Measurement of nutrients in bottom water under and adjacent to the Deepwater Point mussel farm in Totten Inlet, Washington

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ABSTRACT. An in-situ multi port bottom water sampler was designed to assess nutrient regeneration from sediment under and within 30 m downcurrent of raft cultured mussels in Totten Inlet, Washington State. Bottom water was simultaneously pumped through a series of color coded polyethylene tubes conveying water from ports at 2.0, 20.0 and 50.0 cm above the sediment's surface by peristaltic pump. Sediments under the rafts did not have elevated concentrations of total volatile solids when the samples were collected, but were anaerobic and contained between 1,571 and 2,620 μM of free sulfides. Free sulfides declined exponentially with distance from the raft complexes center and were 760 μM $S^{=}$ on the perimeter and at background beyond that. Statistically significant increases in all nutrients except nitrate were observed 2.0 cm above the sediment's surface under the rafts in comparison with reference conditions. Dissolved inorganic nitrogen, ammonium and phosphate were significantly elevated under the farm at elevations of 2.0 and 20 cm but not at 50 cm height above the sediments. Consistent trends in concentrations of silicate were not observed at any distance or elevation. Significant increases were not observed for any nutrient above reference concentrations on the perimeter of the farm or at 30 m downcurrent. These results indicate that significant quantities of dissolved inorganic nitrogen and phosphate were being regenerated from sediments under the center of the rafts but that the regenerating area did not extend to or beyond the raft's perimeter. When combined with simultaneous current speeds in the benthic boundary layer, this methodology will provide a simple and inexpensive means of determining the flux of nutrients from enriched sediments under aquaculture facilities located in waters shallow enough to allow surface connections with polyethylene tubing.

Keywords: Mussel culture, benthos, dissolved nutrients.

INTRODUCTION

In an effort to help federal, state and local resource agencies and the public understand the environmental costs associated with intensive mussel culture on rafts, the Pacific Shellfish Institute (PSI) was funded by the National Oceanographic and Atmospheric Agency (NOAA) to determine the flux of suspended particulate matter through a commercial mussel culture in South Puget Sound and to measure rates of mussel feeding and the associated sedimentation of organic and inorganic matter. This information will be useful in modifying tidal flow models for South Puget Sound to assess the role that cultured mussels play in affecting the region's marine carrying capacity. Mussel cultures provide a complex habitat supporting a variety of plants and animals. These fouling organisms, together with the cultured mussels, consume phytoplankton, organic detritus and oxygen and they produce metabolic waste. Much of that waste, particularly bivalve feces and pseudofeces is deposited under and adjacent to the rafts.

The distances at which benthic effects occur in association with these cultures are a function of the size, shape and density of the discharged particles, water depths below the point of discharge and current speeds. Within the narrow range of salinities and temperatures found in

Totten Inlet, water density will not have an appreciable effect on settling rates. Haamer (1996) reported that the settling speed of feces from harvest size mussels varied between 2 and 10 cm/sec. If one conservatively assumes that mussel feces and pseudofeces settle with an average vertical velocity of 3 cm/sec; that the mean water depth under the mussel lines at the Deepwater Point mussel farm is 7.8 m; and that the mean current speed is 16.0 cm/sec (Gardiner *et al.*, 2004) then the average fecal pellet is expected to be carried 41.6 m from the perimeter of the rafts. This is an average distance and because these tides are harmonically driven, higher deposition is expected under the rafts and lower deposition rates would occur further than 41.6 m from the rafts. In areas of high current speeds in the benthic boundary layer, it is possible for recently sedimented (unconsolidated) fecal material to be resuspended and moved downcurrent. Chromey *et al.* (2002a) estimated a critical resuspension speed of 9.5 cm/sec. However, it should be emphasized that this critical speed is within the benthic boundary layer where currents are typically not measured and where their magnitude may be significantly reduced. Validation studies considered by the Canadian Department of Fisheries and Oceans Science Review Symposium (DFO, 2005) indicated that the DEPOMOD model (Cromey *et al.*, 2002b) did not reasonably predict sediment physicochemical conditions with *resuspension turned on.* Reasonably accurate predictions were obtained when the resuspension module was turned off (Stucchi, unpublished). In an effort to modify DEPOMOD, Brooks (unpublished) has developed a simple spreadsheet model predicting TVS or TOC increases in surficial sediments under and near salmon farms. This model indicates that the deposition of salmon farm waste is accounted for in the near field suggesting little resuspension and transport. This approach was modified and used by Stucchi (unpublished) to verify the conclusions. Questions regarding resuspension and movement downcurrent of organic waste from intensive aquaculture facilities is a current topic of discussion that has not yet been resolved. However, much of the evidence suggests that except where mid-depth maximum current speeds exceed 50 cm/sec, there is little resuspension and further transport of aquaculture wastes following initial integration with the sediments.

