near surface to depths of approximately 1 m) located at the mouth of the Poquonock River (Groton, CT, USA). Colonies were gently rinsed with 0.45 μm filtered seawater and cleansed of fouling organisms under a dissecting microscope. Hydroid colonies were placed in watch bowls with rocks to hold the colonies in position. Feeding polyps were then examined and percent time open was determined by video analysis. Polyp clusters were video taped for 10 min. For each treatment, 20 individual polyps were analysed for three randomly selected 1-min periods. The amount of time each polyp remained closed was measured with a stopwatch and used to determine the percent time open. Fresh polyp clusters were used for each experiment, i.e. none was reused and there were no repeated measures. Mussels, *M. edulis* (shell height 45–60 mm) were collected from rocks along the Poquonock River (Groton, CT, USA). Bay scallops, *A. irradians* (60–80 mm shell height), and eastern oysters, *C. virginica* (80–100 mm shell height) were obtained from Cornell Cooperative Extension (Southold, NY, USA). *A. irradians* and *C. virginica* were cleaned and held in unfiltered, flowing seawater at 18–24 °C and a salinity of 28–30‰. Pacific oysters, *C. gigas*, and foolish mussels, *M. trossulus*, were obtained from Westcott Bay Sea Farms (San Juan Island, WA, USA). *C. fornicata* (35–45 mm shell height) were collected from Long Beach (Sag Harbor, NY, USA). All snails remained attached to their original stones.

The shells of all animals were cleansed of encrusting organisms. All experimental animals were kept for 48 h in the laboratory under ambient conditions before use in experiments, with the exception of *Obelia* sp., which had to be collected fresh daily.

One and a half hours before each experiment, animals were placed in 0.45 μm filtered seawater. Trials were conducted in closed chambers at ambient water temperatures. *R. lens* and loess were held in suspension in each experimental chamber by gentle stirring and aeration.

Samples were analysed using a Coulter Counter Multisizer or a Becten Dickenson FACScan Flow Cytometer. The results obtained using both instruments were shown to be equivalent. Loess particles ranged in size from 1.3 to 4 μm, with a mean particle diameter of 1.79 ± 0.02. Loess used in these experiments was provided by Dr Albert Choi and collected directly from an aquaculture facility in Korea using the loess as a means of eliminating HABs around fishpens. Loess was dried for 3 days at 60 °C and ground with a mortar and pestle and passed through a 125-μm sieve (Tyler screen scale equivalent 115 mesh). Cultured *R. lens* (2.5×10^4 cells mL^{-1}) was used alone and with loess concentrations of 10, 100, 1000, and 10 000 mg L^{-1}. Dry weights were obtained for all test organisms to determine weight-specific clearance rates. One control chamber with no animals was used as a blank for each treatment. The clearance rate was determined by depletion after varying periods of time (t) ranging from 15 min to 1 h, depending on the species and cell concentration. The rates were calculated according to the formula (Coughlan 1969):

$$\mathrm{CR} = Mnt^{-1}(\log_e C_0 C_t^{-1}) - \text{blank}$$

where CR is the clearance rate, M the volume of water at the start, n the number of animals in the container, t the time elapsed, C_0 the concentration of particles at the start and C_t the concentration of particles at time t.

For all genera, except *Obelia* and *Crepidula*, the weight-specific filtration rate was calculated. For all bivalve species, weight-normalized rates were determined using the allometric equation:

$$\mathrm{FR} = (W_s/W_e)^b Y_e$$

where FR is the filtration rate for an animal of standard weight, W_s the standard weight of animal, W_e the observed weight of animal, Y_e the measured clearance rate, b the weight exponent for the physiological rate of species.

The b exponent used for *A. irradians* was 0.75 with a standard weight of 1 g (Bricelj & Kuenstner 1989). For *C. virginica* and *C. gigas*, an exponent of 0.67 with a standard weight of 1 g (Newell & Langdon 1996) was used. For *M. edulis* and *M. trossulus*, an exponent of 0.66 with a standard weight of 1 g was used (Møhlenberg & Riisgard 1979). No weight exponent was available for *Crepidula*. Animal dry weights were in a narrow range and therefore, individual clearance rates were divided by the dry weight of the animal to obtain weight-specific clearance rates.

