Modeling Nitrogen and Carbon Removal by Pacific Oysters in Hood Canal

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Abstract

Studies have suggested that suspension-feeding bivalves can remove nitrogen and phosphorus from water bodies and ultimately contribute to the reduction of eutrophication. These bivalves serve a crucial role in the biogeochemistry of estuarine systems and can directly influence primary production. Knowing how much nutrients these bivalves are capable of removing is a fundamental question for Puget Sound aquaculture, but more importantly for the future of water quality management. Our study models how biologically and physically feasible it would be for Pacific oysters (*Crassostrea gigas*) to suppress algal biomass and alter nutrient cycling in Hood Canal. We did this by composing a simple spreadsheet model to determine how much nitrogen and carbon these bivalves could remove from the water column on a monthly and annual basis by varying grazing rates and oyster population densities. We have included sensitivity analysis to estimate which parameters are most influential for these calculations and which parameters contribute the most to obtaining realistic results.

Acronyms

C	carbon
chla	chlorophyll
DO	dissolved oxygen
DW	dry weight
Ecology	Washington Department of Ecology
HCDOP	Hood Canal Dissolved Oxygen Project
N	nitrogen (total nitrogen)
NOAA	National Oceanic & Atmospheric Administration
P	phosphorus (total phosphorus)
PPR	primary production rate
std	standard deviation
USGS	U.S. Geological Survey

1. Introduction

Suspension feeding bivalves can play an integral role in the reduction of eutrophication in coastal estuarine systems. Anthropogenic inputs of nitrogen and phosphorus can support primary production and ultimately enhance eutrophication. Oysters' reliance on the feeding of suspended material in the water column can remove nitrogen and phosphorus concentrations directly by eliminating phytoplankton. They are able to rid water of excess nutrients by transferring nitrogen and phosphorus to the sediments in their biodeposits (1). Their grazing reduces turbidity in the water column and increases light penetration that leads to the support of benthic plants. Thus, by studying the impacts of bivalve grazing in these water bodies, this process of nutrient cycling has the potential to negate some of these detrimental issues.

In the state of Washington, and more specifically in Puget Sound, shellfish harvesting and bivalve grazing is currently a key topic of discussion. According to the Washington Shellfish Initiative, the "Puget Sound Partnership has targeted a net increase from 2007 to 2020 of 10,800 harvestable shellfish acres" (2). This increase will be critically important for bringing both revenue and jobs to this area. The USGS, NOAA, and the Washington Sea Grant have recently proposed several nutrient cycling projects to look at the potential for implementing new plans to ultimately mitigate N pollution (2). Therefore, examining the effects bivalves will have on the ecosystem is essential to answer eutrophication questions and reduce the amount of nitrogen and phosphorus in Puget Sound.

The influence of oysters on nutrient cycling has been studied and modeled in parts of the eastern United States, specifically Chesapeake Bay. Newell constructed a simple spreadsheet model to examine the potential effects of restoring the Eastern oyster (Crassostrea virginica) population to the Choptank River estuary, a tributary to Chesapeake Bay (1). This study estimated monthly amounts of nitrogen and phosphorus buried and denitrified. Newell compiled monthly environmental data in this river, including seston concentration, water temperature, and chlorophyll a. From this information, along with a number of assumptions, they then calculated the amount of nutrient removal by the Eastern oyster population.

In order to look at this issue a bit further and apply it to a local setting, we chose to create a similar model using Newell's study as a foundation for our work. Our main goal was to estimate how much nitrogen and carbon the Pacific oyster (*Crassostrea gigas*) could remove in Hood Canal on a monthly and annual basis by varying grazing rates and population densities. We chose to focus specifically on Pacific oysters because they are the primary commercial species in Puget Sound and along the entire Pacific coast. We concentrated on Hood Canal because of its known problem with low summertime DO that leads to fish kills, suspected anthropogenic eutrophication, and especially because of data availability. Though there are some significant differences between the physical, chemical, and biological systems of Hood Canal and Chesapeake Bay, our model adjusts to these differences based on assumptions, uncertainty, and localized inputs.

2. Methods

2.1 Inputs

Temperature & Chlorophyll

Water temperature and chlorophyll (chla) data inputs are from the Twanoh ORCA bouy, which collects continuous water quality measurements for the Hood Canal Dissolved Oxygen Project (3). The location of this buoy is shown below in Figure 1. Upon request, Wendi Ruef emailed us an Excel file with raw daily water temperature (°C) and chla (mg/m^3) measurements averaged over the top 15 meters of the water column from 2005 through May 2012. The top 15 meters was assumed to be the euphotic zone (where algal growth occurs). We then calculated the monthly mean and monthly standard deviation for these data for our model's inputs. Raw data for two other bouys, Hoodsport and Duckabush, were also obtained but not used because there were multiple extended periods of missing data, particularly for chla. The Hoodsport buoy is located near the "elbow" of Hood Canal, and the Duckabush buoy is located near Dabob Bay and the mouth of Hood Canal. Figure 2 and Figure 3 show the temperature and chla data from the Twanoh buoy used for our model's inputs, respectively.

Primary Production

A second question our model addresses is the capacity of Pacific oysters to remove algal biomass (primary production rate, PPR). Because we did not have primary production data for Hood Canal, we converted the same Hood Canal chla data into primary production (mg C/m^3*d) using the relationships presented in Figure 5 of the Washington Department of Ecology's (Ecology) *Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound* for Puget Sound (4), which presents linear relationships between chla and primary production data for four locations throughout Puget Sound (not including Hood Canal). We applied each of these four relationships to the range of Hood Canal chla concentrations (0-15 mg/m^3), calculated the average resulting primary production values, and determined the new corresponding linear relationship, shown below in **Equation 1**.

Equation 1. *Linear equation relating PPR and chla for model input*

$$y = 30.75x + 521.7$$

Equation 2.

$$y = 1^{\circ}\, production = \frac{mg\ C}{m^2 \cdot d}$$

Equation 3.

$$x = \frac{mg\ chl}{m^2} = \left(\frac{mg\ chl}{m^3}\right)(15\ m)$$

$$15\ m = data\ set\ depth\ \&\ assumed\ euphotic\ zone$$

Equation 1 gives an unrealistic primary production of 521 mg C/m^3*d when chla concentrations are 0, which is likely due to the increased scatter at the lower range of the chla data obtained by Ecology and the data's non-linear pattern (4). Further data processing would likely be able to remove this excess scatter and provide an equation better fit to the data.

Using Equation 1, we calculated a mean and standard deviation for primary production for each month.

