Watershed Influences on Oyster Pond

Cape Cod, MA

A project conducted by the 2001 Marine Ecology class
Boston University Marine Program
Marine Biological Laboratory, Woods Hole, MA 02543

BOSTON UNIVERSITY MARINE PROGRAM

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EXECUTIVE SUMMARY

Concerns with the ecological health of Oyster Pond have been increasing as urbanization on watershed has taken place. On October 2001, the 2001 Marine Ecology class of the Boston University Marine Program me with stakeholders with an interest in Oyster Pond, Falmouth MA. From this meeting, a number of issues of concerns emerged, which the members of the class translated into a five part research program, and designed a plan to include junior high and high school students. in further research.

Oyster Pond, situated on the shore between Woods Hole and Falmouth MA, was once a fresh water pond, then an estuary, and now a pond again that is closely associated with the ocean. Oyster Pond got its name by being abundant with oysters till the 18th century, when oysters extinct, due to the closure of an inlet from the ocean and caused the pond to be too fresh for oysters. Oyster Pond is about 1050 meters long, and its maximum width is 400 m. Its total surface area is 0.250 km^2 (Emery et al. 1997). The pond consists of three basins. The deepest basin is at the south, while the intermediate is at the north, and the shallowest area is between them. The total volume of water in Oyster Pond is about 750,000 m^3. In this project, the studies were conducted in Oyster Pond, Lagoon, and Vineyard Sound, where their typical salinity gradient ranges from 0-32 $^{0}/_{00}$ (Emery et al. 1997).

The project has multiple components to provide citizen volunteer, and classroom teachers and students with scientific information about Oyster Pond. It might assist them to restore and preserve the pond and help them play a meaningful role in solving management issues. The specific objectives of the project are:

1) Measure land-derived nitrogen entering Oyster Pond;

   Use NLM to estimate sources and amount of nitrogen contributed from groundwater into the pond; determine the magnitude of nitrogen load by comparing it to nitrogen loads to other Cape Cod estuaries; examine the presence of waterfowl input to nitrogen loading; and use NLM to suggest possible management systems to reduce nitrogen loads to Oyster Pond.

2) Examine the salinity, nutrient, and chlorophyll distributions throughout Oyster Pond, and compare the present status to previous conditions.

3) Determine nutrient limitation of phytoplankton along salinity gradient of Oyster Pond.

4) Evaluate the response of submerged and emergent aquatic vegetation in Oyster Pond to nutrient loading from watershed influx.

5) Evaluate the distribution and growth rates of fish fauna along Oyster Pond's salinity gradient and its physical habitat variations, and also investigate how differences in watershed-derived nutrients may also alter these characteristics of the fish community.

The first part of the study consists of an examination of the land-derived nitrogen load to Oyster Pond. In this study, the nitrogen load was modeled using a published nitrogen-loading model, whose productions were verified against measured estimates. The contribution of the wastewater and the atmospheric deposition to the watershed are almost the same, 43% and 47% respectively. Yet, the contribution of wastewater is much higher then the atmospheric deposition to Oyster Pond, 71% and 22% respectively.

Nitrogen loads to Oyster Pond are low compared o those received by other Cape Cod estuaries, for example the Quashnet River and the Childs River. The contribution of waterfowl to the nutrient in Oyster Pond was small compared to land-derived nitrogen.

Second, we defined the water quality and phytoplankton of Oyster Pond. Throughout the top 4 meters of the pond, the concentrations of nitrate, dissolved organic nitrogen, phosphate, dissolved oxygen, and chlorophyll *a, b,* and *c*, remain consistent. However, below this depth, concentrations of chlorophyll *a, b,* and *c* were variable within the mixed layer and increased just above the anoxic zone. Concentrations of phosphate, ammonium, and nitrate were higher at the north end of Oyster Pond.

Third, an enrichment study was conducted to determine the nutrient limitation of phytoplankton along the salinity gradient of Oyster Pond. Freshwater sites showed little response to nutrient enrichments. This result suggests either that nutrients were already in excess, or that there was not sufficient time for algal growth. Concentrations of chlorophyll *a* increased only in the Vineyard Sound water, where nitrate was added to the bottles, indicating that Vineyard Sound is nitrogen limited. Cyanobacteria were most abundant in freshwater sites and least abundant in coastal waters, while dinoflagellates showered the opposite trend. Diatoms showed no preference along the salinity gradient.

Fourth, it evaluates the responses of submerged and emergent aquatic vegetation in Oyster Pond to nutrient loading from watershed influx using mapping of vegetation coverage, percent nitrogen in vegetation tissue, and stable nitrogen isotope analysis. In recharge areas where the nutrient load was highest, the tissue nitrogen and _^{15}N were greatest. *Lemna minor* and *Najas gracillema* were abundant in those regions with the highest nutrient loads, while they were absent in other recharge areas. This result suggest a unique response to nitrogen loading, and also confirms that vegetation chemistry along with the mapping of vegetation is a good evaluating tool to examine nitrogen loading.

Finally, it investigates the occurrence and growth of the fish fauna of the Oyster Pond estuary. Killifishes (*F. heteroclitus and F. majalis*) dominated the fish community. *F. heteroclitus* was more dominant in the lagoon, while *F. majalis* was more abundant in the south end of Oyster Pond. Three age classes of *F. heteroclitus* were present in the north end of pond and four age classes were present in the lagoon. Three age classes of *F. majalis* were found in each area of the estuary. First year growth rates of both *F. heteroclitus* and *F. majalis* in Oyster Pond were higher than the first year growth rate found in other estuaries. In Oyster Pond, $\delta^{15}N$ values increase with higher trophic levels. Herbivorous fish have the lowest $\delta^{15}N$ (7.52 $^0/_{00}$), while carnivorous have $\delta^{15}N$ values from 10 to 14 $^0/_{00}$.

Human activity seriously threatens the vulnerable ecosystems found in the estuaries. As our population grows and the demands imposed on our natural resources increase, so too does the importance of protecting these resources for their natural and aesthetic values. Oyster Pond can remain to be enjoyed for about 4000 years more as long as the sea level stays about the same as it is now, and if human's activities do not alter the pond.

The goal of this project is transfer scientific information to communities about Oyster Pond water quality and to increase availability of information about the pond to people who may be interested in its conditions to protect this coastal resource into the next century.

Chapter 1

Land-derived nitrogen to Oyster Pond estuary

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Abstract:

Eutrophication prompted by the increasing nitrogen load is the major impact of human activities on ecosystems. Concern with nitrogen loading to Oyster Pond is wide spread because the watershed is nearing build-out. The major sources of nitrogen include wastewater, fertilizer use, and atmospheric deposition. In our study, we measured the land-derived nitrogen load to Oyster Pond, modeled the load using the Nitrogen Loading Model, which is based on the land use of the watershed, and assessed environmental management for reducing the nitrogen load. The measured nitrogen load was 1320 kg N yr^{-1}, while the modeled load was 878 kg N yr^{-1}. In this study, we also measured the maximum possible contribution of waterfowl to the nutrient load, which was a trivial133.3 kg N yr^{-1}. The understanding of the sources of nutrient loads into estuaries is crucial when making management decisions about how to regulate nutrient influx. Further studies can also use this information to asses the impacts of nitrogen loads on ecosystems.