For each species of mollusc, the effect of loess on clearance rate was examined using a one-way analysis of variance procedure (GLM; Systat 1998). If a significant treatment effect was found, then a one-tailed Dunnett test was used to compare the four loess treatments with the algal control. We were primarily interested in whether the clearance rates of molluscs delivered loess were significantly lower than those delivered algae. Before statistical analyses, data were adjusted using a logarithmic transformation (Zar 1984) to conform to assumptions of normality and homogeneity of variance. For hydroids, the effect of clay on the percentage of time (1 min) that feeding polyps were open was examined using a nested analysis of variance procedure (GLM; Systat 1998). Data for the three replicate polyp clusters (trials) were nested within each treatment level. If a significant treatment effect was found, then a Bonferroni *post hoc* test was performed to determine the differences among the three trials and the five treatments. Again, we were primarily interested in whether the behaviour of polyps delivered clay was different from those delivered algae, but a Dunnett test cannot be used with nested designs (Systat 1998). Therefore, the Bonferroni test was employed. Before statistical analysis, hydroid data were transformed using an arcsine procedure (Zar 1984), so that they conformed to assumptions of normality and homogeneity of variance.

Linear regression analyses were carried out on each data set relating loess/algal concentrations and clearance rates.

Results

All species studied were negatively impacted by the presence of loess particles. Scallops, *A. irradians*, appeared to be the most sensitive, filtration rate being significantly lower than controls at experimental loess concentrations ≥ 0.01 g L^{-1}. Pseudofaeces production was noted, but not quantified, in all species of bivalves at loess concentrations ≥ 0.01 g L^{-1}. The filtration rate by the slipper limpet, *C. fornicata*, decreased significantly relative to controls at loess concentrations ≥ 1 g L^{-1}. The filtration rates of mussels, *M. edulis* and *M. trossulus*, and oysters, *C. virginica* and *C. gigas*, were not significantly impacted until loess concentrations reached 1 g L^{-1}. The activity of the hydroid, *Obelia* sp., measured as the percent (%) time closed, was significantly affected at the lowest concentration of loess, 10 mg L^{-1}.

Hydroids (*Obelia*)

Nested ANOVA indicated that there was a significant effect of trial within each treatment on percentage of time that feeding polyps were open (df = 10, $P < 0.01$). Bonferroni *post hoc* tests revealed that this effect was localized with 100 mg of loess treatment. Trial 1 was significantly different from trial 3 ($P = 0.02$). No other differences were found among trials within treatments. Nested ANOVA indicated that there was a significant effect of treatment on the percentage of time that feeding polyps were open (df = 4, $P < 0.0001$). Bonferroni *post hoc* tests revealed that hydroids

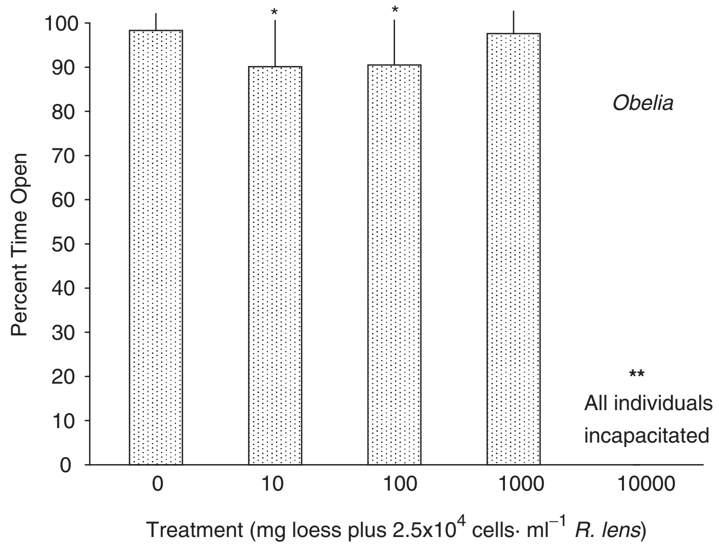

Figure 1 Average percent time open for polyps of *Obelia* exposed to loess. Error bars are standard deviations and asterisks represent statistical significance ($P \leq 0.05$).