Oyster Habitat Area

The total Hood Canal surface area was calculated in ArcGIS from the Ecology basemap of Puget Sound (5). The area of oyster habitat was assumed to be the total area of Commercial Shellfish Areas within Hood Canal, as identified by the Washington Department of Health (6). These areas were within the ArcGIS polygon shapefile available on the DOH's website, which we clipped to Hood Canal in ArcGIS to calculate the area. Figure 1 shows the DOH commercial shellfish areas in Hood Canal used in our model as potential oyster habitat area (29,096.2 acres, or 1.7 million m^2 as put into our model spreadsheet). This potential oyster habitat area is approximately 30 percent of the total Hood Canal surface area (93,275 acres).

Total Nitrogen

Total watershed and marine nitrogen inputs were obtained from the HCDOP. To calculate the marine N, we used the following equations for the obtained monthly data.

Equation 4

$$Q_{upwelling} = \frac{Q_{freshwater}}{\left(\frac{S_{deep}}{S_{surface}}\right) - 1}$$

Equation 5

$$UpwellingDIN = deepDIN \times 14$$

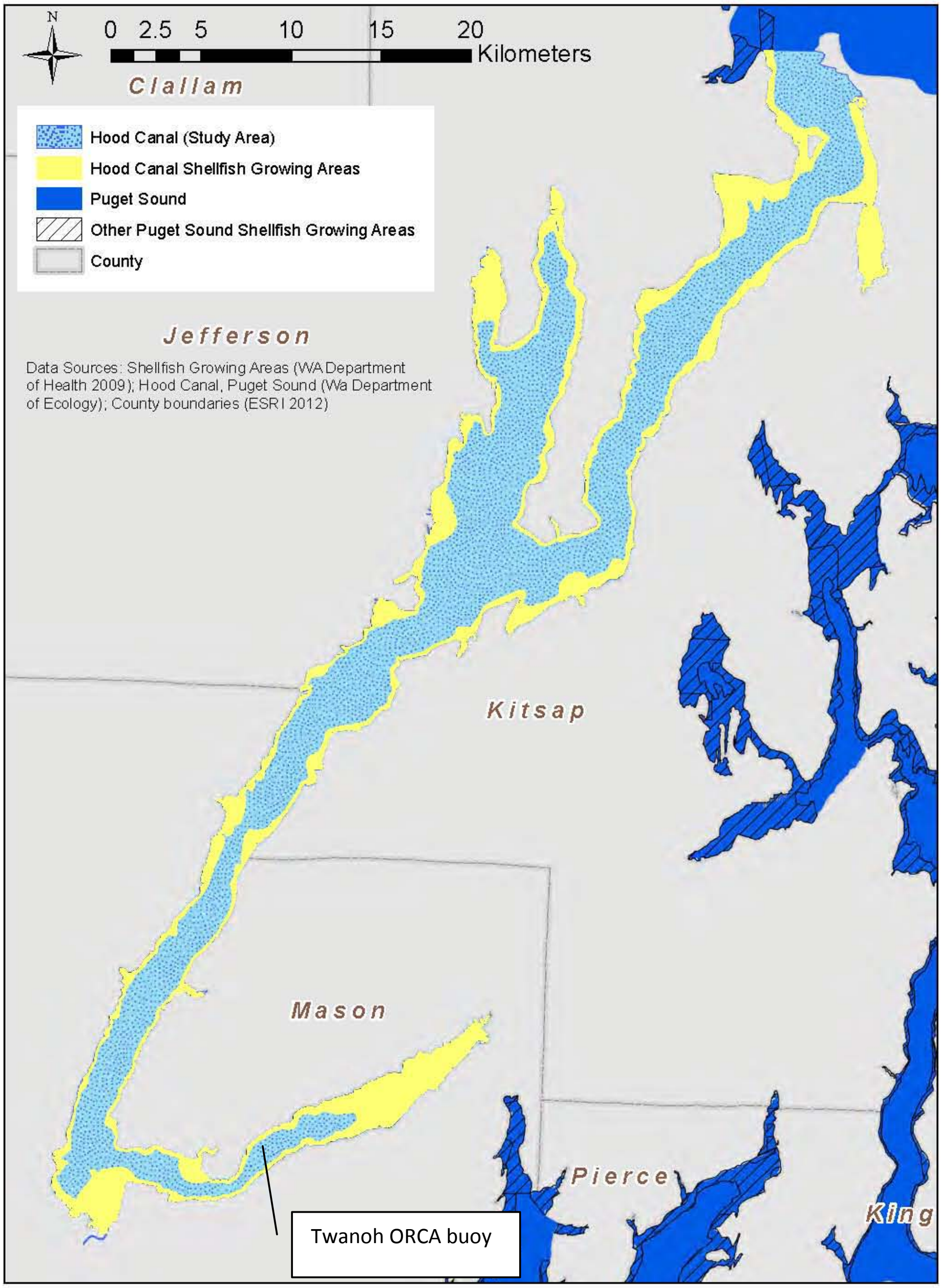
Equation 6

$$Multiplier = \frac{Q_{freshwater} \times DIN}{Q_{upwelling} \times DIN}$$

We then applied the multiplier calculated to the monthly watershed nitrogen inputs to calculate total N inputs into Hood Canal. Below is a table showing these inputs.

Table 1.*Total N inputs into Hood Canal.*

Month	Total watershed N inputs (tons)	Total watershed N inputs (kg)	Multiplier	Total N (Marine and watershed, kg)
Jan	116	116,000	44	5,096,927
Feb	31	31,000	39	1,199,586
Mar	65	65,000	44	2,856,914
Apr	79	79,000	69	5,439,989
May	47	47,000	94	4,417,418
Jun	33	33,000	130	4,304,192
Jul	18	18,000	150	2,705,973
Aug	9	9,000	127	1,143,558
Sept	11	11,000	120	1,321,066
Oct	18	18,000	102	1,828,657
Nov	64	64,000	64	4,092,610
Dec	208	208,000	48	9,920,545



Data Sources: Shellfish Growing Areas (WA Department of Health 2009); Hood Canal, Puget Sound (Wa Department of Ecology); County boundaries (ESRI 2012)

