ASSESSMENT OF DREDGING-INDUCED SEDIMENTATION EFFECTS ON WINTER FLOUNDER (*PSEUDOPLEURONECTES AMERICANUS*) HATCHING SUCCESS: RESULTS OF LABORATORY INVESTIGATIONS

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ABSTRACT

Historically of significant commercial and recreational value, winter flounder (*Pseudopleuronectes americanus*) stocks have declined steadily over the last 20 years and are currently at an all-time low. Although overfishing and climate change have been implicated, habitat alteration and dredging impacts have also been identified as sources of concern. Winter flounder eggs are demersal and adhesive. In response to a specific concern that winter flounder eggs are therefore vulnerable to elevated sedimentation rates, seasonal constraints have been imposed on many dredging projects in northeastern estuaries where winter flounder spawn. Such constraints can substantially increase the costs of dredging. Previous unpublished laboratory experiments indicated that viable hatch of winter flounder eggs can be reduced when the eggs are exposed to as little as one half of one egg diameter (~ 0.5 mm) of sediment, but these experiments were not specifically designed to measure the effects of burial. In the present study laboratory experiments were performed to determine the effects of sedimentation on hatching success. Recently spawned (3-5 days after fertilization) eggs were exposed to clean, fine-grained sediment at treatment depths including a control (no sediment), dusting (< 0.5 mm), and up to 9.3 mm (>10 egg diameters) of sediment until hatch. Despite variability among experiments, a trend of decreased hatching success and increased time to hatch with increasing sediment depth relative to controls was observed. Percent total hatch of eggs exposed to $\leq$ 1.0 mm of sediment was not statistically different from that of the controls. Percent total hatch was highly variable in eggs buried in approximately 3 mm of sediment, whereas few eggs hatched successfully when buried in > 3 mm of sediment. Delayed hatch was observed in eggs buried in as little as 1 mm of sediment. Overall, these results confirm that winter flounder eggs are vulnerable to burial in sediments. These data should be taken into account whenever seasonal constraints for the protection of winter flounder are considered.

Key words: Demersal eggs, dredging, Narragansett Bay, seasonal dredging constraints, sediment deposition.

INTRODUCTION

Winter flounder *Pseudopleuronectes americanus* populations have been in steady decline for the past 20 years (ASMFC 2006). This decline is partially due to heavy commercial and recreational fishing pressure (ASMFC 2006), however, environmental factors such as climate change (Collie et al. 2008) are also considered contributing factors. Winter flounder eggs are demersal and adhesive (Collette and Klein-MacPhee 2002). The eggs take up to several weeks to hatch. Keller and Klein-MacPhee (2000) found mean time to hatch to be 20 days at a mean temperature of 4.1°C and 30 days at a mean temperature of 1.6°C.

The winter flounder's demersal egg and relatively long incubation time render the eggs of this species vulnerable to elevated sedimentation rates from anthropogenic activities. Two previous studies have attempted to address the effects of sediment exposures on winter flounder eggs. One laboratory study (Nelson and Wheeler 1997) not specifically designed to look at the effects of sedimentation, found that viable hatch was significantly reduced when winter flounder eggs were exposed to increased sediment in Nitex mesh bags. However, it was not possible to precisely measure the extent of egg-sediment coverage in the bags. In a field study, Klein-MacPhee and Macy

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(2005) deployed sediment trap/chambers containing winter flounder eggs for 14 days in Narragansett Bay, RI, USA, at two locations: one within meters of the upper edge of a channel being actively dredged and one in the same general area of the bay, but as far "landward" from the dredge as possible, at a distance of approximately 730 m. There was no significant difference in hatching rate between eggs placed in sediment trap/egg chambers near the dredged channel and those placed 730 m from the dredge, but the hatching rate at both sites was very low. The near-dredge chambers had a mean depth of 7.8 mm of sediment deposition whereas the far-field chambers had a mean depth of 3.8 mm of sediment deposition.

One anthropogenic activity which can lead to elevated sedimentation rates is navigation dredging. Navigation dredging operations are crucial for maintaining our nation's waterways and typically result in the resuspension and redeposition of sediments in the vicinity of the dredging and dredged material placement sites. One potential impact of these operations is habitat alteration, which is of particular concern for species such as winter flounder which have sensitive life stages dependent on the quality of the benthic habitat. For these reasons, federal and state regulatory agencies have developed seasonal constraints as a management tool for reducing adverse impacts on living resources. A seasonal constraint is simply a restriction or ban on dredging during periods that coincide with fish migrations, reproductive cycles, larval development, or other sensitive life stages. The seasonal constraint is put into effect for certain areas during certain times of the year until the threat to living resources is obviated. However, due to the cost and complexities involved with navigation dredging, these restrictions should be given careful consideration before they are sanctioned. Because different species have different environmental requirements, the combined seasonal constraints for multiple species can cause the permissible dredging season to be very short in some regions (LaSalle et al. 1991).

The goal of this study was to determine directly the potential effects of sediment deposition on the hatchability of newly spawned winter flounder eggs under controlled laboratory conditions. To accomplish this goal, we conducted a series of three experiments in which we exposed recently-spawned winter flounder eggs to varying depths of clean sediment and observed their hatching rate and time to hatch.