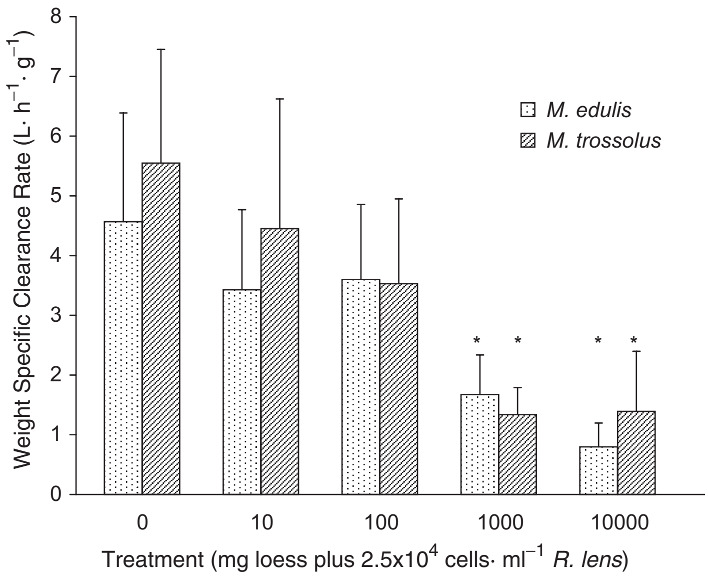

Figure 2 Average weight-specific clearance rate by treatment for *Mytilus edulis* and *M. trossulus* exposed to loess. Error bars are standard deviations and asterisks represent statistical significance ($P \leq 0.05$).

delivered 10 000, 100, and 10 mg L^{-1} of loess were closed for a significantly longer time compared with hydroids delivered algae ($P < 0.0001$). Differences among the clay treatments were also found (Fig. 1).

A. irradians

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.0001$). Dunnett *post hoc* tests revealed that scallops delivered loess at 10 000, 1000, and 10 mg L^{-1} had significantly lower clearance rates than scallops delivered algae ($P < 0.0001$, $P < 0.0001$, $P < 0.05$ respectively). No significant difference in clearance rates was found between scallops delivered 100 mg L^{-1} of loess and those delivered algae ($P = 0.076$) (Fig. 2).

C. gigas

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.0001$). Dunnett *post hoc* tests revealed that oysters delivered loess at 10 000 and 1000 mg L^{-1} had significantly lower clearance rates than oysters delivered algae ($P < 0.0001$). No significant difference in clearance

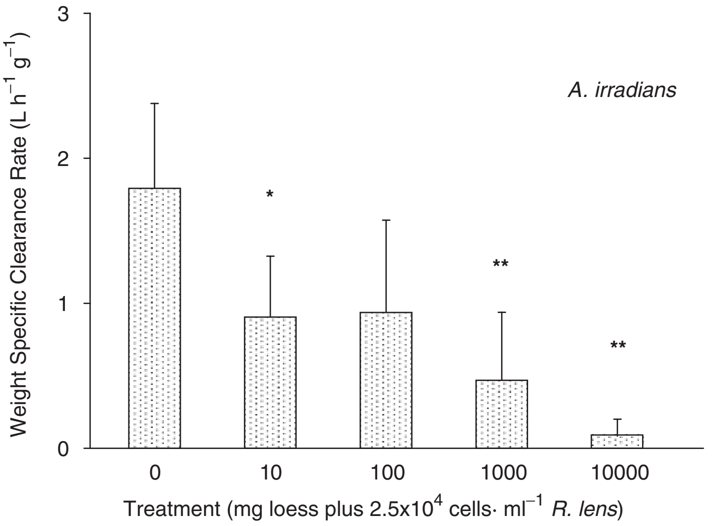

Figure 3 Average weight-specific clearance rate by treatment for *Argopecten irradians* exposed to loess. Error bars are standard deviations and asterisks represent statistical significance ($P \leq 0.05$).

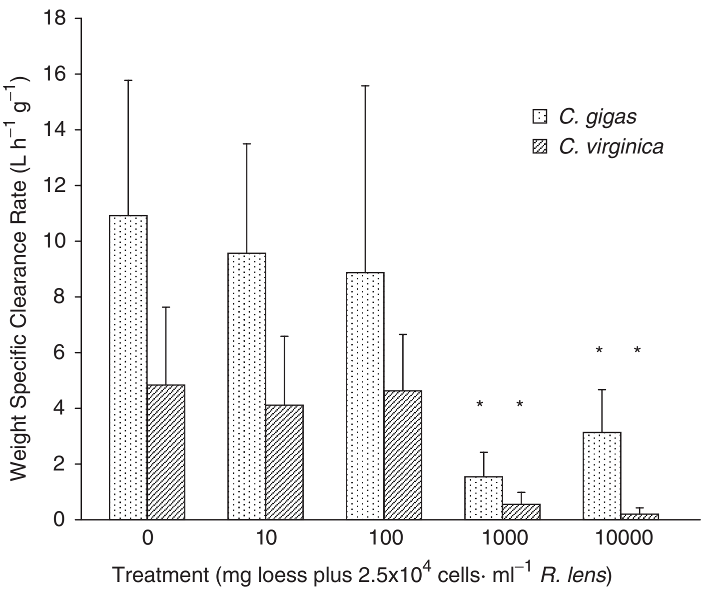

Figure 4 Average weight-specific clearance rate by treatment for *Crassostrea gigas* and *C. virginica* exposed to loess. Error bars are standard deviations and asterisks represent statistical significance ($P \leq 0.05$).