Figure 1. *Potential Oyster Habitat Area Assumed Within Hood Canal*

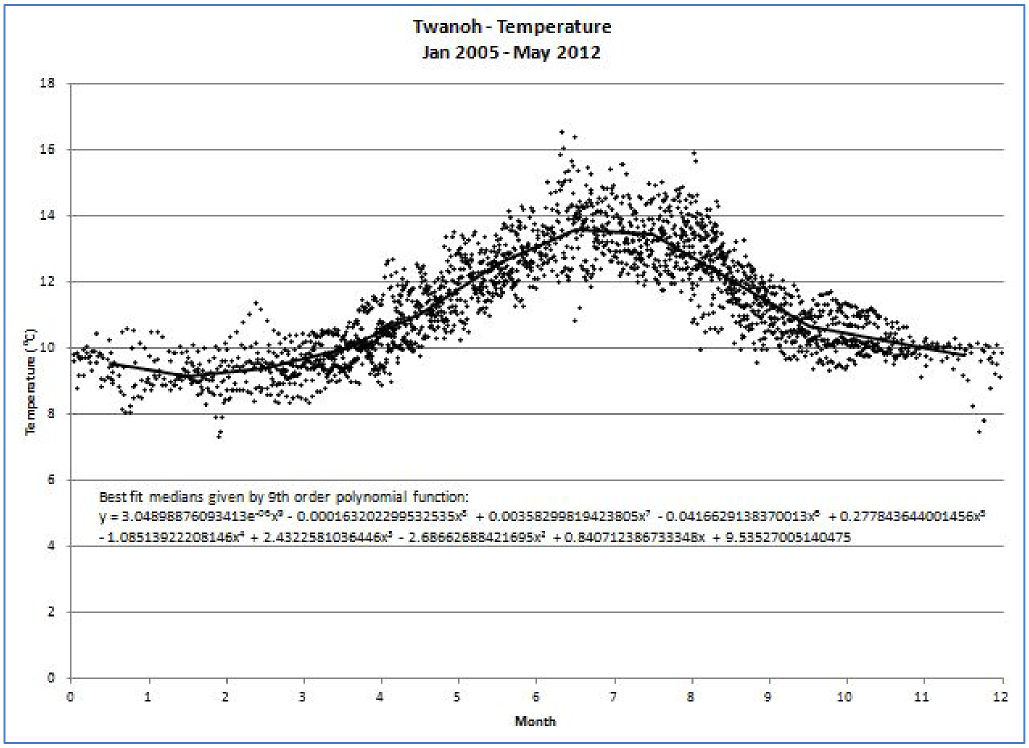


Figure 2. *Temperature Data for Model Input*

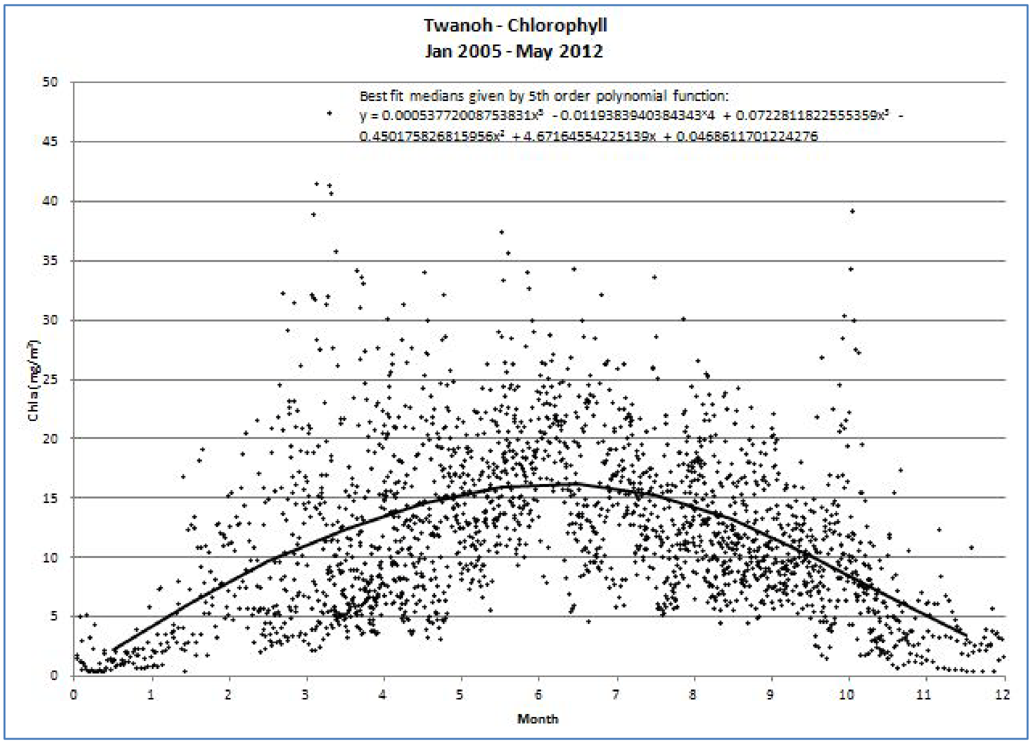


***Figure 3**. Chlorophyll Data for Model Input*

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3. Model Calibration

The first step in creating the model was to determine the process Newell used to calculate total nitrogen removed. **Table 2** below shows the inputs to Newell's spreadsheet model.

Table 2. *Newell Inputs*

Month	Days	Water temp (°C)	Seston (mg/L)	Chla (µg/L)	Clearance Rate (L/(h-gDW))
Jan	31	3	11.4	5.5	0
Feb	28	3	14.3	8.7	0
Mar	31	6	13.2	8.9	0.45
Apr	30	11	16.7	9.6	0.9
May	31	17	14.5	12.2	1.72
Jun	30	23	10.7	12.3	3.74
Jul	31	27	13	15.4	9.62
Aug	31	27	13	16	9.62
Sept	30	25	13.4	11.9	7.46
Oct	31	19	12.8	7.3	2.34
Nov	30	11	9.4	6	1.38
Dec	31	6	11.4	5.7	0.44

To reproduce the same output we followed the process described in Newell's paper and created **Equation 7** and **Equation 8** shown below.

Equation 7. *Calculation of mg N removed per gram dry weight for reproducing Newell's results*

$$\frac{mg\ N\ removed}{g\ DW\ \cdot month} = \left(chla\,\frac{\mu g}{L}\right)\left(\frac{14\ \mu g\ N}{\mu g\ chla}\right)\left(\frac{1\ mg}{1000\ \mu g}\right)\left(\frac{L}{hr\cdot g\ DW}\{Clearance\ rate\}\right)\left(\frac{24\ hr}{day}\right)\left(\frac{days}{month}\right)* \\ (fraction\ N\ assimilated)(fraction\ PON\ lost\ to\ denitrification/burial)$$

Equation 8. *Calculation of mg P removed per gram DW for reproducing Newell's results*

$$\frac{mg\ P\ removed}{g\ DW\ \cdot month} = \left(chla\,\frac{\mu g}{L}\right)\left(\frac{14\ \mu g\ N}{\mu g\ chla}\right)\left(\frac{1\ \mu g\ P}{18\ \mu gN}\right)\left(\frac{1\ mg}{1000\ \mu g}\right)\left(\frac{L}{hr\cdot g\ DW}\{Clearance\ rate\}\right)\left(\frac{24\ hr}{day}\right)\left(\frac{days}{month}\right)* \\ (fraction\ P\ lost\ to\ burial)$$

It should be noted that Newell calculated the clearance rate based on the water temperature and seston concentration and we did not. We only used the clearance rate when reproducing the results because we did not have the relationship he used to get clearance from seston. In our model for Hood Canal, data for seston concentrations was not available nor was a relationship to relate seston to clearance rates for the pacific oyster. All of the same assumptions were used to calculate mg N denitrified and mg N burried such as: 50% assimilation efficiency, 14N: 1Chla, 20% denitrification, 10% N burial, 90% P burial, and 18N: 1P. Newell cites the sources for these assumptions in his paper (1).