MATERIALS AND METHODS

Sediment collection/preparation/characterization

Surficial sediment (0-10 cm) used in all experiments was collected from a relatively uncontaminated site in Narragansett Bay, RI, USA, with a modified Van Veen grab. The sediment was stored in a sealed 5 gallon plastic bucket at 4°C. Prior to experimentation, the sediment was frozen at -4°C and then thawed at room temperature. Sediment was refrozen and re-thawed to kill any macrofauna and was wet sieved through a 2 mm stainless steel screen to remove debris (Hinchey et al. 2006). The sediment was then re-homogenized by gentle stirring and placed into 4 liter glass jars for long-term storage at 4°C. It is important to note that this defaunating procedure could have disaggregated flocculated sediments, causing the experimental sediments to be finer than *in situ* sediments.

Sediment total organic carbon, measured with a Flash EA 1112 Elemental Analyzer (ThermoQuest, Milan, Italy) was 4.17 ± 0.11%, Sediment grain size, analyzed with a Mastersizer 2000 (Malvern Instrument, Malvern, UK), was 84% silt/clay and 16% sand, and most of the sand (9% of the total) was in the "very fine" sand category (62.5 -125 microns). Sediment dry weight/wet weight ratio had a mean value of 0.37.

Experimental Egg Sources

Three separate experiments (designated Experiments 1-3) were performed (Tables 1 and 2). Eggs for Experiments 1 and 2 were provided by Llenco Inc. of Chatham, MA, from spawning stock collected in Cape Cod Bay, MA. Eggs were produced as a result of natural spawning. Eggs used in Experiment 3 were strip-spawned in the U.S. EPA Atlantic Ecology Division laboratory from a single female collected from a mixed stock from Narragansett Bay, RI, and Point Judith Pond, RI. Eggs were mixed with the sperm from a single male. All eggs were held in running seawater, with aeration, until experiment initiation. Prior to the start of all experiments egg clumps were separated by gently rolling them between thumb and forefinger underwater.

Experimental treatments

Each of the three experiments tested either four (Experiment 1) or five (Experiments 2 and 3) sediment treatment depths and a control (no sediment) treatment (Table 1). Sediment depths ranged from 0.02 to 10 mm, and were modified in successive experiments, depending on the results of previous experiments.

Table 1. Weight of sediment (g) added to test chambers and corresponding calculated sediment depth (mm), mean percent hatch (with standard deviation) and mean time to hatch (d) for each experiment.

Burial regimes (Experiments 1-3)		Experiment 1		Experiment 2		Experiment 3	
Sediment added (g)	Calculated sediment depth (mm)	Mean percent hatch (% ± std dev)	Mean time to hatch (d)	Mean percent hatch (% ± std dev)	Mean time to hatch (d)	Mean percent hatch (% ± std dev)	Mean time to hatch (d)
0.0	0.0	66.8 (10.44)	20.7	61.2 (7.58)	21.7	51.6 (11.86)	11.8
0.1	0.02	49.6 (20.46)	20.5	--	--	--	--
1.0	0.2	54.8 (17.18)	21.5	--	--	34.0 (5.48)	12.0
2.5	0.6	59.2 (10.90)	21.7*	2.4 (1.68)**	†	41.2 (19.22)	12.9
5.0	1.2	--	--	37.2 (19.00)**	27.5*	43.2 (14.94)	13.0*
10.0	2.5	42.4 (16.08)	23.4*	14.8 (26.58)**	28.1*	0.8 (1.78)**	†
20.0	5.0	--	--	0.4 (0.88)**	†	0.4 (0.88)**	†
40.0	10.0	--	--	0.8 (1.78)**	†	--	--

*significantly different from control ($p<.05$); **significantly different from control ($p<.0001$);
-- burial regime not tested in this experiment;
† < 5% total hatch rate, therefore mean time to hatch not calculated.

Experimental set-up

Three to five day-old winter flounder eggs were pipetted into plastic cups filled with sand-filtered Narragansett Bay seawater until 25 eggs were counted, then the contents of the cups were added randomly to test chambers. Fifty eggs were used per replicate, with five replicates per treatment. Eggs were checked for viability (clarity and obvious cell division) before being added. The eggs were allowed to acclimate in the test chambers overnight. Test chambers were 600 ml glass beakers (8.2 cm i.d.) with a 150 µm Nitex-screened outflow (Figure 1). Sand-filtered Narragansett Bay seawater was delivered below the water surface through a slit in a test tube attached to the side of the beaker. A siphon/splitter delivery system was used to maintain constant flow to the test chambers. Water flow to each chamber was approximately 40 turnovers per day during Experiment 1. In Experiments 2 and 3, flow was reduced to approximately 20 turnovers per day, in an attempt to reduce impingement of hatched larvae on the outflow screens. Gentle aeration was provided in all test chambers. Replicate chambers were randomly placed within a water bath to maintain constant temperature between test chambers. A 12/12 hour light/ dark cycle was used. Further information on experimental salinity and temperature ranges is summarized in Table 2.