Introduction:

In most coastal waters, the growth of phytoplankton and aquatic plants is restricted by the availability of phosphate and nitrogen. Problems can occur in densely populated areas, however, when both of these nutrients enter coastal water via the effluent from wastewater, fertilizers, animal waste, atmospheric deposition, and groundwater (Behnke 1975). Accumulation of such nutrients in a body of water, referred to as eutrophication, usually results in algae-choked waters. Eventually these algae die and decompose, after which the aerobic decomposers deplete the water's dissolved oxygen, causing the depletion of fishes and other aerobic organisms (Paerl 1997).

Oyster Pond, situated on the shore between Woods Hole and Falmouth, Massachusetts, is dominated by glacial outwash (Emery 1997). Since the permeability of the surface sediments is very high, groundwater flow is the principal mechanism of derived nutrients to the estuary (Millham and Howes 1994). Water travels through the top layer of soil, down through dry sediment, the vadose zone, and then into the water aquifer (Figure 1). About 50% of the precipitation, the amount left after evapotranspiration, travels in this way through the water table of the Oyster Pond watershed (Emery 1997). Along a narrow band of land, called the seepage face, groundwater drains into Oyster Pond. The concentration of land-derived nutrients prior to entering the estuary can be obtained from the seepage face in groundwater (Kroeger et al. 1999).

In this paper, we first, measured N loads by estimating concentration of nutrients in groundwater per recharge zone. These estimates allowed us to quantify a total N load into Oyster Pond. Secondly, to be able to differentiate the loads from individual source contributions (wastewater, fertilizer, atmospheric deposition) we needed to apply another approach. We estimated the total N loads to Oyster Pond by applying Nitrogen Loading Model (NLM) (Valiela et al. 1997), and verified the NLM estimates by comparing NLM predictions to the measurements of nutrient concentrations taken from groundwater samples of Oyster Pond. The model estimates individual inputs to Oyster Pond from the three main sources of nitrogen: atmospheric deposition, fertilizer use, and wastewater; through the surfaces of the major types of land use, such as natural vegetation, turf, agriculture land, residential area, and impervious surfaces. The NLM model was used to measure each source of nitrogen based on land use within the watershed. (Valiela et al. 1997).

Thirdly we considered another source of nitrogen into Oyster Pond. One aspect not included as an external N source in NLM is waterfowl, which contribute nutrients through their feces (Manny et al. 1994). Previous studies (Gwiazda, 1996, Mitchell et al. 1994, Gere and Andrikovics, 1992) have shown that birds do not provide an external source of nutrients but rather cycle it. This is because birds in the watershed eat and defecate within the pond. Public concern regarding poor water quality, which inhibits activities such as swimming and shellfish harvesting, may place pressure on wildlife managers to solve the problem by eliminating waterfowl without accessing their actual input (Valiela et al. 1991). Waterfowl studies of Oyster Pond attempt to verify waterfowl nutrient input and convey that their presence has a minimal contribution to the N load of Oyster Pond.

In this paper, we 1) measure land-derived nitrogen and phosphorus concentrations entering Oyster Pond; 2) use NLM to estimate sources and amount of nitrogen contributed from groundwater into Oyster Pond; 3) determine the magnitude of N load by comparing it to N loads to other Cape Cod estuaries; 4) examine the presence of waterfowl and their input to nitrogen loading; and 5) use NLM to suggest possible management systems to reduce nitrogen loads to Oyster Pond.

Methods:

Calculation of the measured nitrogen load

The Geographic Information System (GIS) was designed to include land use areas consisting of the following themes within the entire watershed of Oyster Pond: fertilized fields, impermeable surfaces, water bodies, and the number of houses. The GIS-based information about the area of the recharge zone within the greater watershed was then used to determine an adequate number of sampling sites within each zone. A 200 m boarder around the pond was demarcated so that we could look at the land use within that area and later use it in NLM.

To get the measured nitrogen concentrations, we collected 35 groundwater samples around the periphery of Oyster Pond during October of 2001 (Figure 2). Sampling was done where the soil allowed; in many places cobbles in the underlying sediments made several well point samples impossible. As samples of groundwater were taken, they were analyzed to make sure it was fresh groundwater. Groundwater samples with a salinity > 2 ppt or those with sulfide odors were rejected. Sample sites ranged from 0-2 m distance from the edge of the pond. The depth of sample collection ranged between 0.25-1.5 m. beneath the top layer of soil. We also collected two samples directly from Mosquito Creek (Figure 2, recharge zone 2), one about 200 m from where it meets with the pond, and the other, directly at the junction between the creek and Pond.

Groundwater samples were analyzed for phosphorus (PO_4), ammonium (NH_4), nitrate (NO_3), and total dissolved nitrogen (TDN) using standard techniques (Strickland and Parsons 1972). Nitrate concentration was measured by shaking with spongy cadmium to reduce nitrate to nitrite (Jones, 1984). We measured both nitrate and nitrite concentrations (D'Elia et al. 1977), but as nitrite is normally one degree of magnitude lower than nitrate, we report results as nitrate (Kroeger et al 1999). We summed the values for nitrate and ammonium to calculate DIN. The TDN procedure called for persulfate digestion followed by the nitrate procedure (D'Elia et al. 1977). We then subtracted the calculated DIN concentration from the TDN concentration to calculate DON concentrations.

As mentioned, we divided the watershed of Oyster Pond into six recharge zones (Figure 2) to examine how nitrogen concentration in groundwater varied depending on the land use of one contributing recharge zone. The nitrogen load from each recharge zone to Oyster Pond was calculated by multiplying mean nutrient concentration discharging for each recharge zone by the annual water flow. We calculated groundwater flow rates by multiplying the surface of each recharge zone by the average yearly rainfall of 1170 mm per year multiplied the annual precipitation by 0.45 to account for evapotranspiration (Giblin and Gaines 1990). The total annual nitrogen load to Oyster Pond was then calculated by summing the load from all recharge zones.

Model estimate of the nitrogen load

We obtained the input data for NLM from a GIS data (1998) base and checked the data against aerial photos (1993). Input data needed by NLM consisted of number of houses, area of wetlands, impervious areas, areas of ponds, and agricultural areas (Table 1). Previous measurements of atmospheric deposition and fertilizer application rates were used from estimates from Waquoit Bay study (Valiela et al. 1997) and data from three decades of Oyster Pond (Emery 1997).

Waterfowl inputs

We periodically made a census of the waterfowl population of Oyster Pond, and collected literature on waterfowl defecation rates and nutrient inputs into various bodies of water (Mitchell and Wass 1995, Gere and Andrikovics 1992, McCann et al 199-, Gwiazda 1996, Manny et al 1975, 1994). We used this information in our calculations of total waterfowl load in kg $year^{-1}$. We used the maximum observed number of individuals to provide the highest possible estimates of the total population.