rates was found between oysters delivered 100 or 10 mg L^{-1} of loess and those delivered algae ($P > 0.05$) (Fig. 3).

C. virginica

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.0001$). Dunnett *post hoc* tests revealed that oysters delivered loess at 10 000 and 1000 mg L^{-1} had significantly lower clearance rates than oysters delivered algae ($P < 0.0001$). No significant difference in clearance rates was found between oysters delivered 10 or 100 mg L^{-1} of loess and those delivered algae ($P > 0.05$).

M. edulis

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.0001$). Dunnett *post hoc* tests revealed that mussels delivered loess at 10 000 and 1000 mg L^{-1} had significantly lower clearance rates than mussels delivered algae ($P < 0.0001$). No significant difference in clearance rates was found between mussels delivered 100 or 10 mg L^{-1} of loess and those delivered algae ($P > 0.05$) (Fig. 4).

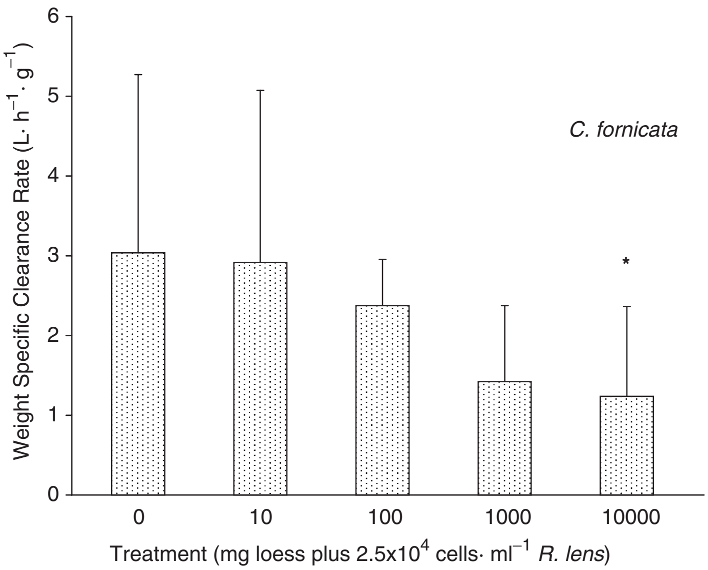

Figure 5 Average weight-specific clearance rate by treatment for *Crepidula fornicata* exposed to loess. Error bars are standard deviations and asterisks represent statistical significance ($P \leq 0.05$).

M. trossulus

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.0001$). Dunnett *post hoc* tests revealed that mussels delivered loess at 10 000 and 1000 mg L^{-1} had significantly lower clearance rates than mussels delivered algae ($P < 0.0001$). No significant difference in clearance rates was found between mussels delivered 10 or 100 mg L^{-1} of loess and those delivered algae ($P > 0.05$) (Fig. 4).

C. fornicata

One-way ANOVA indicated a significant effect of treatment on the clearance rate (df = 4, $P < 0.01$). Dunnett *post hoc* tests revealed that snails delivered clay at 10 000 mg L^{-1} had significantly lower clearance rates than snails delivered algae ($P < 0.01$). No significant difference in clearance rates was found between snails delivered 1000, 100, or 10 mg L^{-1} of loess and those delivered algae ($P > 0.05$) (Fig. 5).

Statistical analyses for Figs 1–5 and the regression analyses are presented in Tables 1 and 2.

Discussion

The results presented here corroborate previous studies in that all benthic filter-feeders investigated were negatively impacted by the presence of loess. Of particular significance is the fact that the filtration rates of oysters, normally exposed to high particulate loads and known to handle them very efficiently, were negatively impacted by the presence of high concentrations of loess. Oysters in Delaware experience particulate inorganic matter concentrations ranging from 8–171 mg L^{-1} annually (Ali 1981). Further, scallops, known to be highly sensitive to environmental perturbation (Bricelj & Shumway 1991), were negatively impacted at the lowest levels of clay tested.