Table 2. Experimental conditions

	Experiment 1	Experiment 2	Experiment 3
Start date	12 February 2004	10 February 2005	7 April 2005
Experiment duration	30 d	34 d	18 d
Mean egg diameter ± S.D.	0.70 (± 0.03) mm	0.80 (± 0.01) mm	0.74 (± 0.01) mm
Water temperature	4.0–6.0°C	4.5–5.0°C	7.5–10°C
Salinity	32–35 ppt	30–34 ppt	27–32 ppt

Ten eggs were measured with an ocular micrometer on a dissecting microscope at 30x at the start of each experiment (Table 2). Eggs used within each experiment were almost uniform in diameter, and most were almost perfectly round. In cases where eggs were oval the smaller diameter was measured. Mean egg diameter showed little variation between experiments (Table 2). Overall mean egg diameter for the three experiments was 0.75 ($\pm$0.04) mm. This was consistent with the egg diameters reported in previous studies (Collette and MacPhee 2002). On day 1 of each experiment, wet sediment was homogenized and weighed (Table 1) into tared plastic cups and covered until needed. Immediately prior to sediment addition, seawater and air flow were turned off, and 200 ml of surface water was pipetted from each test chamber. Thirty ml of filtered seawater was added to each cup of sediment to form a slurry. That slurry was then rinsed into the test chamber. The sediment was allowed to settle onto the eggs for approximately 5 hours in Experiment 1 and for 7 hours in Experiments 2 and 3 before the flow-through seawater and aeration were reinstated.

Experimental monitoring

Flow rate, temperature, and salinity in one randomly selected test chamber were recorded daily. Dissolved oxygen, pH, salinity, and temperature measurements were made in every replicate at least once during the course of each experiment. Dissolved oxygen was always greater than 90% saturation. Numbers of live and dead larvae were recorded and removed daily. Results are reported as percent total hatch. Each experiment was monitored for at least 2 days after no eggs were observed to hatch in any replicate. All unhatched eggs were assumed to be nonviable.

At the beginning of each experiment two extra replicates of each treatment were established without winter flounder eggs in order to measure sediment burial depth. Sediment depths were measured within a few days of the beginning of each experiment with a plastic ruler to the nearest 0.5 mm in five locations within each of the two extra replicates: four locations around the edge of the beakers and one location near the center of each beaker. Due to physical limitations in measuring sediment depth with a ruler we report calculated depths with experimental treatments. Calculated depth was derived using a linear regression with the line forced through the origin (Microsoft Office Excel 2003) using the data from the treatments greater than 1.0 mm (1.2 mm – 10.0 mm). The relationship is shown in Figure 2. The r^2 of the relationship was 0.976. Hereafter whenever the term "depth" is used it will refer to "calculated depth".

Statistical methods

One-way analysis of variance (SAS Institute 2002-2004, Cary, NC) was conducted for two variables, time to hatch and percent total hatch. Significance was measured at α=0.05. Time to hatch data were not considered in treatments where fewer than 5% of the eggs hatched. In several of the thick sediment layer treatments there were a few eggs that were on or near the surface of the sediment, however, the majority of eggs were buried completely.

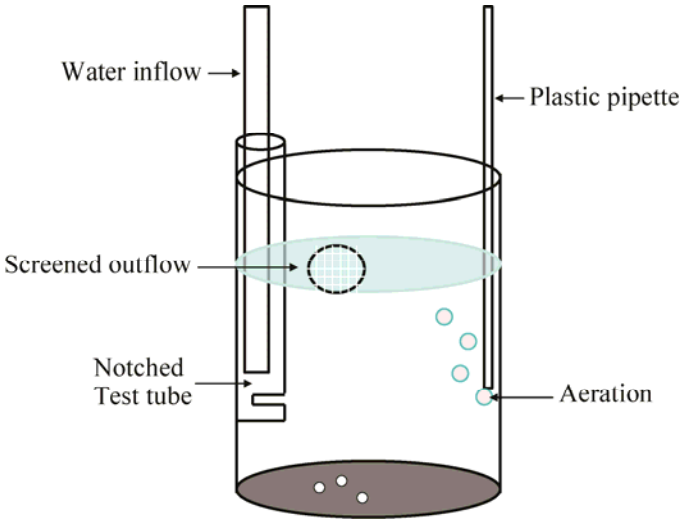

Figure 1. Exposure chambers for sediment deposition experiments

RESULTS

Relationship of hatching success to sediment burial depth

In Experiment 1, total hatch was highest in the control treatment and lowest in the 2.5 mm treatment, but the relationship of reduced hatch with depth did not monotonically decrease with increasing sediment depth and no significant difference was detected in the percent total hatch between the control and any of the sediment depths tested (Table 1, Figure 3). In Experiment 2, percent total hatch was significantly lower in all sediment depths tested when compared to the control (Table 1, Figure 3). Eggs in the 0.6 mm treatment hatched at a very low rate (2.4%) whereas eggs buried in twice that depth (1.2 mm) had a much higher proportion of hatch (37.2%) (Table 1, Figure 3). In Experiment 3, no significant difference in percent total hatch was detected between the control and sediment depths of 0.2 mm, 0.6 mm, and 1.2 mm. Percent total hatch was significantly lower in treatments containing 2.5 mm and 5.0 mm of sediment (Table 1, Figure 3).