Stenton-Dozey *et al.* (1999) observed that ammonium (NH_4^+) was the principal form of nitrogen released from sediments under *M. e. galloprovincialis* culture rafts in Saldanha Bay, South Africa. The mean observed rate was 1,400 μM NH_4^+ /m^2-hr. Other forms of DIN (nitrate and nitrite) generation were 2 to 3 orders of magnitude lower than ammonium releases. Other estimates of ammonium release from sediments vary between 1,000 and 10,000 μM NH_4/m^2-hr (Dame *et al.,* 1989, 1991a, 1992; Asmus and Asmus, 1991) with higher rates in summer when compared with winter (Dame *et al.* 1992)

Newell (*In-review*) reviewed nitrogen cycling in estuaries associated with intensive bivalve culture and suggested that when surficial sediments are maintained at positive redox conditions, there is a potential for the conversion of ammonium to N_2 gas, which is unavailable to primary producers and is ultimately lost to the atmosphere. This process requires oxidation of the NH_4^+ to NO_2^- and then to NO_3^-. Therefore, surficial sediments must have positive redox potential or the NH_4 simply diffuses both back into the water and/or deeper into the sediment. In aerobic conditions, some of the nitrate is recycled back into the water where it is available for uptake by phytoplankton. Another portion diffuses downward into sediments reaching depths having negative redox potential. This fraction is converted to N_2 gas by denitrifying bacteria (Henriksen and Kemp, 1988; Risgaard-Petersen, *et al.,* 1994). Where benthic flora is absent, the resulting N_2 is unavailable to phytoplankton as it rises to the water's surface where it is lost to the atmosphere. In contrast, under anaerobic conditions, nitrogen is primarily released from the sediments as ammonium and can further stimulate primary production. However, Newell (*In-review*) noted

that, "Nonetheless, the total amount of nutrients regenerated directly by bivalve excretion and the microbial degradation of their biodeposits cannot be any greater than if the phytoplankton was being degraded solely by pelagic organisms. Consequently, maximum phytoplankton standing stock supported by the nutrients regenerated through bivalve populations cannot exceed the level that can be sustained by ambient conditions." To demonstrate this process, Newell *et al.* (2002) inoculated sediments with palletized phytoplankton cells to mimic oyster feces and pseudofeces. Under aerobic conditions (positive redox), coupled nitrification – denitrification resulted in nitrification (N_2) of about 20% of the total added nitrogen. Ideal conditions for the coupled nitrification – denitrification and ultimate loss of nitrogen from estuaries occurs at depths where light penetration is insufficient to support benthic flora and where the reduction-oxidation potential discontinuity is sufficiently shallow to create short diffusion distances between the necessary oxidative and reducing processes. Mussel rafts may provide an ideal environment for this extractive process because they shade the benthos reducing the growth of benthic plants and because biodeposits from the cultured mussels and their symbiotic communities can create negative redox potentials at shallow depths (a few millimeters). This process provides another pathway for extracting nitrogen from eutrophic systems.

Brooks (2005a) observed that fine grained surficial sediments (upper 2.0 cm) were composed of 75.7 $\pm$ 6.2 percent silt and clay south of the entrance to Totten Inlet. Sediments were significantly organically enriched with elevated TVS (7.8 $\pm$ 0.45%), slightly elevated sulfides (162.1 $\pm$ 28.2 μM), and near zero redox potentials (-26.0 $\pm$ 20.3 mV). The depth of the redox potential discontinuity (RPD) was 3.4 $\pm$ 0.4 cm) suggesting that surficial sediments were not anaerobic. Underwater video at the North Totten and Deepwater Point sites in Totten Inlet recorded little macroalgae and scattered mats of benthic diatoms of varying densities. The high TVS, elevated sulfides and low redox potential indicates significant biological oxygen demand associated with the biogeochemical processing of this sedimented TVS leading to the accumulation of dissolved inorganic nitrogen. The moderate depth of the RPD and lack of significant coverage of the benthos by primary producers indicates that at least a portion of the nitrogenous waste may be released as elemental nitrogen and another portion as dissolved inorganic nitrogen (NO_2, NO_3, and NH_4^+).

The purpose of this preliminary study was to assess a new approach to measuring dissolved nutrient concentrations at heights of 2.0, 20.0 and 50.0 cm above the sediment water interface as a function of distance from the center of Taylor Resources Deepwater Point mussel farm in Totten Inlet. This report describes the results of a single sampling event conducted on July 8, 2002.

2. Methods. Triplicate water samples were collected, using the device described in Figure 2, at heights of 2, 20 and 50 cm above the bottom in the center of the inner row of rafts at the Deepwater Point mussel farm; on the perimeter of the array of rafts; at 30 m downcurrent from the perimeter where sulfides have been seen to reach background concentrations; and at a local reference station (Table 1 and Figure 1). Samples were collected into new 250 ml HDPE bottles using a Portable Masterflex L/S™ peristaltic pump on July 10, 2002. The pump was run for 3 to 5 minutes to evacuate all water from the lines and the tube ends were then placed in the sample bottles. The pump was run until approximately three volumes of water had flowed through the sample bottles. They were then capped with no head space and stored on ice while in the field. Subsamples were filtered on 0.45 μm glass filters into 25 ml glass scintillation vials with approximately one cm of headspace on the day of collection, frozen, and shipped on phase change gel packs via an overnight delivery service to the University of Washington Oceanographic

Laboratory, using standard chain-of-custody procedures (PSEP, 1996). Samples analyzed for PO_4, SiO_4, NO_3-N, NO_2-N and NH_4, using a Technicon Auto Analyzer Model AAII.

3. Results. Thirty-six water samples were collected on July 10, 2002 within 1.5 hours of slack tide. A copy of the Statistica™ Version 6 database is provided in Appendix (1) and summarized by sample station in Table 2. Figure 2 summarizes the total dissolved nitrogen results as a function of distance from the rafts.