We calculated nutrient loads for year-round residents birds by multiplying individual daily defecation rates by the observed population and by 365 days to obtain annual input of nitrogen in kg $year^{-1}$. For seasonal residents, we used previous information about annual N load for a specific population, and adjusted the numbers to Oyster Pond's population and the amount of time they spend in this area. This adjustment gave us the annual load for the pond in kg $year^{-1}$ (Table 2).

Results and Discussion:

Measured nitrogen loads

Concentrations of NO_3, NH_4, and PO_4 in groundwater about to enter Oyster Pond averaged 21.2, 11.3, and 0.41 M respectively (Figure 3). For NO_3, most groundwater showed lower concentrations with random peaks, which were probably sampled individual septic system discharge. The concentration of NO_3 in the different recharge zones are varied (Figure 3a) with recharge zone 3 showing the largest convincing homogenous concentrations of NO_3 (Figure 3).

Groundwater concentrations of NH_4 were greatly varied as well (Figure 3b). High NH_4 concentrations were not as consistent in recharge zone 3 as they were for NO_3. These findings may represent ammonium preference by bacteria (Valiela 1995). In marine environments, organisms prefer assimilating ammonium rather than nitrate because more energy is required to reduce nitrate to the amino form. Concentrations of PO_4 were generally low with one peak in recharge zone 2 (Figure 3c). This particular sample was one of the two taken directly from Mosquito Creek. The water sample did not have an anoxic scent, but leaves in the creek and anoxic sediments below probably skewed results for the 4.5 μM concentration (Valiela 1995).

Figure 4 shows the linear relationship between the number of houses and the measured nitrogen load for almost all recharge zones in Oyster Pond, r^2=0.83. This supports other findings that the magnitude of the nitrogen load is related to the number of houses present within a given recharge zone (Kroeger et al. 1999).

Comparison of measured and modeled nitrogen loads

To verify that NLM estimates reasonably depict measured N loads (measured TDN values) to Oyster Pond we verified our measured estimates by multiplying annual recharge to mean concentration of nitrogen in freshwater. If model accurately depicts measured values, values should fall around a 1:1 line (Figure 5). For context, we used data from other Cape Cod estuaries (Valiela 2000). In Figure 5, the points for Oyster Pond fell reasonably close to the scatter points from Waquoit watersheds. This result supports that our NML model yields an accurate estimate.

As mentioned, NLM estimated the nitrogen load of different nitrogen sources based on land uses (Table 1). The total expected nitrogen load was highest in recharge zone 3 and lowest in recharge zone 6, where total N was 385 and 55 kg per year respectively. The total land usage was also highest in recharge zone 3 and lowest in recharge zone 6, where total land usage was 61 and 11 ha respectively (based on GIS). Land usage (Table 1) and nitrogen input to pond (Table 3) show a relationship between the total nitrogen load and the land usage as stated by Kroeger et al (1999).

N loads to Oyster Pond are low compared to those received by other Cape Cod estuaries (Table 4). Relative N loads of Oyster Pond are low even compared to Sage Lot, an estuary whose watershed is largely forested and hence an example of a near pristine state (Kroeger 1999). Therefore, the total annual N load to Oyster Pond is 31.7 Kg N ha^{-1} yr^{-1} and is small falling well below Childs River (601 Kg N ha^{-1} yr^{-1}) and slightly above Sage Lot Pond.

Waterfowl Input

As aforementioned, waterfowl is not considered an external source of nitrogen into Oyster Pond estuary because they recycle the nutrients already within the watershed. Even if this were not the case, nitrogen input from waterfowl is trivial(Table 2) compared to atmospheric deposition, wastewater, and fertilizers (Table 3). We found that even our maximum estimates of possible N input by waterfowl were only 13% of the total nitrogen load. The Double-Crested Cormorants contributed 56.7 kg N yr^{-1} to the overall 133.3 kg N yr^{-1} from waterfowl. Because this species is only a part-time resident of Oyster Pond and not all defecation took place in the pond, their N input is even more overestimated than the other species of birds observed. This small nitrogen contribution supports that the complete absence of waterfowl would not significantly lower the load to Oyster Pond.

The evident lack of significant N load from waterfowl necessitates other targets for effective nitrogen load management. The influx of nitrogen from wastewater makes septic systems a likely candidate for practical management efforts in Oyster Pond (Table 5). This becomes more important as the watershed of Oyster Pond nears build-out. It is currently at 73% and will most likely increase in the next few years (pers.com. Marci Cole). This is why our understanding of the main sources of nitrogen to estuaries are paramount; especially when considering how to manage our use of land today and in the future.

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Table 1. Land usage within the Oyster Pond determined from recharge zone delination maps from aerial photographs (1993) and GIS (1998). Differences in land uses could be due to urbanization changes in a 5 year time period or classification techniques.

	Recharge zone 1		Recharge zone 2		Recharge zone 3		Recharge zone 4		Recharge zone 5		Recharge zone 6		Total	
	1993	1998	1993	1998	1993	1998	1993	1998	1993	1998	1993	1998	1993	1998
Total number houses	28	29	33	34	81	84	14	14	34	35	10	11	200	207
Land uses														
Fresh water ponds	0	0	0	0.4	2.2	0.4	2.6	2.3	0	0	0.4	0.2	5.2	3.3
Wetlands	0.8	0.9	0	0	0	2	0	0	0.3	0	1.1	0	2.2	2.9
Natural vegetation	14	17	13	19	24	38	8	11	6	9	5	8	70	102
Fertilized turf	1	1	2	2	4	4	1	1	2	2	0	1	10	11
Lawns	1	1	2	2	4	4	1	1	2	2	0	1	10	11
Other turf	2	0	4	0	11	3	0	0	3	0	1	0	21	3
Impervious area	1	1	2	2	3	5	1	1	1	1	1	1	9	11
Roofs	1	1	1	1	2	2	0	0	1	1	0	0	5	5
Roads	1	1	1	1	1	2	0	0	0	0	0	0	3	4
Others	0	0	0	1	0	1	0	0	0	0	0	0	0	2
Total land area/recharge	**22**	**23**	**25**	**28**	**51**	**61**	**14**	**16**	**15**	**15**	**9**	**11**	**135**	**155**
Grand total of land areas for whole watershed	**135**	**155**												

Table 2. The number of individuals from four species of birds is recorded here, along with their annual defication rates. Annual rate was calculated from daily rates and the percentages were calculated from the total nitrogen loads.

Species	**No. of Individuals** (max # of indiv)	**Daily N Defecation** (g indiv-1day-1)	**Annual N Defecation** (kg yr-1)	**N load to OP** (%)
Mallards (a)	32	2.6(a)	30.6	3
Mute Swans(b)	32	1.2 (b)	14	1.4
Canada Geese (c)	6	1.4	3.2(c)	0.3
Double-Crested Cormorants (d)	27	-	56.7 (d)	5.6
Total	97		133.3	13.2

a) Gwiazda 1996; b) Mitchell and Wass 1994; c) Manny et al. 1975; 1994; d) McCann et al. 1997, Gere and Andrikovics 1992

Table 3 : Expected atmospheric deposition, wastewater, and fertilizer use for each recharge zone (kg N yr-1, %).