The percent total hatched when exposed to less than 2.5 mm of sediment was not statistically different from the number of eggs hatched in controls in Experiments 1 and 3. However, in Experiment 2 significant differences were detected for all sediment depths tested compared to the control, including treatments with 0.6 and 1.2 mm of sediment. Percent total hatch in sediment depths of 2.5 mm were highly variable among the three experiments (0.8% – 42.4%), however less than 1% of winter flounder eggs hatched in any treatment from any of the experiments when sediment burial depths were greater than 2.5 mm. Taken together these experiments show a trend towards decreasing hatch with increasing depth of sediment deposition, but the variability between experiments makes it difficult to point to a detrimental effect threshold depth (Figure 3).

Effect of sediment thickness on time to hatch

In all three experiments delayed hatching was observed in several treatments containing sediment when compared to the no-sediment control treatment (Figures 4a-c). Mean days to hatching increased relative to the control when eggs were exposed to $\geq$0.6 mm of sediment in Experiments 1 and >1.2 mm in Experiments 2 and 3 (Table 1). Mean days to hatching may have increased relative to the control when eggs were exposed to $\geq$0.6 mm of sediment in Experiment 2 as well, but this was not a definite conclusion because of the low hatch rate in this treatment (2.4% of total hatch). Onset of hatch was delayed in sediment treatments in all three experiments, by as much as a week in some treatments, but the effect did not monotonically increase with increasing sediment depth (Figure 4a-c). This effect was particularly apparent in Experiment 2 (Figure 4b).

Seawater temperature regimes were similar for Experiment 1 and 2 (Table 2) and in both experiments eggs began hatching in the controls on day 18 (Figure 4a, b). Experiment 3 was conducted later in the year at seawater temperatures that averaged 2.5°C to 4.0°C higher, resulting in a shorter time to hatch. Eggs in Experiment 3 began hatching on day 11 (Figure 4c).

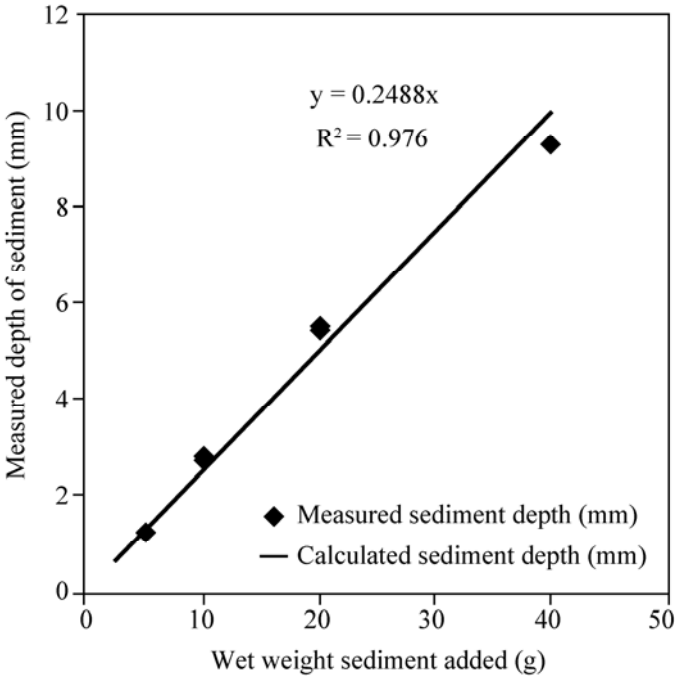

Figure 2. Determination of sediment depth via regression of measured sediment depth vs. wet weight of sediment added. Data are from all three experiments combined.

DISCUSSION

The goal of this study was to answer a simple question, "How much sediment can you deposit on winter flounder eggs before you affect their hatching?" Variability among experiments makes it difficult to determine a "no effect" depth of deposition. However, a trend of decreased hatching success and increased time to hatch with increasing depth of deposition relative to control treatments (no sediment added) was observed (Figure 3 and Table 1). Percent total hatch of eggs exposed to ≤1.0 mm sediment was generally not statistically different from that of the no sediment controls. There was little or no hatch in eggs exposed to >2.5 mm of sediment. Delayed time to hatch was observed in eggs exposed to as little as 0.6 mm of sediment.