Table 3. *Calculated Outputs and Newell Outputs*

Month	Calculated			Newell's report			% Differences		
	mg N denitrified	mg N buried	mg P buried	mg N denitrified	mg N buried	mg P buried	Mg N denitrified	mg N buried	mg P buried
Jan	0.00	0.00	0.00	0	0	0	0%	0%	0%
Feb	0.00	0.00	0.00	0	0	0	0%	0%	0%
March	4.17	2.09	2.09	4.08	2.04	2.21	2%	2%	6%
April	8.71	4.35	4.35	8.69	4.35	4.71	0%	0%	8%
May	21.86	10.93	10.93	21.2	10.6	11.5	3%	3%	5%
June	46.37	23.19	23.19	46.35	23.17	25.13	0%	0%	8%
July	154.31	77.16	77.16	149.26	74.63	80.92	3%	3%	5%
Aug	160.32	80.16	80.16	155.08	77.54	84.08	3%	3%	5%
Sept	89.48	44.74	44.74	89.52	44.76	48.53	0%	0%	8%
Oct	17.79	8.90	8.90	17.25	8.62	9.35	3%	3%	5%
Nov	8.35	4.17	4.17	8.36	4.18	4.53	0%	0%	8%
Dec	2.61	1.31	1.31	2.52	1.26	1.37	4%	4%	5%
	Annual:								
	513.98	256.99	256.99	502.31	251.15	272.33	2%	2%	6%

To show how similar the values are, the percent differences were calculated and are displayed in **Table 3**. We assumed that the differences are due to the fact that Newell's spreadsheet might have included more significant figures when calculating all variables. Something interesting is how we obtained the exact same values for mg N buried and mg P buried even though Newell did not. Since our calculations were based on the chla and clearance rate he already calculated, the assumptions and factors are what produced the final answer of mg N or mg P. If we compare the assumptions and factors for mg N buried and mg P buried we can see they are the same. **Equation 9** and **Equation 10** show how we achieved the same values for mg N buried and mg P buried but we were not sure how Newell calculated different values for these parameters. We excluded phosphorus from our final model calculations.

Equation 9. *mg N buried factors*

$$mg\ N\ buried = .5\ assimilation * \frac{14\ \mu gN}{1 \mu g\ Chla} * .1\ burial = .7$$

Equation 10. *mg P buried factors*

$$mg\ P\ buried = \left(\frac{14\ \mu gN}{1 \mu g\ Chla}\right)(.9\ burial) * \left(\frac{1 \mu g\ P}{18 \mu g\ N}\right) = .7$$

Seston data was not available for Hood Canal nor was a relationship to find the grazing rate based on temperature, so we used Newell's data to calculate a grazing rate at 20°C and a theta (θ) value to adjust the rate based on temperature. To determine these values we performed a least squares fit on the temperature and grazing rate and used solver to predict these values in order to minimize the error and maximize the R-squared value. Below in **Equation 11** is this grazing equation we were trying to optimize.

Equation 11. Temperature adjusted grazing rate equation

$$Grazing(T)\left(\frac{L}{h - gDW}\right) = grazing(20°\mathrm{C}) * \theta^{T-20}$$

Table 4 below shows the spreadsheet layout used to calculate the grazing rate at 20°C and the theta value.

Table 4. Theta and Grazing at 20C calculation

temp	Observed rate	Predicted Rate		
°C	L/h g DW	L/h g DW	Error Squared	
3	0.00	0.18	0.03	
3	0.00	0.18	0.03	
6	0.45	0.30	0.02	
11	0.90	0.67	0.05	
17	1.72	1.85	0.02	
23	4.80	5.01	0.04	
27	9.62	9.71	0.01	
27	9.62	9.71	0.01	
25	7.46	6.97	0.24	
19	2.34	2.58	0.06	
11	0.90	0.69	0.05	
6	0.44	0.30	0.02	
				R Squared
		Sum of squares (minimized):	0.57	0.9962
	Adjusted parameters:	**grazing at 20°C**	**3.05**	
		Theta	**1.18**	

The grazing rate and theta that we solved for were later used for the Hood Canal calculations.

We used Newell's assumptions and added variability or we used comparable assumptions that were found in the literature. For example, Newell assumed a 50% assimilation efficiency for the Eastern oyster but we found in the literature that the assimilation efficiency for the pacific oyster was approximately 75 percent (9). To account for variation in the N content of marine phytoplankton, we used the mean and standard deviation of the 32 N:chla ratios we calculated from the data in Table 1 of Montagnes et al 1994 (7). We used **Equation 12** below to calculate the nitrogen lost in our model. Newell combined denitrification and burial into one nitrogen loss rate when he calculated the total nitrogen removed. Our group calculated the total nitrogen removed in mg N per g DW by combining the denitirfication and burial rate to be 30% nitrogen lost and adding +/-15% uncertainty.

Equation 12: *Calculation for mg N removed per gram DW for Hood Canal Model*

$$\frac{mg\ N\ removed}{g\ DW\ \cdot month} = \left(chla\,\frac{mg}{L}\right)\left(\frac{g\ N}{g\ chla}\right)\left(\frac{L}{hr\cdot g\ DW}\{Clearance\ rate\}\right)\left(\frac{24\ hr}{day}\right)\left(\frac{days}{month}\right)$$
$$(fraction\ N\ assimilated)(fraction\ PON\ lost)(0.9\{fraction\ time\ underwater\})$$

The model was set up to allow for plenty of flexibility and adjustments to the inputs. Many of the assumptions listed before by Newell were implemented in our spreadsheet model in a manner so they could be easily adjusted. Due to considerable uncertainty in reported data, the parameters found in the literature were used as mean values with standard deviations to account for variability. We assumed that all of the parameters are normally distributed. The mean and standard deviations for the water temperature and chla were calculated from the buoy data previously mentioned. **Table 5** below shows the assumptions and ratios that we used in the model.