The results of a multifactor analysis of variance are provided in Table 3 following by post hoc testing using Duncan's test with multiple ranges in Table 4a for total nitrogen ($NO_2 + NO_3 + NH_4$); 4b for ammonium (NH_4); 4c for nitrite; 4d for nitrate; 4e for phosphate; and 4f for silicate. In general dissolved nutrient concentrations were high under the mussel rafts and at the reference station located 1,120 m to the north, with reduced concentrations on the raft's perimeter and at 30 m downcurrent. Significant differences as a function of height above the sediment were not observed at the reference station for any of the dissolved nutrients. Concentrations of total nitrogen and ammonium were significantly higher in the center of the farm at elevations of 2.0 and 20.0 cm, but not at 50 cm above the sediment-water interface when compared with concentrations on the perimeter, at 30 m or at the reference station. This suggests that nitrogen, including ammonium, was being released from sediments under the farm back into the water column. Brooks (2005b) observed total free sediment sulfide concentrations of 1571, 2050 and 2160 μM in sediments from the center of this farm on July 8, 2002. Free sulfides were lower (1110 μM) in sediments on the perimeter of the farm on that same day.

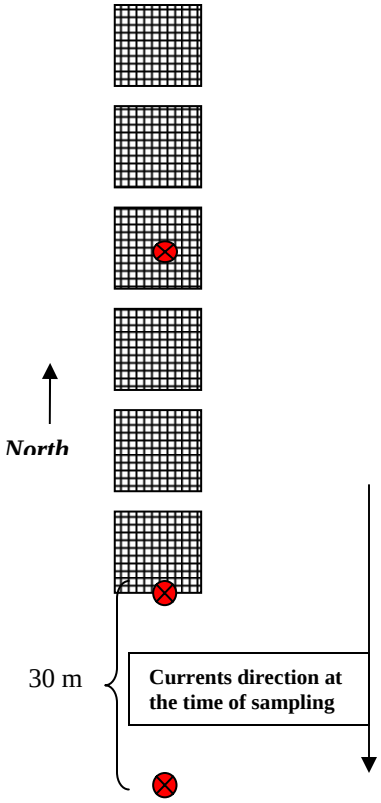

Figure 1. Schematic location of bottom nutrient water samples collected at the Deepwater Point mussel farm on Julv 10. 2002

Table 1. Location of bottom water nutrient samples collected on July 10, 2002 at Deepwater Point in Totten Inlet, Washington. Low tide was -2.8' at 1244 hours.

Station	Bearing	Time	Distance (m)	Depth (feet)	Latitude	Longitude
Farm Center	-	1407	Center	Not measured	Not measured	Not measured
Downcurrent Perimeter	180 ^{o} Mag.	1423	Perimeter	28.7	47^o 07.680' N	123^o 01.190' W
30 m downcurrent	180 ^{o} Mag.	1333	30	26.0	47^o 07.663' N	123^o 01.196' W
Control	000 ^{o} Mag.	1243	1000	30.5	47^o 08.227' N	123^o 00.985' W

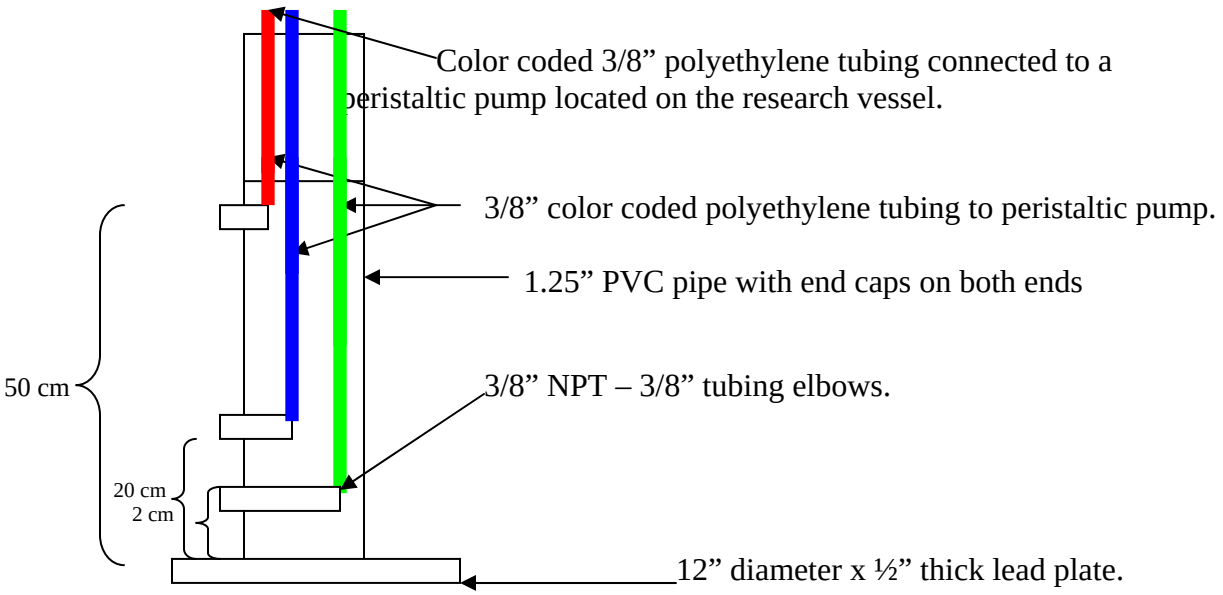

Figure 2. Apparatus used to collect bottom water samples for nutrient analysis at Taylor Resources Deepwater Point mussel farm in Totten Inlet during July 2002.