Sessile, benthic invertebrates are highly susceptible to suspended sediment load and can suffer burial, decreased clearance rates, increased pseudofaeces production and death. While many studies have reported the impact of particulate matter on filter-feeding organisms (Winter 1976; Widdows, Fieth & Worrall 1979; Kiørboe, Møhlenberg & Nøhr 1980; Kiørboe & Møhlenberg 1981; Bricelj & Malouf 1984; Urban & Langdon 1984; Ward & MacDonald 1996; Bayne 1998), few have specifically addressed the fate of suspended clay. Urban & Kirchman (1992) exposed oysters, *C. virginica*, to kaolinate clay particles and found that, while the presence of clay did not significantly affect the amount of algae cleared or rejected, it did interfere with and disrupt the ability of the oysters to select particles on the gill. In an early study on the eastern oyster, *C. virginica*, turbidity was demonstrated to reduce pumping rates over 90% with an increase in inorganic particle load (natural silt and kaolin) of 3.0–4.0 g L^{-1}, and adversely affected at concentrations of only 0.1 g L^{-1} (Loosanoff 1962). More recent studies (Ward, Levinton, Shumway & Cucci 1998a, b; Levinton, Ward & Shumway 2002)

Table 1 Statistical significance (P value, $\alpha = 0.05$) at each concentration of loess as compared with algae alone for each species

Species	Algae vs. 0.01 g loess	Algae vs. 0.1 g loess	Algae vs. 1 g loess	Algae vs. 10 g loess
Argopecten irradians	$P<0.05$	n.s. ($P=0.076$)	$P<0.0001$	$P<0.0001$
Crepidula fornicata	n.s.	n.s.	n.s. ($P=0.068$)	$P<0.01$
Mytilus edulis	n.s.	n.s.	$P<0.0001$	$P<0.0001$
M. trossulus	n.s.	n.s. ($P=0.075$)	$P<0.0001$	$P<0.0001$
Crassostrea gigas	n.s.	n.s.	$P<0.0001$	$P<0.0001$
C. virginica	n.s.	n.s.	$P<0.0001$	$P<0.0001$
Obelia sp.	$P<0.0001$	n.s.	$P<0.0001$	$P<0.0001$

n.s., not significant.

Table 2 Statistical significance (P value, $\alpha = 0.05$; r^2) of the slope of the regression lines relating loess concentration and clearance rate for all species, except *Obelia*

Species	P value	r^2
Argopecten irradians	<0.0001	0.515
Crepidula fornicata	<0.001	0.207
Mytilus edulis	<0.0001	0.541
M. trossulus	<0.0001	0.571
Crassostrea gigas	<0.0001	0.425
C. virginica	<0.0001	0.593

have shown that oysters are highly efficient at differentiating between organic and inorganic particles.

Stevens (1987) found that the impacts on ciliary activity in excised scallop gills were greatest for clay-sized particles, and Morse, Robinson & Wehling (1982) demonstrated an 'unzipping' of gill filaments in the sea scallop at 100–1000 mg L^{-1} clay. Cranford & Gordon (1992) reported extensive and chronic mortalities, and zero reproductive tissue growth at 10 mg L^{-1} in populations of sea scallops (*Placopecten magellanicus*) subjected to dilute suspensions of bentonite clay (0–15 mg dm^{-3}). The clearance rate dropped to 50% at 2 mg L^{-1}. Bay scallops in this study were similarly affected at low clay concentrations.

Cranford (1995) later demonstrated that increasing clay levels reduced food quality, resulting in an exponential decline in absorption efficiency (1 mg L^{-1} clay addition to seston resulted in $\sim$20% decrease in absorption efficiency). He reported a threshold concentration of 2 mg L^{-1} bentonite for causing reductions in somatic and/or reproductive tissue growth in the sea scallop, *P. magellanicus*. His results clearly demonstrated that sea scallops can be adversely affected by prolonged exposure to relatively low concentrations of bentonite clay ($\leq$10 mg dm^{-3}). Laboratory studies of the surfclam, *Spisula solidissima*, examined the effects of concentrations up to 1 g L^{-1} of suspended clay on feeding and showed diminished digestive efficiency at levels as low as 100 mg L^{-1} (Robinson, Wehling & Morse 1984). Results of these studies showed that an increase in particle load increased the amount of food rejected as pseudofaeces. At the same time, there was a decrease in ingestion rate and enzymatic breakdown of food. The authors concluded that anthropogenic turbidity-producing discharges at levels as low as 100 mg L^{-1} could have adverse effects on surfclam populations.