Table 5. *Assumptions, means, and standard deviations*

Parameter	Generated	Mean	Standard deviation (std)	Source
Theta	1.176	1.19	0.01	Calculated based on Newell et al. 2005 (1)
N lost	0.469	0.3	0.15	Newell et al. 2005 (1)
N:Chla ratio	8.162	8.4	3.5	Montagnes et al. 1994 (7)
Grazing at 20°C (clearance rate)	3.100	2.88	0.25	Wheat and Ruesink (8)
Assimilation efficiency	0.869	0.75	0.1	Newell et al. 2005 (1)
Time underwater	0.842	0.9	0.1	Anecdotal (oyster researcher Joth Davis)
C:Chla	48.702	44	17	Montagnes et al. 1994 (7)
Parameter	-	**Value**	-	**Source**
Oyster dry weight (g/oyster)	-	8.3	-	Wheat and Ruesink (8)
Oyster density (oyster/m^2)	-	1 and 100	-	Observed at shellfish facility owned by researcher Joth Davis
Oyster habitat area (m^2)	-	117,747,229		Washington DOH 2012 (6)

The “generated” column is a number generated by a normal distribution function found in the Excel add-in “YASAI.” The add-in “YASAI” was used to run the Monte Carlo analysis simulation for our model and has many statistical distributions incorporated into the add-in to allow one to generate numbers by various distributions. For example, the numbers listed in the column generated are randomly generated from a normal distribution function for each parameter. These numbers are generated every time the Excel file is refreshed, so when we run the model 10,000 times, the function will generate a new number for each parameter for every run. YASAI can also track how sensitive the output of the model, total N removed, is to the input assumption and ratios shown in **Table 5**. **Table 6** below shows the input water temperature and chla concentration from buoy data.

Table 6. *Input Water Temperature and Chlorophyll for model*

Month	Days	Water temp (°C)	Water temp std	Chla (µg/L)	Chla std
Jan	31	9.6	0.5	1.3	0.9
Feb	28	9.2	0.5	6.0	3.9
Mar	31	9.4	0.6	9.5	7.3
Apr	30	10.0	0.6	8.7	7.1
May	31	11.1	0.8	13.3	7.0
Jun	30	12.4	0.7	16.4	5.1
Jul	31	13.6	0.9	17.2	6.4
Aug	31	13.3	0.9	13.9	5.1
Sept	30	12.1	1.1	11.5	5.0
Oct	31	10.6	0.6	9.9	3.8
Nov	30	10.2	0.6	6.1	3.8
Dec	31	10.0	0.4	3.1	2.4

Table 7 shows uniformly generated water temperature and chla numbers for model input as well as the calculated mg N lost per g-DW. These values are just one result of 10,000 automatic simulations performed by YASAI. We then used these values and **Equation 13** below to find the total nitrogen removed per month.

Table 7. *Generated Inputs for model*

	Uniformly Generated Variables			
Month	**Water temp (°C)**	**Chla (µg/L)**	**Clearance rate (L/h-g DW)**	**mg N lost**
Jan	8.8	1.4	0.1	0.3
Feb	8.7	1.4	0.1	0.2
Mar	9.4	21.3	0.1	4.6
Apr	9.6	7.1	0.1	1.5
May	9.9	15.0	0.1	3.6
Jun	12.7	11.1	0.2	4.4
Jul	12.0	14.6	0.2	5.2
Aug	13.3	9.5	0.2	4.4
Sept	13.3	8.5	0.2	3.8
Oct	10.8	8.6	0.1	2.4
Nov	10.6	8.3	0.1	2.2
Dec	10.2	1.3	0.1	0.3

Equation 13: *Total N calculation*

$$\left(\frac{mg\ N\ removed}{g\ DW\ \cdot month}\right)\left(\frac{8.3\ g\ DW}{oyster}\right)\left(\frac{oysters}{m^2}\right) * m^2\ oyster\ habitat * \left(\frac{kg}{1000\ mg}\right) = \frac{kg\ N\ removed}{month}$$

The 8.3 grams of dry weight per adult oyster is a value that was reported in a chapter of Elizabeth Wheat's PhD dissertation and all other parameters have been discussed (8). The output to this equation is shown in **Table 8** below.

Table 8. *Total N removal output*

Area	117,747,229	m^2		
Adult DW	8.3	g		
Density	1 and 100	oysters/m^2		
			Monthly Nutrient Removal	
	Month	Total N inputs (kg)	N (kg)	% N inputs
	Jan	5,096,927	49,345	0.97
	Feb	1,199,586	60,036	5.00
	Mar	2,856,914	1,034,239	36.20
	Apr	5,439,989	1,050,454	19.31
	May	4,417,418	1,117,030	25.29
	Jun	4,304,192	1,709,563	39.72
	Jul	2,705,973	1,759,981	65.04
	Aug	1,143,558	1,108,564	96.94
	Sept	1,321,066	1,050,703	79.53
	Oct	1,828,657	487,623	26.67
	Nov	4,092,610	255,483	6.24
	Dec	9,920,545	224,558	2.26
	Total	**44,327,435**	**9,907,579**	

This is the output to a single generation of number and parameters. We ran the program 10,000 times and calculated the average N removed and % N removed for every month as well as a sensitivity analysis.

Our model went a step further than Newell's by calculating the impact the oysters can have on primary production from grazing. The calculation of primary production was described earlier and the equations were presented. We calculated the amount of carbon the oysters can graze and thus eliminate with **Equation 14** below. This calculation assumes a C:chla ratio of 44 +/- 17, which is the mean and standard deviation of the C:chla ratios in Montagnes et al. 1994 (7).

Equation 14. *Chlorophyll to Carbon ratio*

$$\frac{mg\ Chla\ removed}{m^2 * time} * 44 \pm 17 = \frac{mg\ C\ removed}{m^2 * time}$$

To use this ratio we need to get the chla concentration from µg/L which is was currently in to mg/(m^2*time). This was done by **Equation 15** shown below.

Equation 15. *Chla unit conversions*

$$\left(\frac{Chla\ \mu g}{L}\right)*\left(\frac{Grazing\ L}{h-gDW}\right)*\left(\frac{24\ h}{day}\right)*\left(\frac{8.3gDW}{oyster}\right)*\left(\frac{x\ osyters}{m^2}\right)*\left(\frac{1mg}{1000\mu g}\right)$$

Once chla was in the correct units we applied the ratio and obtained mg C/m^2*time. These units then only need to be multiplied by the area of oyster habitat to find the total amount of carbon the oysters could remove per day, as shown in **Equation 16**.

Equation 16. *Final calculation to find kg C removed per day*

$$\frac{mg\ C\ removed}{m^2 day}*habitat(m^2)*\left(\frac{1\ kg}{10^6 mg}\right) = kg\ C\ removed/day$$

Since the chla concentrations used were for each month, the values reported below are in kg/day for each month. So the amount removed in January for this generation of numbers is 3.98 kg/day for each day of January. This value represents an average daily removal of carbon. The percent difference in primary production and removal was calculated and is displayed in the last column of **Table 9**.