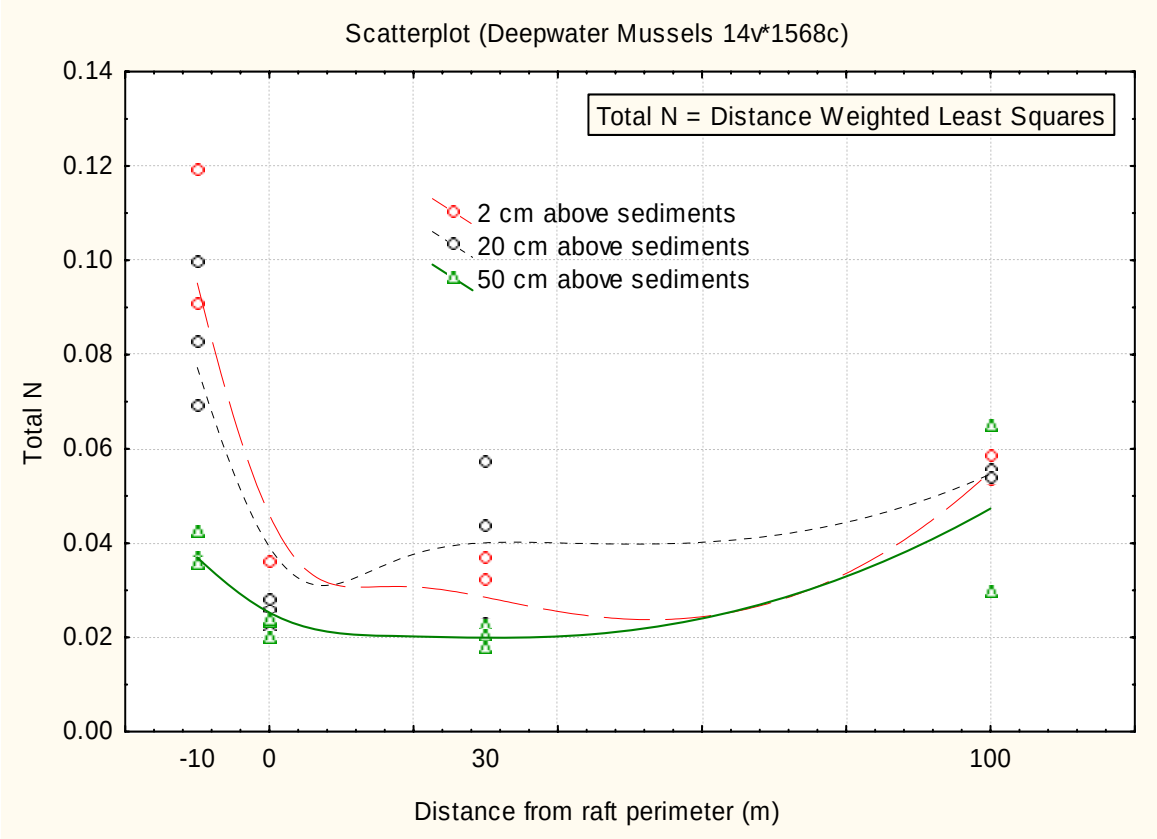

Figure 3. Total dissolved nitrogen concentrations in seawater collected at three elevations above the sediment-water interface near the Deepwater Point mussel farm on July 10, 2002.

Table 2. Summary results describing nutrient concentrations (mg/L) in bottom water samples collected at the Deepwater Point mussel farm in Totten Inlet on July 10, 2002. Distances are measured in meters from the perimeter of the farm and elevations in cm above the sediment-water interface.

Breakdown Table of Descriptive Statistics (Deepwater Point Bottom Nutrients)
N=36 (No missing data in dep. var. list)

Distance	Elevation (cm)	PO4-P Means	Confidence +95.000%	SiO4 (Si) Means	Confidence +95.000%	NO3-N Means	Confidence +95.000%	NO2-N Means	Confidence +95.000%	NH4-N Means	Confidence +95.000%	DIN Means	Confidence +95.000%	N
-10	2	0.061	0.071	1.143	1.229	0.006	0.007	0.002	0.002	0.096	0.133	0.103	0.140	3
-10	20	0.057	0.070	1.096	1.110	0.006	0.007	0.002	0.002	0.076	0.115	0.084	0.122	3
-10	50	0.048	0.049	1.082	1.118	0.005	0.007	0.001	0.001	0.032	0.040	0.038	0.048	3
0	2	0.048	0.049	1.102	1.166	0.003	0.004	0.001	0.001	0.025	0.039	0.029	0.044	3
0	20	0.047	0.049	1.141	1.167	0.003	0.005	0.001	0.001	0.021	0.029	0.025	0.034	3
0	50	0.047	0.048	1.088	1.127	0.003	0.003	0.001	0.001	0.019	0.024	0.022	0.028	3
30	2	0.049	0.053	1.150	1.345	0.003	0.003	0.001	0.001	0.026	0.047	0.030	0.051	3
30	20	0.051	0.057	1.121	1.165	0.004	0.009	0.001	0.002	0.036	0.075	0.041	0.084	3
30	50	0.048	0.050	1.166	1.314	0.003	0.003	0.001	0.001	0.017	0.022	0.020	0.026	3
1120	2	0.053	0.054	1.069	1.099	0.006	0.007	0.001	0.001	0.048	0.055	0.055	0.062	3
1120	20	0.052	0.060	1.050	1.182	0.007	0.014	0.001	0.002	0.070	0.166	0.079	0.181	3
1120	50	0.051	0.072	1.039	1.261	0.008	0.023	0.001	0.002	0.046	0.090	0.055	0.112	3
All Groups		0.051	0.053	1.104	1.122	0.005	0.006	0.001	0.001	0.043	0.052	0.049	0.059	36