		% N by source actual input to pond					
subwatershed	Total N Expected	**Atm. Dep.**		**Wastewater**		**Fertilizer**	
		kg N yr-1	%	kg N yr-1	%	kg N yr-1	%
1	135	31	15	95	14	9	15
2	147	35	17	101	15	10	16
3	385	83	39	277	42	25	40
4	71	28	13	39	6	4	6
5	141	18	8	113	17	11	18
6 (Lagoon)	55	17	8	35	5	3	5
			100		100		100

Table 4. Comparison of the annual measured and modeled nitrogen loads to Oyster Pond with the loads to other local Cape Cod estuaries (a).

	Estuary Size ha	**Modeled N Load** kg-N yr-1	**Modeled N Load** kg-N ha-1 yr-1
Quashnet River	28	8406	300
Childs River	13.5	5536	410
Sage Lot Pond	70	361	5
Oyster Pond	27.7	878	32

(a) Kroeger et al. 1999

Table 5. Contribution of individual sources of nitrogen to Oyster Pond. Values are NLM predicted from GIS land use data of the three main sources of nitrogen. Values are presented as the amount input into the watershed, percent nitrogen lost through the watershed, and actual input in Oyster Pond.

	Input to watershed		**Watershed loss**	**Input to Oyster Pond**	
N Source	(kg N yr-1)	%	%	(kg N yr-1)	%
Atmos. Depos.	1859	47	90	195	22
Natural veg.	1431	36	91	127	14
Turf	190	5	91	18	2
Roofs, drives	55	1	91	5	1
Roads	56	1	75	14	2
Ponds	47	1	72	13	1
Wastewater	1690	43	63	624	71
Fertilizer	379	10	84	59	7
Lawns	379	10	84	59	7
Grand Total	3928	100	78	878	100

Figure Legends

Figure 1. Schematic of NLM, showing inputs of wastewater-, fertilizer-, and atmospheric- derived nitrogen to Oyster Pond. The nitrogen from the three sources traverses downward through the soil, the vadose zone, and the aquifer. It then travels horizontally where it makes its way toward the seepage face and into the estuary.

Figure 2. Map of Oyster Pond on Cape Cod, Massachusetts. Oyster Pond watershed is divided into 6 recharge zones. Black dots show location of sampling stations within each recharge zones for this study.

Figure 3 (a), (b), (c). Individual nitrate, ammonium, and phosphate concentrations (μM) vs. the recharge zones. The vertical bars show the concentration of each nutrient starting on the left with samples of groundwater collected at the Lagoon, moving toward recharge zones 1,2,3, 4, and 5.

Figure 4. Plot of measured nitrogen load (μM) of each recharge zones vs. the number of houses within that zone. The magnitude of the nitrogen load is related to the number of houses ($r^2 = 0.83$).

Figure 5. Comparison of measured N loads on the modeled loads for the 6 recharge zones (black squares) and whole watershed (black dot) of Oyster Pond . Data shows measured vs modeled values for Oyster Pond and Waquoit watersheds, both systems follow a 1:1 ratio line.

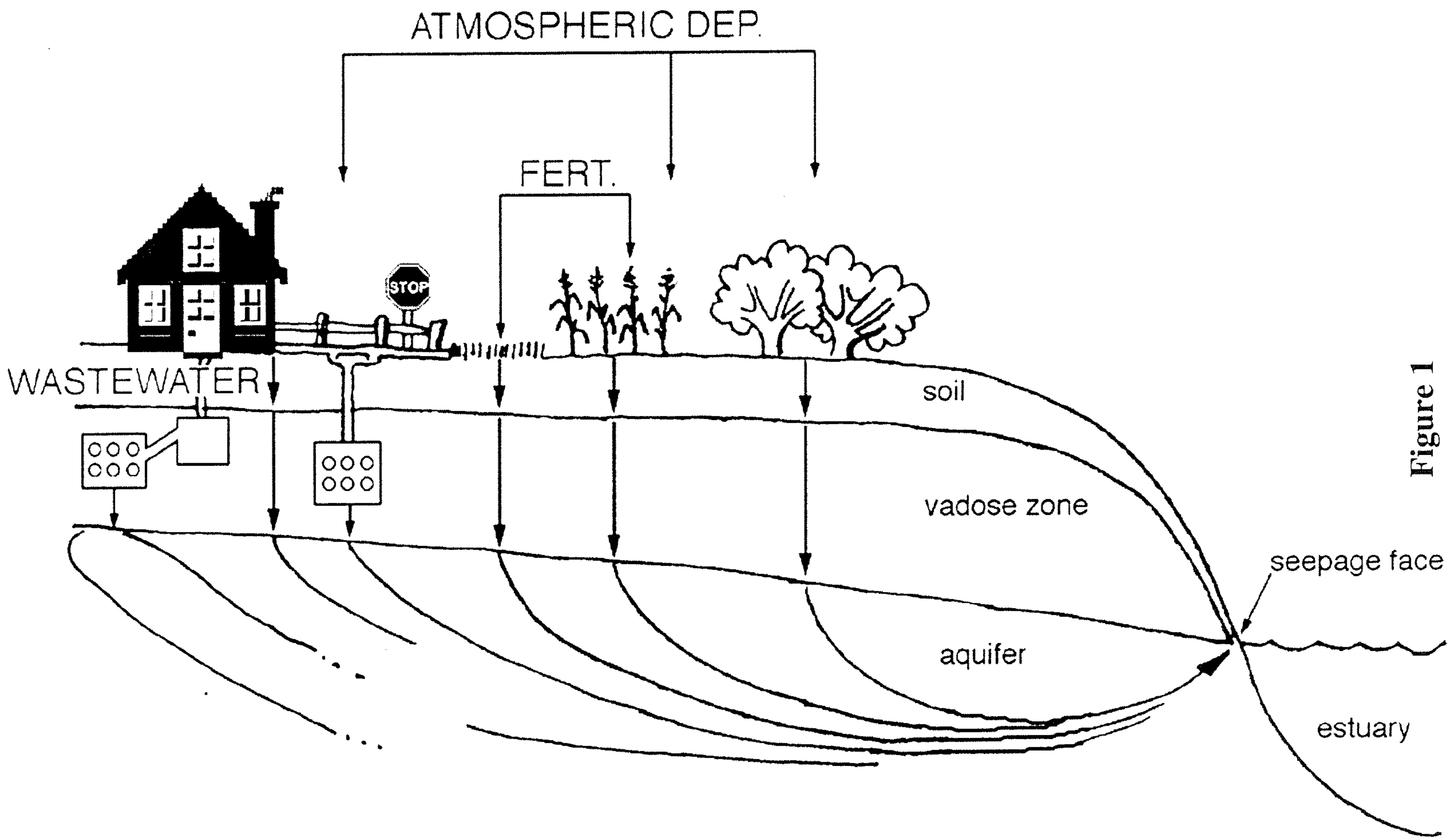


Figure 1

Waquoit Bay NLM (From Valiela et al. 1997. Ecol. Appl.)