What do our results mean in the context of natural sediment deposition in Narragansett Bay? The range of burial depths used in these experiments fell within the range of sediment deposition events observed on short-term time scales in Narragansett Bay and other estuarine and coastal systems. Oviatt and Nixon (1973) measured approximately 0.1 mm /day sediment deposition in the upper bay, and estimated that most of that was due to sediment resuspension. If that is true, then the mean natural net deposition over a two week hatching period should be well below the winter flounder egg sediment deposition tolerance seen in this study. Estuarine benthic organisms are frequently subjected to disturbance events caused by natural hydrodynamic processes as well as anthropogenic activities that disrupt and move sediments (Maurer et al. 1986, Hall 1994, Schaffner et al. 2001). Although sediment disturbance may be considered a stressor for some estuarine organisms (Schaffner et al. 2001, Hinchey et al. 2006), winter flounder eggs appear to be able to survive shallow (< 0.6 mm) sediment deposition. Benthic organisms are subject to respiratory stress upon burial, as molecular diffusion of oxygen into fine-grained sediments in the absence of advective flow, mixing, or bioirrigation only occurs via molecular diffusion and is limited to a distance of 1-2 mm (Rhoads 1974). Thus, it is possible that winter flounder eggs buried under more than 1 mm of sediment in our experiments were deprived of sufficient dissolved oxygen for survival.

Our findings of decreased survival of winter flounder eggs as a function of burial depth are similar to those reported in the few other studies available on the effects of burial on demersal fish eggs. Severe reduction of hatch at greater than several mm burial is generally consistent with studies on whitefish (Fudge and Bodaly 1984), pacific herring (Griffin et al 2009), and white perch (Morgan et al. 1983). It is difficult to make an exact comparison with the only other available winter flounder study done in the laboratory (Nelson and Wheeler 1997) because of the variability in our data, and the fact that the Nelson and Wheeler (1997) study was actually a study of suspended sediment effects and was not specifically designed to measure effects of sedimentation (D. A. Nelson, NOAA, personal communication).

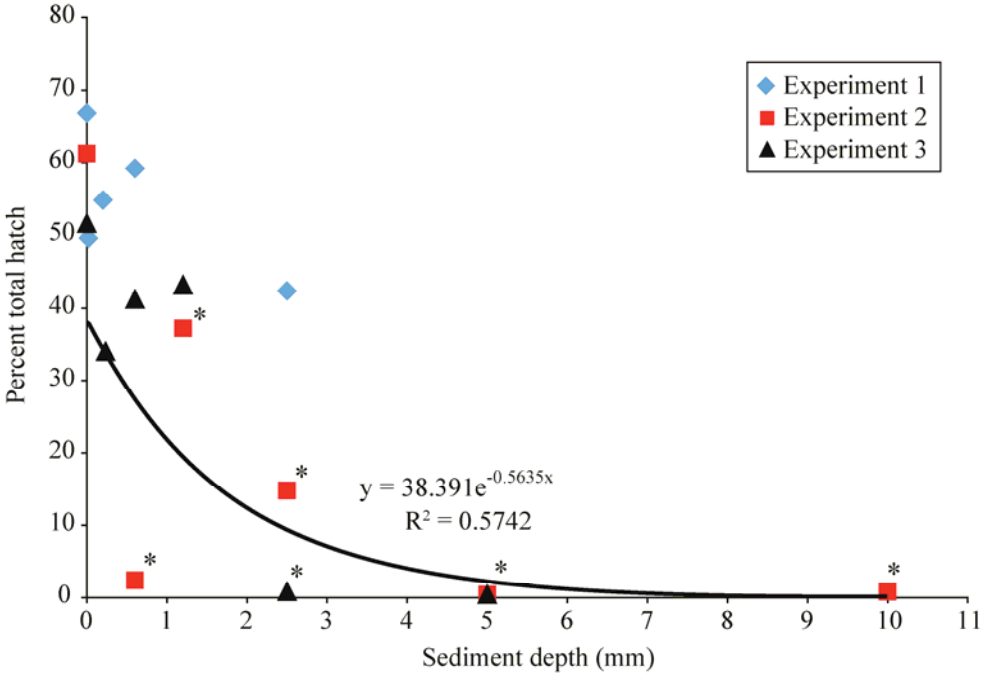

Figure 3. Percent hatch vs. sediment depth in Experiments 1,2, and 3 (n=250)

There have been numerous studies of the effects of siltation on the viability of stream-spawned salmonid eggs, which are actively placed by the female into "redds" and buried under coarse substrates (Waters 1995, Opperman et al. 2005). However, these studies are not directly applicable to winter flounder eggs, which are released by the female in the water column and sink to the sediment surface. Very few studies address the effects of sedimentation and burial on unattended demersal fish eggs (Fudge and Bodaly 1984). In an experiment in a lake in Manitoba, Canada, sedimentation of sand and silt substantially reduced the survival of whitefish (*Coregonus* sp.) eggs (Fudge and Bodaly 1984). In laboratory experiments on white perch (*Morone americana*) eggs (mean diameter of 0.9 mm), Morgan et al. (1983) exposed eggs to sediment thicknesses of 0.8 and 1.0 mm, corresponding to over half and greater than one egg diameter respectively. The thinner sediment layer caused over 50% mortality, whereas the thicker sediment layer caused 100% mortality. Development rates also decreased at sediment thicknesses ≥ 0.8 mm. Pacific herring (*Clupea pallasi)* eggs require a virtual absence of fine sediment to allow attachment to a substrate, and a very fine coating of sediment on the surface of the egg leads to reduced hatch rates (Griffin et al. 2009).