Table 9. *Carbon Production and removal*

Mth	Areal Chla (µg/L)	PPR (mg/m^2/day)	Chla (µg/m^2/day)	Carbon Flux lost (mg/m^2/day)	PPR (kg/day)	Carbon Flux lost(kg/day)	% C removed
Jan	14.3	962.0	7,270	338	363,000	39,800	10.97
Feb	21.3	1177.0	9,790	456	444,000	53,700	12.08
Mar	340.2	10982.0	152,000	7,090	4,150,000	835,000	20.14
Apr	280.7	9152.2	160,000	7,440	3,450,000	876,000	25.37
May	144.3	4959.8	165,000	7,660	1,870,000	902,000	48.17
Jun	328.1	10610.4	260,000	12,100	4,010,000	1,430,000	35.61
Jul	229.5	7578.7	259,000	12,100	2,860,000	1,420,000	49.67
Aug	190.8	6387.8	163,000	7,600	2,410,000	895,000	37.12
Sept	180.5	6073.6	160,000	7,440	2,290,000	877,000	38.23
Oct	143.2	4925.6	71,800	3,340	1,860,000	394,000	21.17
Nov	96.8	3498.5	38,900	1,810	1,320,000	213,000	16.14
Dec	61.2	2404.0	33,100	1,540	907,000	181,000	19.98

4. Results

The results presented below will be for three different scenarios. Scenario 1 represents an oyster density of $1/m^2$ and the Eastern oyster grazing rate; scenario 2 represents an oyster density of $100/m^2$ and the Eastern oyster grazing rate; and scenario 3 represents a density of 100 oysters/m^2 and a grazing rate of .6L/(hr-gDW). For scenario 3, the lower grazing rate is based on a range of field measurements given in a chapter of Elizabeth Wheat's PhD (8). We chose these scenarios because 1 and $100/m^2$ represent extremes in population density. We tracked the nitrogen and carbon removal on a mass basis as well as a percentage of monthly inputs/production.

The nitrogen removal is displayed below in Figure 4. For the majority of the year the nitrogen inputs into Hood Canal by far exceed the nitrogen removal but during August, for scenario 2, the potential removal is actually larger than the inputs. This is the only scenario that is close to removing a significant amount of nitrogen in the euphotic zone. For all of the figures below, the scenario in indicated in parentheses at the end of each series in the legend.