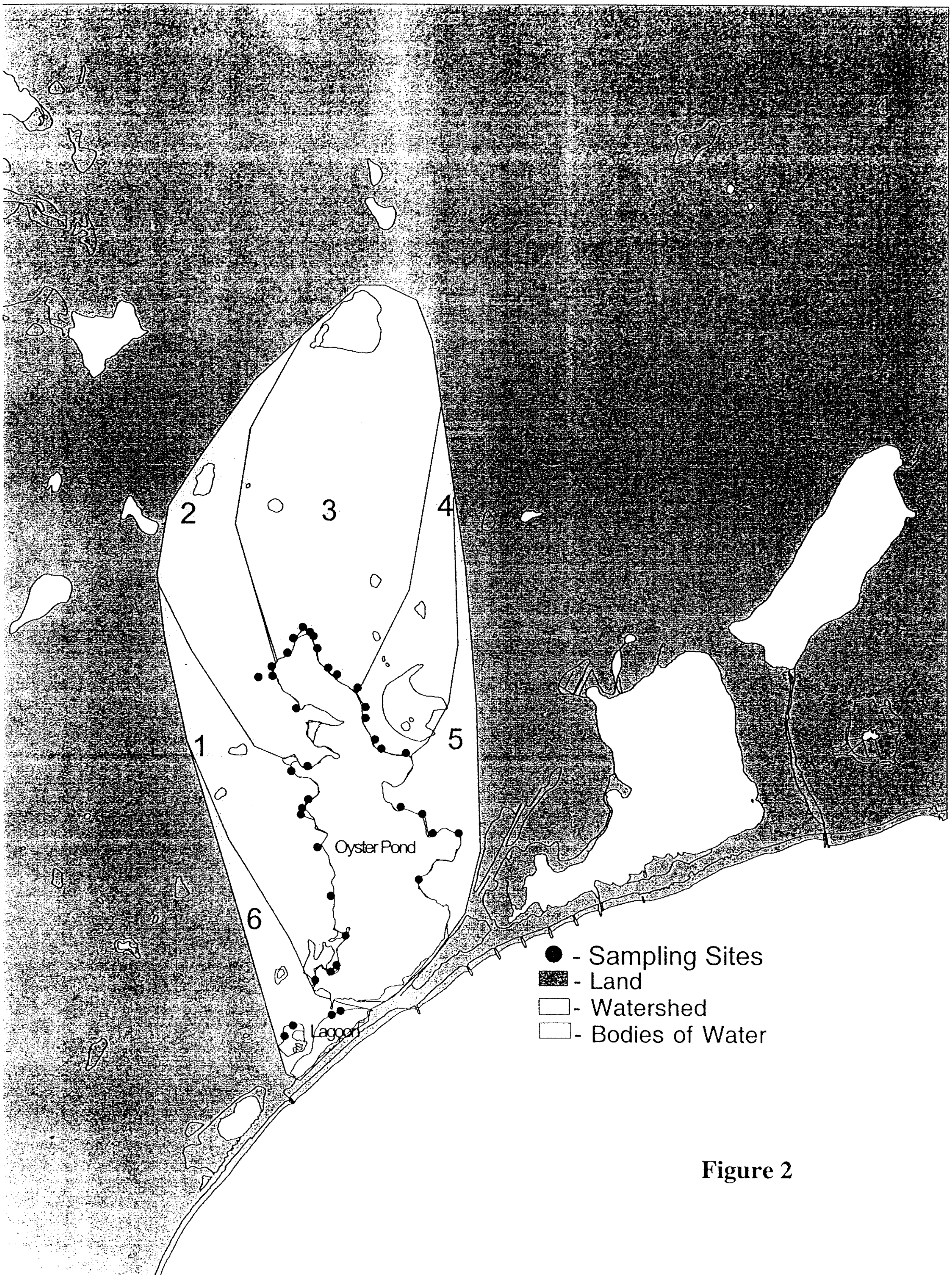

1
2
3
4
5
6
Oyster Pond
Lagoon
- Sampling Sites
- Land
- Watershed
- Bodies of Water