On first examination, the data from the Klein-MacPhee and Macy (2005) field deployment do not seem to correspond well with the data from this study. Klein-MacPhee and Macy (2005) found there was no significant difference in hatching rate between eggs placed in sediment trap/egg chambers near a channel being dredged and those placed in sediment trap/egg chambers farther from the dredge, even though the near-field chambers had a mean depth of 7.8 mm of sediment deposition and the far-field chambers had mean depth of 3.8 mm of sediment deposition. There are several reasons why the results from the Klein-MacPhee and Macy (2005) field deployment differ from those of our experiments. First, their exposure was not constant in the field. There is no way of knowing when the deposition occurred in the egg chambers. Second, the hatching rate at both field sites was very

low. Only 0.6% of the eggs in the near-field chambers were actually recovered as larvae, although a much larger number of eggs (10.6%) were still alive when the chambers were recovered, and a number of empty chorions were present, which can indicate hatching (the size of the screen on the top of the chamber would allow larvae to escape). Based on our results, we would have predicted that hatching rate in both sets of chambers would have been similar, and very low (see best-fit line on Figure 3), which is what Klein-MacPhee and Macy (2005) reported.

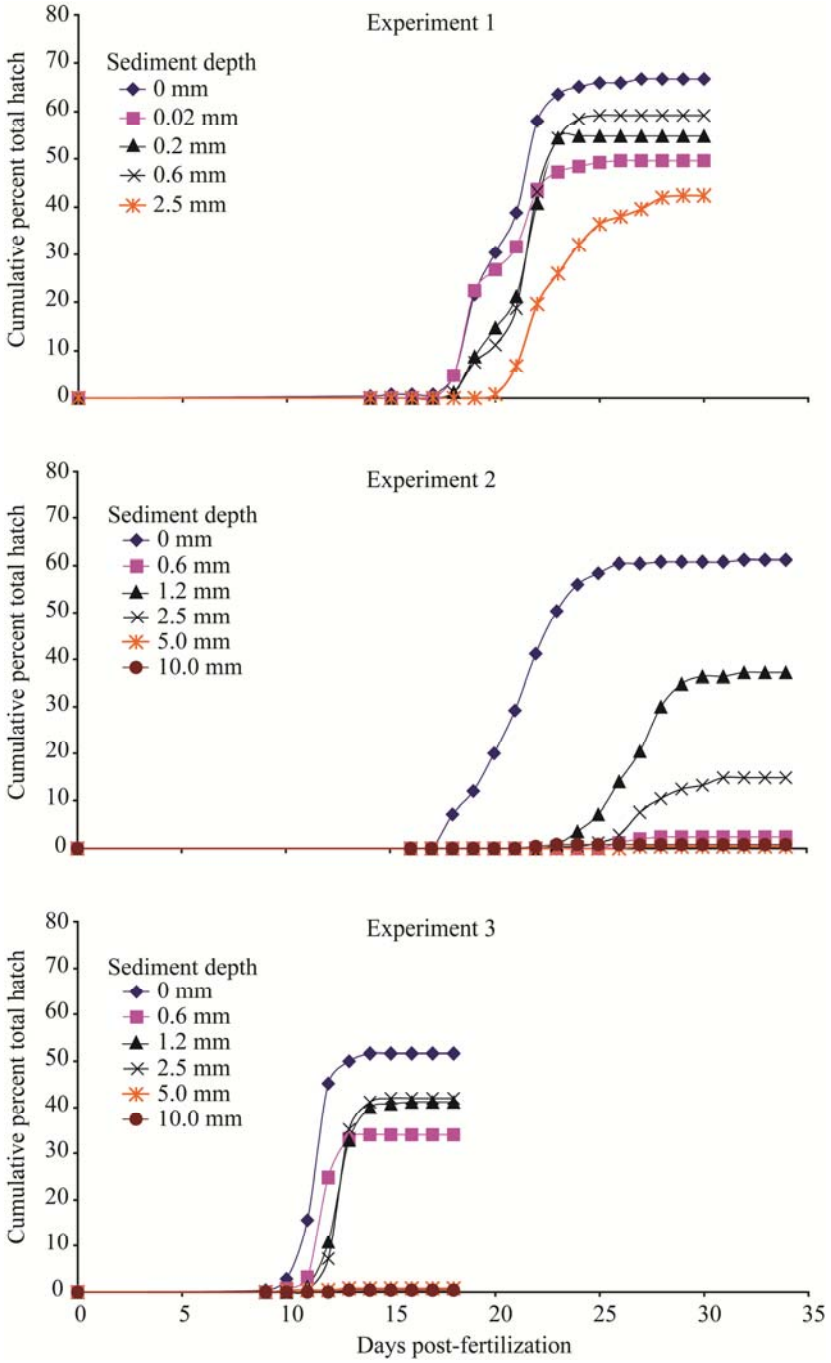

Figure 4. Cumulative percent total hatch vs. days post-fertilization in Experiments 1, 2, and 3.

In our study delayed hatch occurred at shallower treatment depths than reduced total hatch in two of the three experiments (Table 1). Longer time to hatch may allow increased predation of sand shrimp on winter flounder eggs, although burial may provide some refuge from sand shrimp predation (Taylor and Danila 2005). Delayed hatch due to burial might render newly-settled juveniles more vulnerable to predation due to increased temporal overlap of sand shrimp activity and vulnerable winter flounder life stages (Taylor 2005).