While there have been relatively few studies on the impacts of clay on marine organisms, several studies have been carried out on the impact of clay discharges on benthic invertebrates in freshwater streams. The overall results of these studies are clear: increased levels of suspended solids (turbidity loading) result in decreased invertebrate densities and decreased taxonomic richness (Nuttall & Bielby 1973; Wagener & LaPerierre 1985; Quinn, Davies-Colley, Hickey, Vickers & Ryan 1992 and references therein). Quinn *et al.* (1992) reported invertebrate densities in mining-impacted streams of only 9–40% of those in unmined reference streams. They recommended that stringent controls be placed on discharges of clay-size inorganic suspensoids to prevent substantial impacts on invertebrate communities in streams.

Two studies examining the effects of china clay waste on bottom fauna in two British bays reported the quantities of waste carried down the White and Par Rivers from an upstream china clay industry to be approximately 1.25 million tons per year in 1968 (Howell & Shelton 1970; Portmann 1970). They found the benthic community composition drastically altered, with a large decrease in species diversity in areas where china clay wastes comprised more than 20% of bottom deposits. Many epifaunal and infaunal species, e.g. the suspension feeding lamellibranchs, *Venus fasciata*, *Dosinia exoleta*, and the polychaetes *Nephthys hombergi* and *Nereis pelagica*, were intolerant to the clay and were therefore largely absent from these areas, yet prolific in surrounding areas unaffected by the clay discharge.

Only very recently has attention been focused on the potential impacts of clay as it is used to remove red tide organisms. Lewis, Green, Aishao & Anderson (2000) and Lewis, Dantin, Walker, Kurtz & Greene (2003) reported on the effects of clay flocculation of the Florida red tide dinoflagellate, *Karenia brevis*, on benthic organisms. They concluded that the clay was not toxic to the organisms tested. While this study reported no toxicity of clay *per se*, the test organisms included amphipods, a grass shrimp and sheepshead minnow, all of which are motile and could presumably escape, i.e. no sedentary benthic filter-feeding species were represented. So, while the clay was not toxic *per se*, the potential impacts on sedentary animals prone to burial and other impacts on their lifestyle were not addressed. Howell & Shelton (1970) considered it highly likely that changes in the distribution of benthic crustacea almost certainly occurred as a result of china clay deposition; however, they specifically excluded crustaceans from their long-term assessments, noting that they are highly mobile members of the epifauna and could simply relocate. Indeed, they reported that the crab, *Cancer pagurus*, and the lobster, *Homarus vulgaris*, were no longer present in the clay-impacted bays studied.

Most recently, Archambault *et al.* (2000) and Archambault, Bricelj, Grant & Anderson (2002) studied the impact of clay particles and water flow on the northern quahog (= hard clam) *Mercenaria mercenaria*. They reported a highly significant growth effect with a 90% reduction in shell and tissue growth in animals exposed to clay when compared with clams in no-clay controls. They concluded that 'repeated clay applications in the field are likely more detrimental to clams under flow conditions leading to prolonged *in situ* resuspension of clay than under conditions that promote rapid sedimentation.'

Conclusions

Control of HABs is a complex, if not wishful, concept. Of the means proposed thus far, clay and other particulates appear to be the most promising. The results presented here, however, clearly demonstrate the detrimental and potentially lethal impacts of this approach on sedentary, benthic organisms that rely on filtration to meet their energetic needs. The more recent studies by Rensel and co-workers provide more encouraging data; however, further research is still needed before the use of clay can be considered a viable means of HAB control.

As Steidinger (1983) pointed out, red tides in Florida and their associated fish kills are akin to natural fires or other perturbations with regard to ecological function. Fishermen in Florida reported higher catches of fish and crabs following red tides and this may be a direct result of any number of factors, including decreased predation, increased food availability as a result of deposition of dead fish, or reduced competition. Red tides or HABs have prevailed for thousands of years. It is only in relatively recent years where human populations have been inconvenienced or economically impeded by these blooms that thoughts have turned to controlling or eliminating these blooms. Scientists and managers should consider the possibility that no intervention is the best policy and let nature take its course. Before any means of intervention is considered, careful studies of risk assessment must be carried out. While control of active blooms may eventually be possible, it may not necessarily be an environmentally advisable or responsible approach to dealing with HABs.

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