Figure 2

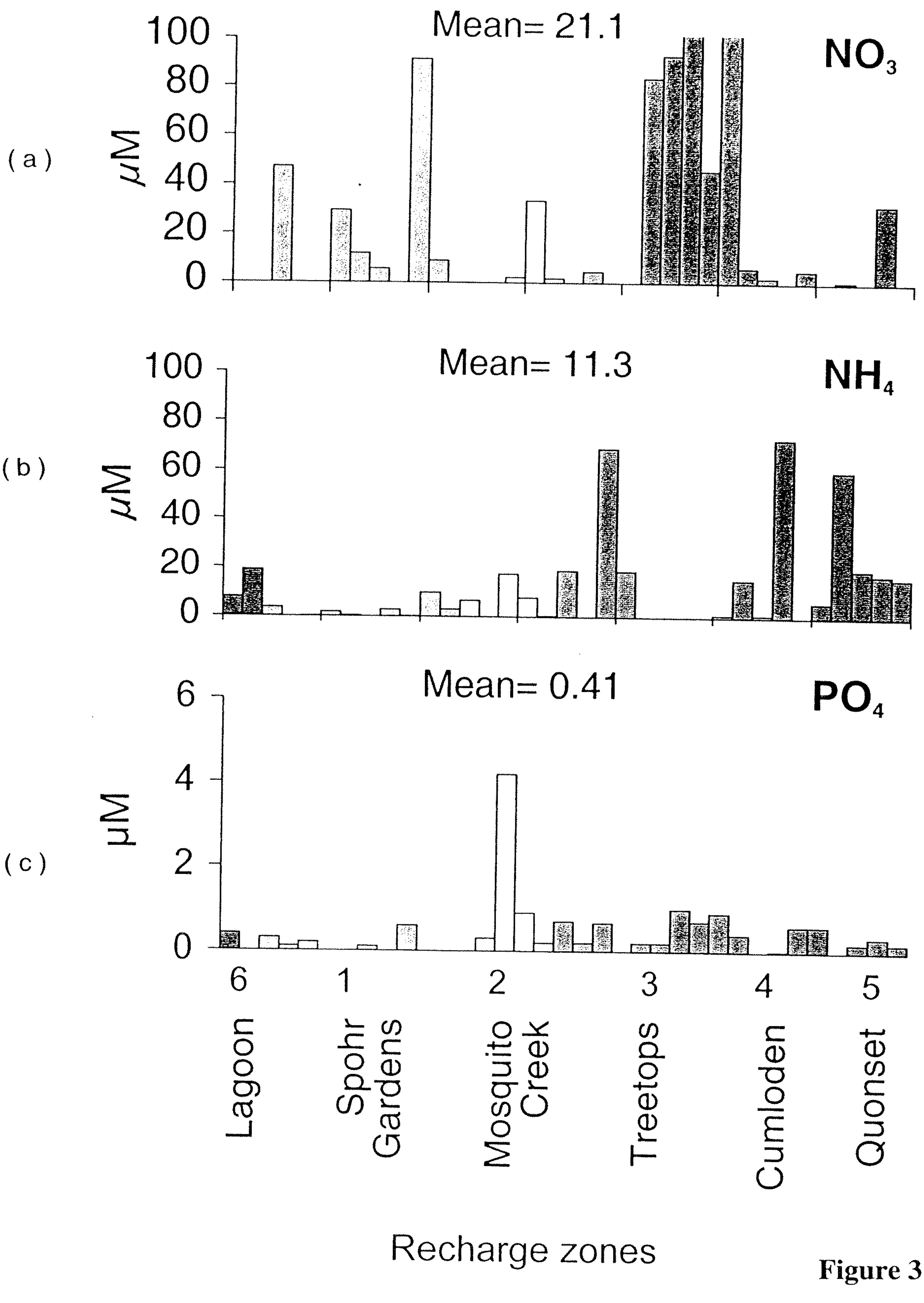
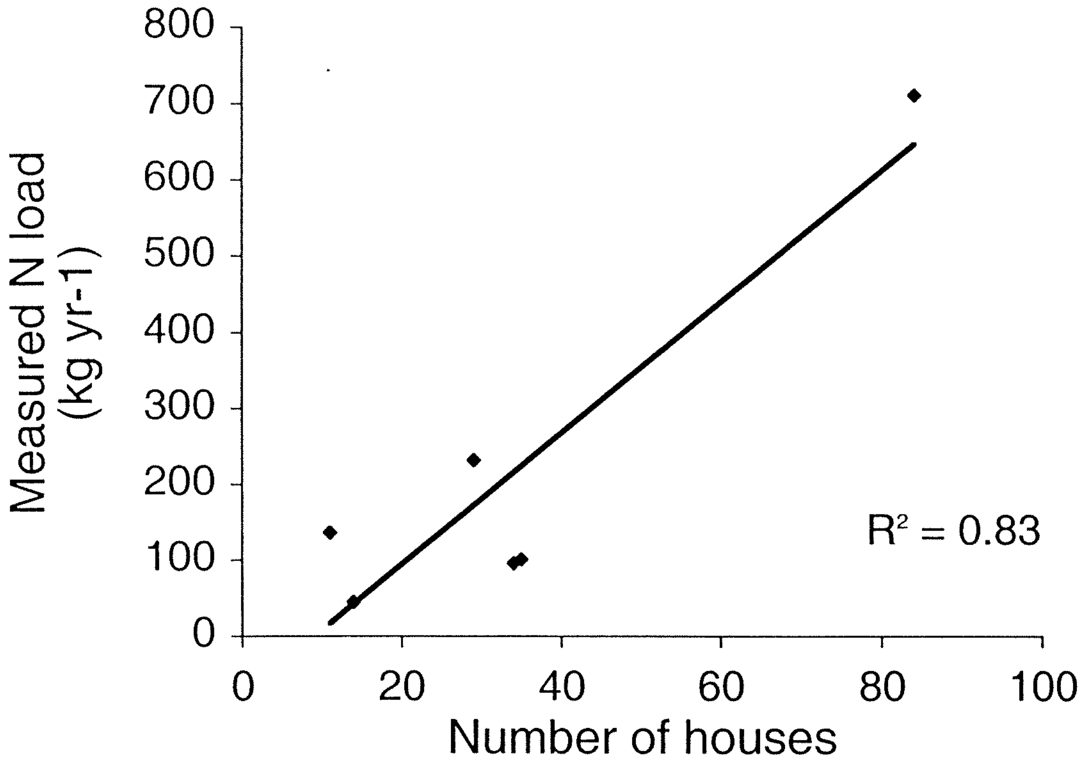

Mean= 21.1
NO3
(a)
µM
100
80
60
40
20
0
Mean= 11.3
NH4
(b)
µM
100
80
60
40
20
0
Mean= 0.41
PO4
(c)
µM
6
4
2
0
6
1
2
3
4
5
Lagoon
Spohr Gardens
Mosquito Creek
Treetops
Cumloden
Quonset
Recharge zones

Figure 3



800
700
600
500
400
300
200
100
0
Measured N load
(kg yr-1)
$R^2 = 0.83$
0
20
40
60
80
100
Number of houses

Figure 4

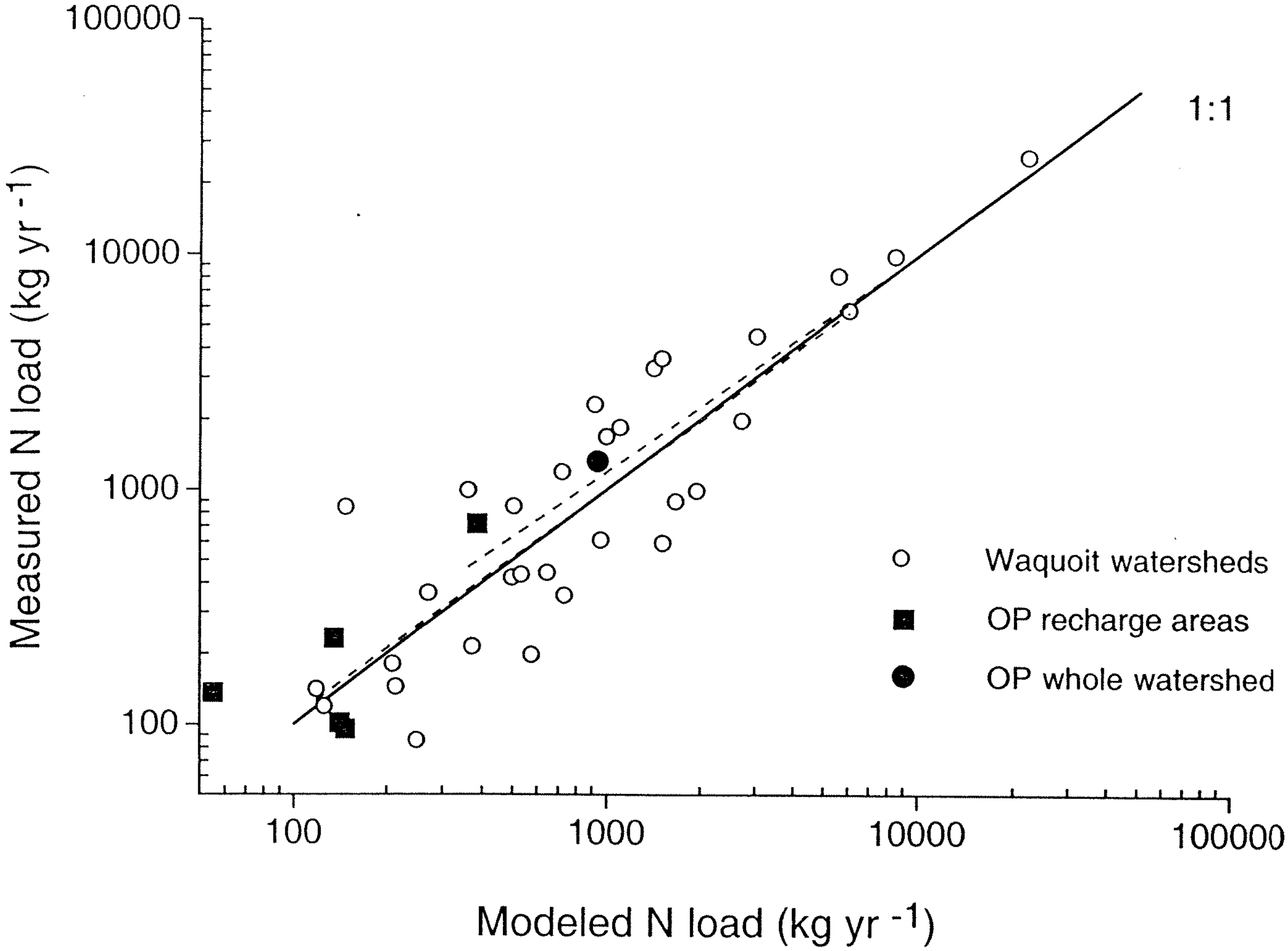


Figure 5

Valiela et al. 2000

Chapter 2

Vertical and horizontal distribution of biogeochemical properties and chlorophylls in the Oyster Pond estuary