Table 3. Results of an analysis of variance describing the significance of differences in bottom water nutrient concentrations as a function of location and elevation above the sediment-water interface near the Deepwater Point mussel farm in Totten Inlet on July 10, 2002.

Analysis of Variance (Deepwater Point Bottom Nutrients)
Marked effects are significant at p < .05000

Variable	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
PO4-P	0.001	11.000	0.000	0.000	23.000	0.000	5.607	0.000
SiO4 (Si)	0.055	11.000	0.005	0.045	23.000	0.002	2.548	0.028
NO3-N	0.000	11.000	0.000	0.000	23.000	0.000	2.269	0.047
NO2-N	0.000	11.000	0.000	0.000	23.000	0.000	9.022	0.000
NH4-N	0.019	11.000	0.002	0.002	23.000	0.000	17.556	0.000
DIN	0.022	11.000	0.002	0.003	23.000	0.000	15.989	0.000

Table 4. Results of post hoc testing evaluating the significance of differences in dissolved nutrients at specific locations and elevations above the sediment-water interface near the Deepwater Point mussel farm on July 10, 2002. Concentrations provided in mg nutrient/L.

Duncan test; Variable: DIN (Deepwater Point Bottom Nutrients)
Marked differences are significant at p < .05000

Distance	Elevation (cm)		{1} M=.10318	{2} M=.08393	{3} M=.03829	{4} M=.02902	{5} M=.02509	{6} M=.02245	{7} M=.02988	{8} M=.04131	{9} M=.02018	{10} M=.05520	{11} M=.05463	{12} M=.05539
-10	2	{1}		0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10	20	{2}	0.049		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.005
-10	50	{3}	0.000	0.000		0.354	0.204	0.137	0.372	0.747	0.095	0.106	0.107	0.110
0	2	{4}	0.000	0.000	0.354		0.675	0.510	0.927	0.236	0.392	0.018	0.019	0.019
0	20	{5}	0.000	0.000	0.204	0.675		0.778	0.631	0.128	0.621	0.008	0.008	0.008
0	50	{6}	0.000	0.000	0.137	0.510	0.778		0.471	0.083	0.808	0.005	0.005	0.005
30	2	{7}	0.000	0.000	0.372	0.927	0.631	0.471		0.255	0.358	0.020	0.021	0.021
30	20	{8}	0.000	0.000	0.747	0.236	0.128	0.083	0.255		0.056	0.168	0.163	0.176
30	50	{9}	0.000	0.000	0.095	0.392	0.621	0.808	0.358	0.056		0.003	0.003	0.003
1120	2	{10}	0.000	0.007	0.106	0.018	0.008	0.005	0.020	0.168	0.003		0.951	0.984
1120	20	{11}	0.000	0.007	0.107	0.019	0.008	0.005	0.021	0.163	0.003	0.951		0.940
1120	50	{12}	0.000	0.005	0.110	0.019	0.008	0.005	0.021	0.176	0.003	0.984	0.940	

4a) Total dissolved inorganic nitrogen

Table 4, continued.

Distance Elevation (cm)	Duncan test; Variable: NH4-N (Deepwater Point Bottom Nutrients) Marked differences are significant at p < .05000											
	{1} M=.09604	{2} M=.07637	{3} M=.03187	{4} M=.02473	{5} M=.02110	{6} M=.01875	{7} M=.02648	{8} M=.03649	{9} M=.01680	{10} M=.04840	{11} M=.04754	{12} M=.04615
-10 2 {1}		0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10 20 {2}	0.027		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.003	0.002
-10 50 {3}	0.000	0.000		0.428	0.250	0.171	0.525	0.585	0.123	0.087	0.097	0.118
0 2 {4}	0.000	0.000	0.428		0.667	0.506	0.836	0.209	0.394	0.019	0.022	0.029
0 20 {5}	0.000	0.000	0.250	0.667		0.781	0.549	0.110	0.632	0.008	0.010	0.013
0 50 {6}	0.000	0.000	0.171	0.506	0.781		0.406	0.071	0.817	0.005	0.006	0.007
30 2 {7}	0.000	0.000	0.525	0.836	0.549	0.406		0.268	0.310	0.028	0.031	0.040
30 20 {8}	0.000	0.000	0.585	0.209	0.110	0.071	0.268		0.049	0.204	0.223	0.259
30 50 {9}	0.000	0.000	0.123	0.394	0.632	0.817	0.310	0.049		0.003	0.003	0.005
1120 2 {10}	0.000	0.003	0.087	0.019	0.008	0.005	0.028	0.204	0.003		0.919	0.802
1120 20 {11}	0.000	0.003	0.097	0.022	0.010	0.006	0.031	0.223	0.003	0.919		0.869
1120 50 {12}	0.000	0.002	0.118	0.029	0.013	0.007	0.040	0.259	0.005	0.802	0.869	