What do our results mean in the context of deposition due to dredging? Deposition near dredging activities is highly dependent on local hydrodynamics, sediment characteristics and dredge type, and even the skill of the dredge operator, so it is difficult to predict how much deposition will occur in the vicinity of a dredging operation. One set of measurements of sediment deposition due to dredging that is directly relevant to this study is available. Sediment traps placed at the same sites in Narragansett Bay at the same time as the Klein-MacPhee and Macy (2005) field egg deployments (plus 3 days when there were no eggs deployed, for a total of 17 days) collected 7.87 mm or 0.289g dry /cm^2 (0.017 g dry/cm^2/day) at the near-dredge site and 0.76 mm or 0.016 g/cm^2 (0.00094 g/cm^2/day) at the far-field site (J. King, U.R.I., personal communication). At the near-dredge deposition rate it would take approximately 5 days to deposit sediment equivalent to that in the 2.5 mm depth treatment in this study based on sediment depth (at 0.46 mm/day) or 3 days based on weight (10 grams wet sediment/test chamber with a 53 cm^2 base). This is a worst-case scenario, because sediment traps measure cumulative rather than net deposition. The traps do not allow for the loss of deposited sediments due to resuspension as would occur on natural bottoms so in the field the actual depth of sediment accumulation could be less.

The actual sedimentation rate probably varied greatly during the 17 days of the sediment trap deployment, peaking over a period of 3-4 days, as the dredge passed near the trap (Wilber and Clark 2001), and the effects of the burial might depend on when it occurred relative to the incubation period, but the total deposition does give an upper bound. Given this scenario, one could assume that most of the sediment in the near-dredge traps came from dredging resuspension since total deposition was 10x higher at the near-dredge site than at the far-field site. Therefore, similar dredging activities could potentially result in enough deposition during their 2-3 week long incubation period to cause reduced hatch, at least in areas very close to the dredging site (where the deposition was 7.8 mm. However, there is no way to know how much of the sediment in the traps (particularly in the far-field trap) was a result of natural vs. anthropogenic sediment deposition.

When interpreting the results of our study it must be remembered that our experiments were performed using only one sediment type, which was relatively clean. It is possible that other sediments, which might have different geophysical properties or different contaminants, might have different effects on winter flounder eggs. Also, it is important to remember that this study represents a worst case-scenario relative to sediment deposition, with the eggs being exposed during almost their entire incubation period. Shorter exposure durations during the incubation period might produce less severe effects. Extrapolation of lab results to the field is further complicated by the fact that lab exposures are largely static while field exposures are likely to be dynamic. Exposures in the field could be influenced by tidal current, resuspension of sediment, and transport of eggs from their original location.

In a modeling exercise Lackey et al. (2009) predicted for a hypothetical dredging scenario in Newark Bay, New Jersey that there would be little risk of detrimental effects of dredging on winter flounder eggs because the estimated sediment deposition rates in the shallow areas adjacent to the dredging site were extremely low. Predicted deposition thicknesses did not exceed a very small fraction of an egg diameter. However, Lackey et al. (2009) did not have detailed information on spawning area locations.

There are published examples where modeling has been used to predict the environmental impacts of dredging operations on the sensitive life stages of other fish species. Fitzpatrick et al. (2009) combined laboratory data on the effects on simulated dredged material on the sensitive life stages of pink snapper (*Pagurus auratus*) with a dredging model to predict the effects of dredging on that species. Similarly, the data on the effects of sediment deposition on hatching of winter flounder eggs contained in this paper should be useful to environmental decision makers when combined with site-specific information on spawning and model predictions of sediment deposition due to proposed dredging activity.

CONCLUSIONS

This study showed that, in the laboratory, winter flounder eggs were affected by deposition of as little as 0.65 mm of clean sediment, equivalent to slightly less than one egg diameter. In deposition depths greater than 2.5 mm there was virtually no hatch. These data should be taken into account whenever seasonal constraints for the protection of winter flounder are considered.

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REFERENCES

ASMFC (Atlantic States Marine Fisheries Commission). (2006). *Fisheries Focus*. 15(8) (November 2006).

Bourne, D. W. and Govoni, J.J. (1988). "Distribution of fish eggs and larvae and patterns of water circulation in Narragansett Bay", *1972-1973 American Fisheries Society Symposium,* 3, 132-148.

Collette, B.B., and Klein-MacPhee, G., editors. (2002). *Bigelow and Schroeder's Fishes of The Gulf of Maine, third edition,* Smithsonian Institution Press, Washington and London.

Collie, J.S., Wood, A.D., and Jeffries, H.P. (2008). "Long term shifts in the species composition of a coastal fish community. *Canadian Journal of Fisheries and Aquatic Science*. 65, 1352-1365.

Fitzpatrick, N., Burling, M., and Bailey, M. (2009). "Modelling the marine environmental impacts of dredge operations in Cockburn Sound, WA." Coasts and Ports 2009, 16-18 September 2009, Wellington, New Zealand, paper 111, CD-ROM.