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Abstract

The different water inputs from terrestrial and marine sources make coastal estuaries unique systems. The Oyster Pond system provides an excellent opportunity to study the basic workings of an estuary in transition from freshwater to saltwater. The purpose of this study is to examine the biogeochemical processes in the Oyster Pond system. In general, the concentrations of nitrate, DON, phosphate, dissolved oxygen, and chlorophyll *a, b,* and *c*, remain consistent throughout the top 4 ms of the pond. Below this depth, concentrations of nitrate and dissolved oxygen decreased, while DON and phosphate increased. Concentrations of chlorophyll *a*, *b*, and *c* varied within the mixed layer and increased just above the anoxic zone. Diatoms, sulfur bacteria, and blue-green bacteria may have contributed to the chlorophyll profile in the mixed layers and near the anoxic zone. Phosphate, ammonium, and nitrate concentrations were higher at the north end of the estuary, probably as a result of the influx of nutrients from the watershed.

Introduction

The salinity, nutrient, and chlorophyll concentrations of estuaries depend on land and marine inputs, as well as on intense hydrographic conditions within the respective estuary being examined. Terrestrial sources of nutrients can be effectively studied by comparing the distribution of these properties to physical properties, such as salinity (Sharp et al. 1982). Increases in the density of human inhabitants in the watershed have a direct influence on the amount of nutrients entering the system (Valiela 1995). Nutrients entering estuaries determine the concentration of primary production (Jordan et al. 1991) and of eutrophication (Howarth 1985).

Marine nutrient sources are minor (Liss, 1976), but the mixing of saltwater can lead to stratification. Stratification, in turn, can influence nutrient distribution in estuaries. Sharp (1982) stresses that hydrographical profiling of estuaries is essential for the understanding of the system.

The Oyster Pond estuary on Cape Cod (Figure 1a) has changed substantially due to management efforts. In the 1980s, Oyster Pond was brackish and had a substantial amount of anoxic bottom water. In 1998, a weir was placed between the lagoon that leads to Vineyard Sound, and the pond itself to restrict seawater flow. Manipulation of the height of the weir controls the flow of seawater in, and freshwater out of the pond. This has increased the amount of freshwater in the pond. Before the introduction of the weir, two studies were conducted on Oyster Pond (Emery et al. 1997).

In this paper we report surveys of the salinity, nutrient and chlorophyll distributions throughout the Oyster Pond estuary, and compare the present status to previous conditions.

Methods

To determine the vertical and horizontal nutrient distributions within Oyster Pond, water samples were collected from the pond (OP), the lagoon (LG), and Vineyard Sound (VS), which can be seen in Figure 1. Samples were collected along the long axis of Oyster Pond starting at the weir, around the perimeter of the pond, in the lagoon, and in Vineyard Sound (Figure 1a and 1b). To create depth profiles, water was collected at each meter from the surface to within a half-meter from the bottom.

Sampling sites were selected using a depth contour map (Emery et al. 1997). A water sampler was used to obtain the samples, and we measured salinity, dissolved oxygen and temperature using a YSI dissolved oxygen meter.

Water samples were filtered using GF/F ashed filters. We measured ammonium according to methods described by Strickland and Parsons (1972), nitrate according to methods described by Jones (1984), phosphorus according to methods described by Strickland and Parsons (1972), and total dissolved nitrogen according to methods described by D'Elia et al. (1977). Dissolved organic nitrogen (DON) was calculated by subtracting nitrate and ammonium from the total dissolved nitrogen. These filters were prepared for chlorophyll analysis according to Lorenzen (1967). The filters were analyzed for chlorophyll a, b, and c using methods described by Lorenzen (1967) and Jeffrey and Humphrey (1975).

Results and Discussion

Temperature and Salinity

The temperature throughout the Oyster Pond system ranged from 14-18°C. The vertical profile (Figure 2) shows that the surface water was approximately one degree higher than the deeper water, with the exception of the saltwater pocket in the deep basin. Surface water in the shallower sections of the pond was generally higher in temperature than in deeper portions (Figure 3).

The salinity of Oyster Pond was relatively uniform, about 2.3 ‰ both horizontally and vertically, with the exception of the bottom 2-3 m of the southern basin (Figure 4 and 5). The salinity distribution reveals the pattern of ocean water entering Oyster Pond from Vineyard Sound. The similarity between salinity values in the surface layers of the pond show that saltwater sinks to the bottom within a short distance (Figure 5). The vertical mixing of the freshwater layer leads to near-uniform distribution of all measured properties in the upper portions of the water column. This mixing does not extend below the halocline due to the sharp density difference between the saltwater and freshwater layers.

Dissolved Oxygen

The dissolved oxygen concentration of the Oyster Pond system was approximately 10 mg L^{-1} (Figure 5), with the exception of the bottom 2-3 ms of the southern basin (Figure 4), where there was no oxygen in the water. Dissolved oxygen concentrations in the bottom water were decreased as a result of the degradation of organic matter by bacteria.

Phosphate

Phosphate concentrations in the Oyster Pond system were less than 1 μM (Figure 6 and 7). Higher concentrations were found below 4 m in the southern basin and at a depth of 2 m at the mouth of the northern basin (Figure 7 and 8). The higher concentrations at the north end of Oyster Pond could likely be attributed to larger nitrogen loads from those recharge areas. Under low oxygen concentrations, phosphate dissolution could account for the concentrations at depth in the southern basin.

Dissolved Inorganic Nitrogen (Ammonium and Nitrate)

The concentrations of ammonium in the Oyster Pond system were less than 4 μM. There were notably higher concentrations at 3 and 6 m in the southern basin of the pond (Figure 9 and 7) and at 1 m in the northern basin (Figure 10 and 7). Concentrations of nitrate were greater along the longitudinal axis of the pond (Figure 10 and 7). This was due to influx from the watershed. A lower concentration was found at depths greater than 4 m in the southern basin, in the southern portion of the lagoon, and in Vineyard Sound (Figure 9 and 7). The process of denitrification was responsible for the low concentrations of nitrate in the deep basin, while the bacterial degradation of organic matter released ammonium.