4b) Ammonium

Distance Elevation (cm)	Duncan test; Variable: NO2-N (Deepwater Point Bottom Nutrients) Marked differences are significant at p < .05000											
	{1} M=.00159	{2} M=.00165	{3} M=.00115	{4} M=.00097	{5} M=.00081	{6} M=.00085	{7} M=.00073	{8} M=.00099	{9} M=.00077	{10} M=.00124	{11} M=.00120	{12} M=.00136
-10 2 {1}		0.690	0.012	0.001	0.000	0.000	0.000	0.001	0.000	0.035	0.024	0.136
-10 20 {2}	0.690		0.006	0.000	0.000	0.000	0.000	0.001	0.000	0.017	0.011	0.077
-10 50 {3}	0.012	0.006		0.266	0.053	0.079	0.022	0.303	0.033	0.567	0.717	0.205
0 2 {4}	0.001	0.000	0.266		0.332	0.437	0.175	0.880	0.235	0.114	0.163	0.027
0 20 {5}	0.000	0.000	0.053	0.332		0.798	0.635	0.283	0.779	0.018	0.028	0.003
0 50 {6}	0.000	0.000	0.079	0.437	0.798		0.490	0.383	0.614	0.028	0.043	0.005
30 2 {7}	0.000	0.000	0.022	0.175	0.635	0.490		0.143	0.823	0.007	0.011	0.001
30 20 {8}	0.001	0.001	0.303	0.880	0.283	0.383	0.143		0.195	0.139	0.192	0.034
30 50 {9}	0.000	0.000	0.033	0.235	0.779	0.614	0.823	0.195		0.010	0.017	0.002
1120 2 {10}	0.035	0.017	0.567	0.114	0.018	0.028	0.007	0.139	0.010		0.805	0.427
1120 20 {11}	0.024	0.011	0.717	0.163	0.028	0.043	0.011	0.192	0.017	0.805		0.328
1120 50 {12}	0.136	0.077	0.205	0.027	0.003	0.005	0.001	0.034	0.002	0.427	0.328	

4c) nitrite

Distance Elevation (cm)	Duncan test; Variable: NO3-N (Deepwater Point Bottom Nutrients) Marked differences are significant at p < .05000											
	{1} M=.00555	{2} M=.00591	{3} M=.00528	{4} M=.00332	{5} M=.00318	{6} M=.00285	{7} M=.00266	{8} M=.00383	{9} M=.00261	{10} M=.00557	{11} M=.00589	{12} M=.00788
-10 2 {1}		0.841	0.867	0.216	0.199	0.150	0.129	0.322	0.125	0.991	0.845	0.204
-10 20 {2}	0.841		0.729	0.171	0.153	0.113	0.095	0.264	0.091	0.843	0.989	0.230
-10 50 {3}	0.867	0.729		0.261	0.244	0.188	0.163	0.376	0.159	0.866	0.732	0.164
0 2 {4}	0.216	0.171	0.261		0.933	0.785	0.714	0.754	0.697	0.221	0.170	0.020
0 20 {5}	0.199	0.153	0.244	0.933		0.837	0.764	0.708	0.749	0.201	0.153	0.018
0 50 {6}	0.150	0.113	0.188	0.785	0.837		0.910	0.583	0.890	0.151	0.113	0.012
30 2 {7}	0.129	0.095	0.163	0.714	0.764	0.910		0.524	0.973	0.129	0.096	0.010
30 20 {8}	0.322	0.264	0.376	0.754	0.708	0.583	0.524		0.510	0.332	0.262	0.035
30 50 {9}	0.125	0.091	0.159	0.697	0.749	0.890	0.973	0.510		0.125	0.092	0.009
1120 2 {10}	0.991	0.843	0.866	0.221	0.201	0.151	0.129	0.332	0.125		0.844	0.199
1120 20 {11}	0.845	0.989	0.732	0.170	0.153	0.113	0.096	0.262	0.092	0.844		0.251
1120 50 {12}	0.204	0.230	0.164	0.020	0.018	0.012	0.010	0.035	0.009	0.199	0.251	