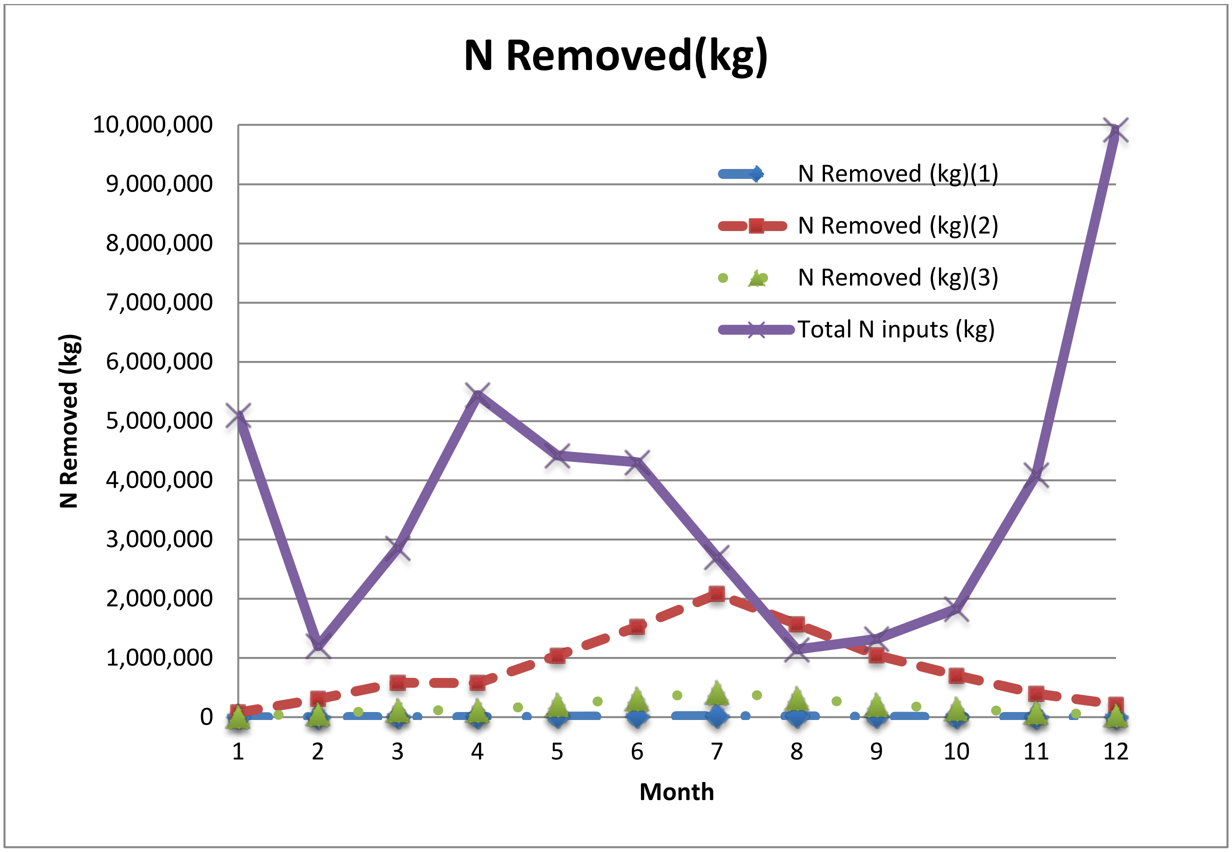

Figure 4. *Nitrogen Removed per month*

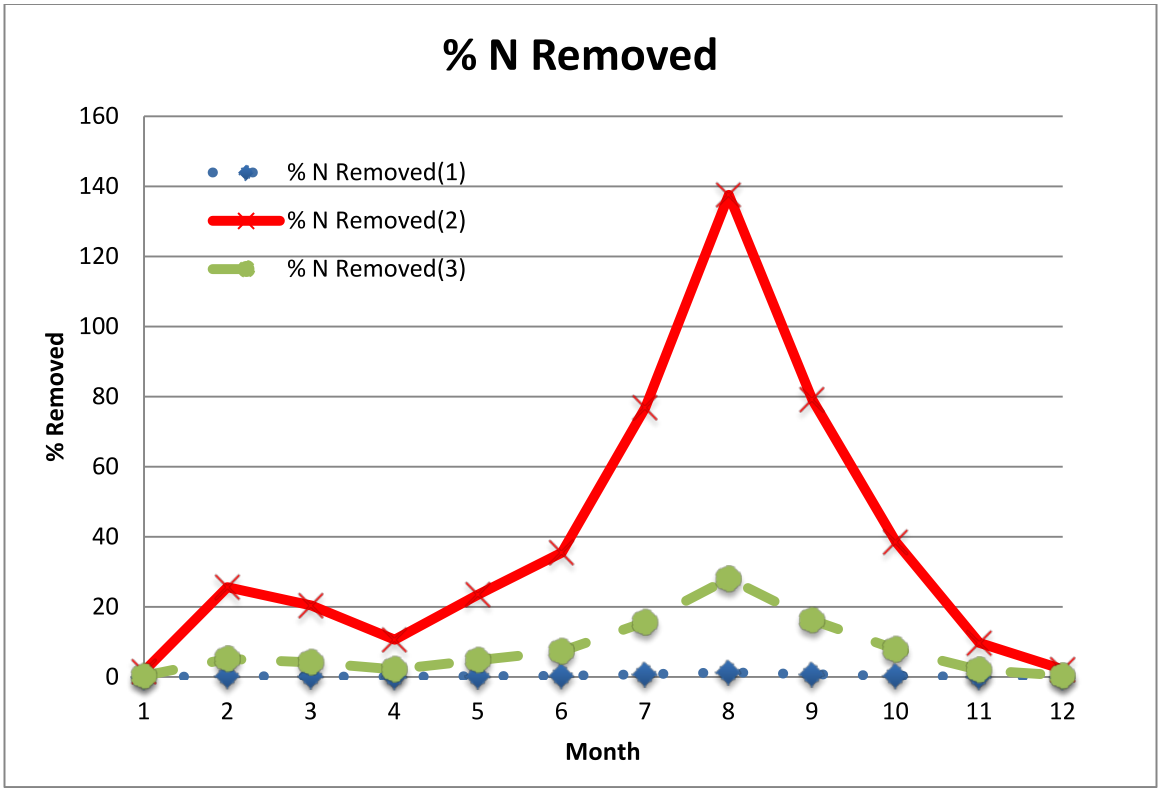

Figure 5: *Percent nitrogen removed each month*

Table 10. *Annual N removed*

		Scenario 1	Scenario 2	Scenario 3
Month	Total N inputs (kg)	N Removed (kg)	N Removed (kg)	N Removed (kg)
Jan	5,096,927	811	80,494	16,452
Feb	1,199,586	3,096	308,024	62,185
March	2,856,914	5,881	582,911	120,490
April	5,439,989	5,828	578,763	119,548
May	4,417,418	10,327	1,040,251	214,518
June	4,304,192	15,362	1,527,945	317,103
July	2,705,973	20,864	2,079,539	423,203
Aug	1,143,558	15,814	1,573,343	321,008
Sept	1,321,066	10,444	1,045,770	214,631
Oct	1,828,657	7,112	705,250	144,092
Nov	4,092,610	3,988	398,705	81,510
Dec	9,920,545	2,126	214,966	43,107
Sum	**44,327,435**	**101,652**	**10,135,961**	**2,077,847**
	Annual % removal	0.23	22.87	4.69

As one can see from the annual nitrogen removal presented above, the first and third scenarios have very little impact on total nitrogen. The second scenario can have a significant impact on annual nitrogen. This shows that not only is the amount of oysters an important factor for nitrogen removal but the grazing rate is important. This is confirmed by the sensitivity analysis shown below in **Table 11**. The only difference between scenario 2 and 3 is the grazing rate and it changes the annual removal by more than 15%. When the grazing rate was high in the first two scenarios, the most important factor for nitrogen removal was the nitrogen loss term, which is the denitrification and burial, and the nitrogen to chla ratio. The decrease in the grazing rate for scenario 3 made it a more influential parameter in total nitrogen removed. The sensitivity analysis below is only for the month of April but the dominant factors were approximately the same for each month.

Table 11. *Nitrogen Sensitivity Analysis*

Scenario	Forecast	Assumption	Spearman's Rho	Contribution to variance
1	Apr%N removed	N lost	0.4762	54%
1	Apr%N removed	N to Chla	0.4092	40%
2	Apr%N removed	N lost	0.4778	56%
2	Apr%N removed	N to Chla	0.3847	36%
3	Apr%N removed	N lost	0.4379	42%
3	Apr%N removed	N to Chla	0.3634	29%
3	Apr%N removed	Grazing 20C	0.3474	26%

The following figures show the model's predictions for total and percent carbon removal.