Fudge, R.J., and Bodaly, R.A. (1984). "Postimpoundment winter sedimentation and survival of lake Whitefish (*Coregonus clupeaformis)* eggs in Southern Indian Lake, Manitoba." *Canadian Journal of Fisheries and Aquatic Science,* 41, 701-705.

Griffin, F.J., Smith, E.H. Vines, C.A. and Cherr, G.N. (2009). "Impacts of suspended sediments on fertilization embryonic development, and early larval life stages of the Pacific herring, *Clupea pallasi." Biological Bulletin,* 216, 175-187.

Hall, S.J. (1994). "Physical disturbance and marine benthic communities: life in unconsolidated sediments." *Oceanography and Marine Biology Annual Review,* 32, 179-239.

Hinchey, E.K., Schaffner, L.C., Hoar, C.C., Vogt, B.W., and Batte, L.P. (2006). "Responses of estuarine benthic invertebrates to sediment burial; the importance of mobility and adaptation." *Hydrobiologia,* 556, 85-98.

Keller , A. A. and Klein-MacPhee, G. (2000). "Impact of elevated temperature on the growth, survival, and trophic dynamics of winter flounder larvae: a mesocosm study." *Canadian Journal of Fisheries and Aquatic Science*, 57, 2382-2392.

Klein-MacPhee, G., and Macy, W. K. (2005). "*In Situ* Effects of Suspended Particulate Loads Produced by Dredging on Eggs of Winter Flounder (Pseudopleuronectes americanus)." Final Report to Hudson River Foundation. HRF Grant Number 001/04E. March 14, 2005.

Lackey, T.C., Kim, S.-C. and Clarke, D.G. (2009). "Assessment of dredging-induced sedimentation on winter flounder spawning habitat." *Proceedings, Western Dredging Association, Twenty-Ninth Annual Technical Conference, Tempe,* AZ., USA.

LaSalle, M.W., Clarke, D.G., Homziak, J., Lunz, J.D., Fredette, T.D. (1991). *A framework for assessing the need for seasonal restrictions an dredging and disposal operations."* Technical Report D-92-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Maurer, D., Keck, R.T., Tinsman, J.C., Leathem, W.A., Wethe C., Lord, C. and Church, T. M. (1986). "Vertical migration and mortality of marine benthos in dredged material: a synthesis." *International Revue der Gesampten Hydrobiologia,* 71, 50-63.

Morgan, R.P. II, Rasin, V.J., Jr., and Noe, L. A. (1983). "Sediment effects on eggs and larvae of striped bass and white perch." *Transactions of the American Fisheries Society,* 112, 220-224.

Nelson, D.A., and Wheeler, G.L. (1997). "The influence of dredging-induced turbidity and associated contaminants upon the hatching success and larval survival of winter flounder, *Pseudopleuronectes americanus*: A laboratory study." Final Report on Grant CWF #321-R. University of New Haven, Institute of Analytical and Environmental Chemistry, New Haven, CT.

Opperman, J.J., Lohse, K.A., Brooks, C., Kelly, N.M., and Merenlender, A.M. (2005). "Influence of land use on fine sediment in salmonids spawning gravels within the Russian River Basin, California." *Canadian Journal of Fisheries and Aquatic Science,* 62, 2740-2751.

Oviatt, C. A., and Nixon, S.W. (1973). "Sediment resuspension and deposition in Narragansett Bay" *Estuarine and Coastal Marine Science*, 3, 201-2-17.

Rhoads, D. C. (1974). "Organism-sediment relations on the muddy sea floor." *Oceanography and Marine Biology Annual Review,* 12, 263-300.

SAS Institute Inc. (2002-2004). *SAS 9.1.3 Help and Documentation*, Cary, NC.

Schaffner, L.C., Dellapenna, T.M., Hinchey, E.K., Friedrichs, C.T., Neubauer, M.T., Smith, M.E., and Kuehl, S.A. (2001)."Physical energy regimes, sea-bed dynamics and organism-sediment interactions along an estuarine gradient." In Aller, J.Y., Woodin, S.A., and Aller, R.C. (editors), *Organism-Sediment Interactions*. University of South Carolina Press, Columbia, SC: 161-182.

Taylor, D.L. (2005). "Predation on post-settlement winter flounder *Pseudopleuronectes americanus* by sand shrimp *Crangon septemspinosa* in NW Atlantic estuaries." *Marine Ecology progress Series*, 289, 245-262.

Taylor, D.L.,and Danila, D.J. (2005). "Predation on winter flounder (*Pseudopleuronectes americanus)* eggs by the sand shrimp (*Crangon septemspinosa*)." *Canadian Journal of Fisheries and Aquatic Science*, 62, 1611-1625.

Waters, T.F. (1995). *Sediment in streams: sources, biological effects, and control*. American Fisheries Society, Monograph No.7: Bethesda, Md.

Wilber, D.H., and Clarke, D.G. (2001). "Biological effects of suspended sediments: A review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries." *North American Journal of Fisheries Management,* 21, 855-875.

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