4d) Nitrate

Distance Elevation	Duncan test; Variable: PO4 (Deepwater Mussels) Marked differences are significant at p < .05000											
	{1} M=.06138	{2} M=.05744	{3} M=.04759	{4} M=.04768	{5} M=.04743	{6} M=.04704	{7} M=.04884	{8} M=.05062	{9} M=.04762	{10} M=.05328	{11} M=.05224	{12} M=.05142
-10 2 {1}		0.156	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.008	0.004	0.002
-10 20 {2}	0.156		0.004	0.003	0.003	0.002	0.008	0.030	0.003	0.135	0.079	0.050
-10 50 {3}	0.000	0.004		0.978	0.952	0.848	0.678	0.324	0.991	0.078	0.143	0.221
0 2 {4}	0.000	0.003	0.978		0.936	0.837	0.671	0.312	0.984	0.077	0.140	0.215
0 20 {5}	0.000	0.003	0.952	0.936		0.885	0.645	0.305	0.947	0.072	0.133	0.206
0 50 {6}	0.000	0.002	0.848	0.837	0.885		0.562	0.255	0.845	0.057	0.107	0.170
30 2 {7}	0.000	0.008	0.678	0.671	0.645	0.562		0.513	0.675	0.151	0.258	0.373
30 20 {8}	0.001	0.030	0.324	0.312	0.305	0.255	0.513		0.319	0.376	0.575	0.768
30 50 {9}	0.000	0.003	0.991	0.984	0.947	0.845	0.675	0.319		0.077	0.141	0.218
500 2 {10}	0.008	0.135	0.078	0.077	0.072	0.057	0.151	0.376	0.077		0.704	0.522
500 20 {11}	0.004	0.079	0.143	0.140	0.133	0.107	0.258	0.575	0.141	0.704		0.763
500 50 {12}	0.002	0.050	0.221	0.215	0.206	0.170	0.373	0.768	0.218	0.522	0.763	

4e) phosphate

Table 4, continued.

Distance	Elevation (cm)		Duncan test; Variable: SiO4 (Si) (Deepwater Point Bottom Nutrients) Marked differences are significant at p < .05000											
			{1} M=1.1425	{2} M=1.0963	{3} M=1.0815	{4} M=1.1017	{5} M=1.1410	{6} M=1.0881	{7} M=1.1498	{8} M=1.1208	{9} M=1.1659	{10} M=1.0691	{11} M=1.0351	{12} M=1.0393
-10	2	{1}		0.275	0.163	0.325	0.968	0.207	0.847	0.586	0.558	0.098	0.019	0.023
-10	20	{2}	0.275		0.711	0.885	0.281	0.826	0.215	0.540	0.113	0.509	0.157	0.181
-10	50	{3}	0.163	0.711		0.624	0.169	0.861	0.123	0.353	0.061	0.740	0.263	0.293
0	2	{4}	0.325	0.885	0.624		0.327	0.732	0.257	0.612	0.138	0.439	0.128	0.149
0	20	{5}	0.968	0.281	0.169	0.327		0.213	0.826	0.590	0.546	0.102	0.020	0.024
0	50	{6}	0.207	0.826	0.861	0.732	0.213		0.158	0.429	0.080	0.634	0.212	0.241
30	2	{7}	0.847	0.215	0.123	0.257	0.826	0.158		0.482	0.667	0.072	0.014	0.017
30	20	{8}	0.586	0.540	0.353	0.612	0.590	0.429	0.482		0.286	0.230	0.055	0.065
30	50	{9}	0.558	0.113	0.061	0.138	0.546	0.080	0.667	0.286		0.034	0.006	0.007
1120	2	{10}	0.098	0.509	0.740	0.439	0.102	0.634	0.072	0.230	0.034		0.395	0.430
1120	20	{11}	0.019	0.157	0.263	0.128	0.020	0.212	0.014	0.055	0.006	0.395		0.909
1120	50	{12}	0.023	0.181	0.293	0.149	0.024	0.241	0.017	0.065	0.007	0.430	0.909	

4f) Silicate

4.0. Conclusions. The methodology employed in this study (Figure 2) successfully detected significant increases in dissolved nutrient concentrations at elevations of 2 and 20 cm above the sediment-water interface in the center of the Deepwater Point mussel farm where free sediment sulfide concentrations suggested significant enrichment. With further refinement, this technique could be used to estimate the flux of nutrients from sediments back into the water column. However, the methodology is only appropriate in relatively shallow water depths where the sampling fixture can be serviced using polyethylene tubing to a surface pump.

When compared with the reference station, significant increases in total nitrogen or ammonium were not detected at a height of 50 cm above the sediments in the center of the farm, nor at stations on the perimeter or 30 m downcurrent suggesting rapid dilution of the bottom derived nutrients. Nutrient concentrations on the perimeter of the farm and at 30 m distance downcurrent were significantly less than observed at the reference station but internally the same. This may be associated with more coarse sediments in the immediate vicinity of the farm. The increased coarseness is likely a function of natural current flows and venturi effects created by the raft structure and hanging mussel lines, which are located in shallow water.

In marine systems, inorganic nitrogen is generally the nutrient that limits overall primary production. Intensively cultured bivalve populations can ameliorate overproduction of phytoplankton and macroalgae in eutrophied systems in several ways:

- They extract nitrogen by consuming phytoplankton and detritus. The nitrogen is fixed in their tissues and shell and is removed from the inlet when the mussels are harvested. This is sometimes referred to as *Top Down* control.

- Mussels and oysters also exercise *Bottom Up* control of phytoplankton by changing the rates and processes of nutrient cycling. This is accomplished through the filter feeding process in which bivalves aggregate phytoplankton and other seston into larger particles that have higher settling velocities. The widely dispersed organic material is then incorporated into local sediments around intensive culture sites. Some of the phosphorus is bound to iron and buried in the sediments. Under aerobic sediment conditions, a portion of the nitrogen is denitrified and released through the water column as N_2.