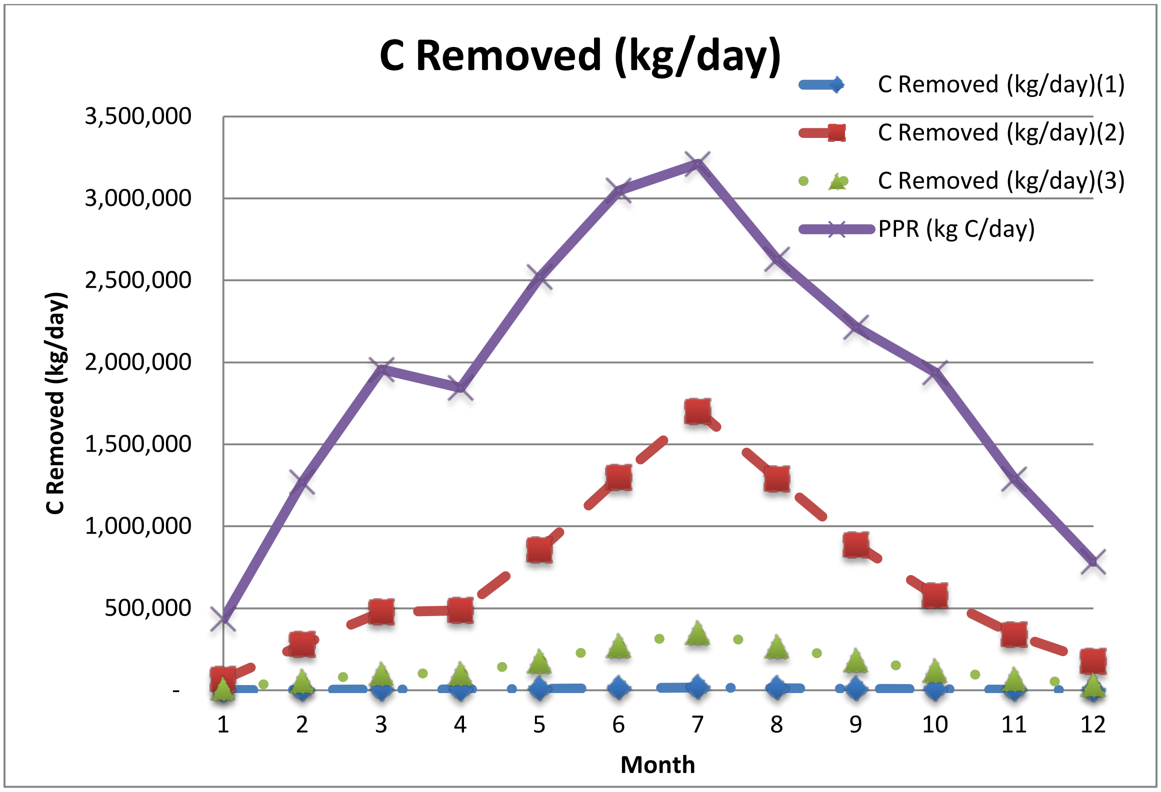

Figure 6. *Average carbon removed each day per month*

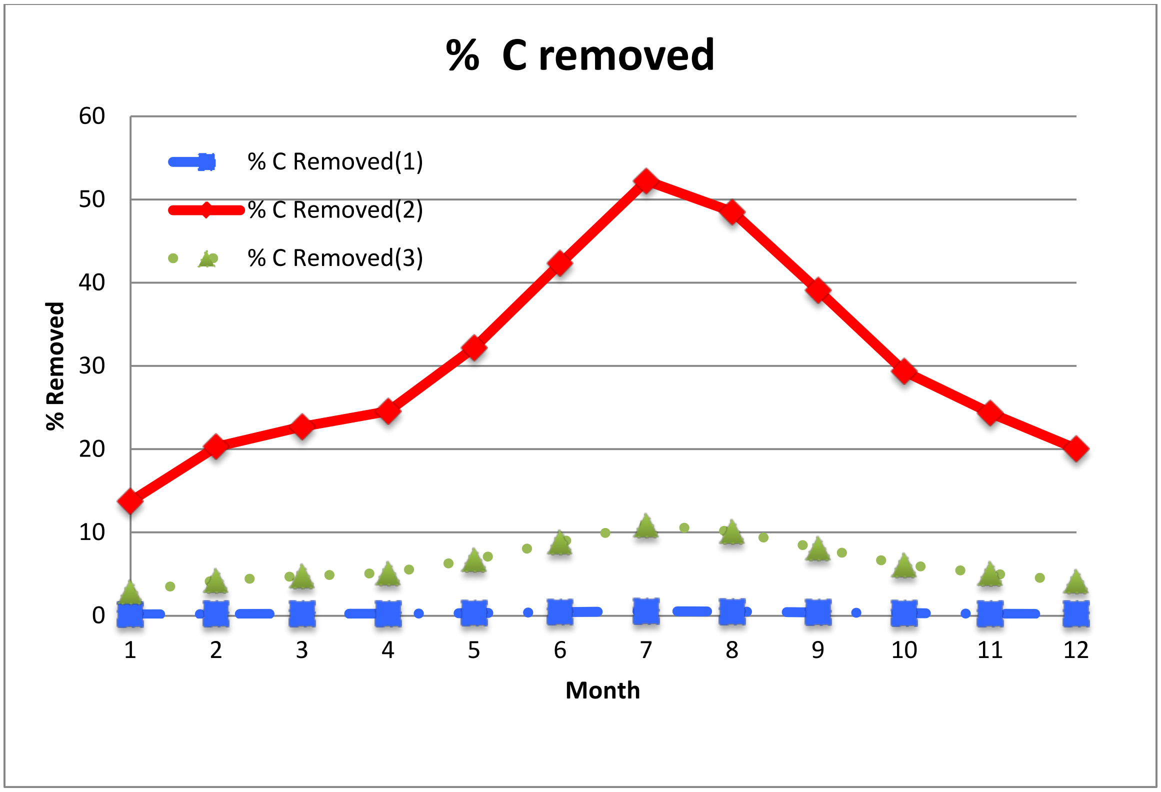

Figure 7. Percent C removed each month

Table 12. *Annual C removed*

		Scenario 1	Scenario 2	Scenario 3
Month	PPR (kg C/day)	C Removed (kg/day)	C Removed (kg/day)	C Removed (kg/day)
1	434,575	674	65,972	13,769.1
2	1,270,274	2,822	278,374	57,873.8
3	1,956,934	4,873	477,264	101,683.6
4	1,845,150	5,002	487,290	102,764.9
5	2,521,163	8,604	856,045	179,208.7
6	3,048,525	13,210	1,297,056	274,866.9
7	3,210,894	17,257	1,701,744	352,416.1
8	2,628,555	13,170	1,290,096	268,726.2
9	2,215,724	8,968	886,400	184,687.1
10	1,938,244	5,898	576,662	120,105.3
11	1,289,704	3,429	338,465	70,574.6
12	783,793	1,767	174,944	36,078.8
Total	23,143,536	85,674	8,430,312	1,762,755
	Annual % removal	**0.37**	**36.43**	**7.62**

The three scenarios show relatively the same impact on carbon as they do on nitrogen. Scenario 2 can potentially remove a third of the overall annual primary production. Scenarios 1 and 3 show very little effect on overall carbon removal. The difference in the grazing rate between scenarios 2 and 3 shows how important the grazing rate is not only to nitrogen removal to but carbon removal, as well. The sensitivity analysis confirms that the theta value to adjust the rate based on temperature and the grazing rate itself are the most important parameters for the carbon removal calculations.

Table 13. *Carbon Sensitivity analysis*

Scenario	Forecast	Assumption	Spearman's Rho	Contribution to variance
1	Apr%C removed	Theta	-0.1801	50.99%
1	Apr%C removed	Grazing 20C	0.1759	48.62%
2	Apr%C removed	Theta	-0.1705	50.75%
2	Apr%C removed	Grazing 20C	0.1670	48.72%
3	Apr%C removed	Grazing 20C	0.6309	97.28%
3	Apr%C removed	Theta	-0.1023	2.56%

5. Conclusions

Our results indicate that even at very high densities, the Pacific oyster’s capacity to remove total nitrogen and carbon flux from Hood Canal is limited throughout most of the year. More importantly, our sensitivity analysis identifies the grazing rate and its response to water temperature (the theta value) as the two most important factors in making these predictions.

The oyster habitat area could also be estimated from Hood Canal bathymetry, tidal information, and oyster depth ranges. We suspect this area would not be substantially different than the area we calculated from the DOH commercial shellfish areas, based on a quick visual comparison of these areas with a NOAA bathymetry map.

Our recommendations for future study and modeling efforts related to Puget Sound bivalve effects on water quality are to:

- Confirm the Pacific oyster’s grazing rate & determine theta with field measurements
- Confirm the fraction N lost (buried and denitrified)
- Incorporate other Puget Sound bivalves
- Incorporate hydrodynamics
- Account for other means of N loss (such as oyster harvest)
- Confirm the appropriate oyster population and density to assume

Though more accurate data and further research may lead to more realistic calculations, a model such as this one could be used to make valuable policy and management decisions in terms of increased aquaculture in Puget Sound.

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