- As seen in these results, a portion of the nitrogenous waste is recycled back into the water column following some delay while sedimented organic matter is being broken down by

detritivores and microbes. The cropping of phytoplankton during spring blooms followed by a delayed release of nutrients from sedimented waste may function to ameliorate reduced primary production during summer months when nutrients might otherwise become depleted. This may help to stabilize marine systems where bivalves are intensively cultured – providing a more steady source of phytoplankton to the first consuming trophic levels and stabilizing the entire food chain.

Newell (In-Review) hypothesized that bivalve culture may provide an important management tool for curbing anthropogenic N and P inputs and reducing phytoplankton production in eutrophied aquatic systems. However, he emphasized that maximization of this potential is achieved when sediments remain aerobic – allowing the fixation of N_2 and its loss to the atmosphere. When sediments become anaerobic, the nitrogen bound mussel biodeposits are released back into the water column as ammonium, which simply replenishes the cycling pool of bioavailable nutrients. This does not stimulate phytoplankton production in comparison with the *no-bivalve* alternative, but it diminishes the value of the bivalves for ameliorating the eutrophied condition. The documented release of significant quantities of dissolved inorganic anaerobic sediments underlying the mussel cultures in Totten Inlet are a good real world example of the processes discussed by Newell (In-Review).

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Appendix (1) Bottom Nutrient database. All nutrient values are mg/L.

	Date	Distance	Elevation (cm)	PO4-P	SiO4 (Si)	NO3-N	NO2-N	NH4-N	DIN
1	07/10/2002	-10	2	0.0656	1.1816	0.0053	0.0018	0.1122	0.1194
2	07/10/2002	-10	2	0.0596	1.1151	0.0052	0.0015	0.0928	0.0996
3	07/10/2002	-10	2	0.0589	1.1308	0.0061	0.0015	0.0830	0.0906
4	07/10/2002	-10	20	0.0632	1.1029	0.0054	0.0017	0.0926	0.0998
5	07/10/2002	-10	20	0.0534	1.0929	0.0064	0.0015	0.0612	0.0692
6	07/10/2002	-10	20	0.0557	1.0932	0.0059	0.0017	0.0753	0.0828
7	07/10/2002	-10	50	0.0468	1.0986	0.0051	0.0011	0.0306	0.0369
8	07/10/2002	-10	50	0.0481	1.0725	0.0060	0.0011	0.0354	0.0425
9	07/10/2002	-10	50	0.0479	1.0735	0.0047	0.0011	0.0296	0.0355
10	07/10/2002	0	2	0.0481	1.0997	0.0028	0.0009	0.0202	0.0239
11	07/10/2002	0	2	0.0479	1.0770	0.0034	0.0011	0.0227	0.0273
12	07/10/2002	0	2	0.0470	1.1285	0.0037	0.0009	0.0313	0.0359
13	07/10/2002	0	20	0.0469	1.1288	0.0029	0.0008	0.0177	0.0214
14	07/10/2002	0	20	0.0480	1.1470	0.0038	0.0007	0.0212	0.0258
15	07/10/2002	0	20	0.0474	1.1473	0.0028	0.0009	0.0244	0.0281
16	07/10/2002	0	50	0.0473	1.0733	0.0028	0.0009	0.0197	0.0234
17	07/10/2002	0	50	0.0470	1.1043	0.0028	0.0009	0.0203	0.0240
18	07/10/2002	0	50	0.0468	1.0866	0.0029	0.0008	0.0163	0.0200
19	07/10/2002	30	2	0.0478	1.0821	0.0026	0.0007	0.0172	0.0204
20	07/10/2002	30	2	0.0508	1.2359	0.0030	0.0007	0.0333	0.0369
21	07/10/2002	30	2	0.0480	1.1313	0.0025	0.0008	0.0290	0.0323
22	07/10/2002	30	20	0.0518	1.1392	0.0028	0.0009	0.0401	0.0438
23	07/10/2002	30	20	0.0524	1.1191	0.0061	0.0014	0.0497	0.0572
24	07/10/2002	30	20	0.0477	1.1040	0.0026	0.0007	0.0197	0.0229
25	07/10/2002	30	50	0.0486	1.1298	0.0028	0.0009	0.0189	0.0225
26	07/10/2002	30	50	0.0475	1.2349	0.0025	0.0007	0.0170	0.0202
27	07/10/2002	30	50	0.0467	1.1330	0.0025	0.0007	0.0145	0.0178
28	07/10/2002	1120	2	0.0530	1.0594	0.0050	0.0012	0.0471	0.0534
29	07/10/2002	1120	2	0.0531	1.0827	0.0059	0.0012	0.0466	0.0537
30	07/10/2002	1120	2	0.0537	1.0651	0.0059	0.0012	0.0515	0.0586
31	07/10/2002	1120	20	0.0529	1.0807	0.0063	0.0012	0.0480	0.0555
32	07/10/2002	1120	20	0.0551	1.0810	0.0104	0.0014	0.1145	0.1263
33	07/10/2002	1120	20	0.0487	0.9894	0.0055	0.0012	0.0471	0.0538
34	07/10/2002	1120	50	0.0496	1.0969	0.0024	0.0012	0.0259	0.0296
35	07/10/2002	1120	50	0.0605	1.0844	0.0068	0.0011	0.0571	0.0651
36	07/10/2002	1120	50	0.0443	0.9367	0.0144	0.0018	0.0554	0.0715