Chlorophyll

Chlorophyll *a, b,* and *c* concentrations in the mixed layer ranged from 1-6 μg ml^{-1} (Figure 11, 12, 13). Higher concentrations of chlorophyll are found below 3 m in both the northern and southern basins (Figure 14). Concentrations of chlorophyll *a*, *b*, and *c* increased with decreasing nitrate, increasing DON, and increasing phosphate (Figure 15 and 16).

The presence of three types of chlorophyll supports that a variety of phytoplankton must be present (diatoms, blue-green bacteria, sulfur bacteria, and dinoflagellates). The peak at 4-5 m may have several explanations. The organisms might be a colony of cells using the relatively larger concentrations of nutrients released in the deeper layer. Other explanations might also be possible. Experimental manipulations are needed to address this issue.

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Figure Legend

(Depth of vertical profiles is given in m)

Fig. 1a. Map of Oyster Pond with locations of collecting sites, Treetops Condominium Complex, and watersheds. Grey areas indicate marshes and beach.

Fig. 1b. Map of weir with collecting sites. Openings on weir are measured in meters.

Fig. 2. Vertical distribution of temperature in °C along longitudinal axis (depth is given in meters).

Fig. 3. Horizontal distribution of temperature in °C using surface data.

Fig. 4. Vertical distribution of salinity in ‰ and dissolved oxygen along longitudinal axis. Contour lines are in increments of 10 ‰ and 5 mg L^{-1} (depth is given in meters).

Fig. 5. Horizontal distribution of salinity in ‰ and dissolved oxygen in mg L^{-1} using surface data.

Fig. 6. Horizontal distribution of phosphate in μM using surface data.

Fig. 7. Graphs of nitrate, ammonium, and phosphate versus depth (depth is given in meters; nutrients are given in μg L^{-1}).

Fig. 8. Vertical distribution of phosphate in μM along longitudinal axis. Contour lines are in increments of 1 μM (depth is given in meters).

Fig. 9. Vertical distribution of ammonium and nitrate in μM. Contour lines are in increments of 5 μM and 1 μM, respectively (depth is given in meters).

Fig. 10. Horizontal distribution of ammonium and nitrate in μM using surface data. Contour lines are in increments of 10 μM and 1 μM, respectively.

Fig. 11. Horizontal distribution of chlorophyll *a* using surface data. Contour lines are in increments of 5 μg ml^{-1}.

Fig. 12. Horizontal distribution of chlorophyll *b* using surface data. Contour lines are in increments of 1 μg ml^{-1}.

Fig. 13. Horizontal distribution of chlorophyll *c* using surface data. Contour lines are in increments of 1 μg ml^{-1}.

Fig. 14. Graphs of chlorophyll *a*, *b*, and *c* versus depth (depth is given in meters; chlorophyll is given in μg ml^{-1}).

Fig. 15. Graphs of nitrate, phosphate, and DON versus chlorophyll *a* and *b* (depth is given in meters; nutrients are given in μM; chlorophyll is given in μg ml^{-1}).

Fig. 16. Graphs of nitrate, phosphate, and DON versus chlorophyll *c* (depth is given in meters; nutrients are given in μM; chlorophyll is given in μg ml^{-1}).

Oyster Pond Collection Sites

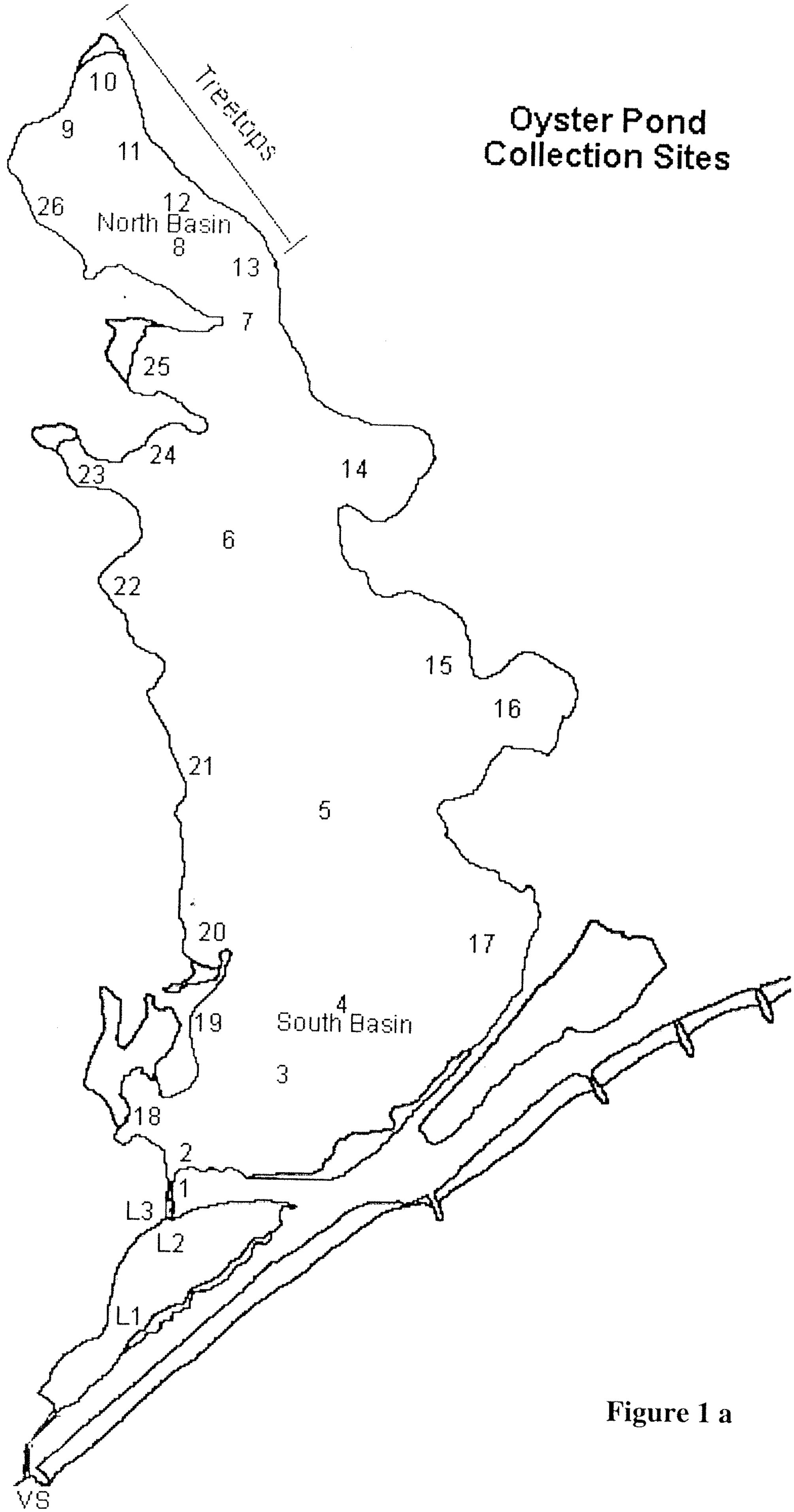


Figure 1 a

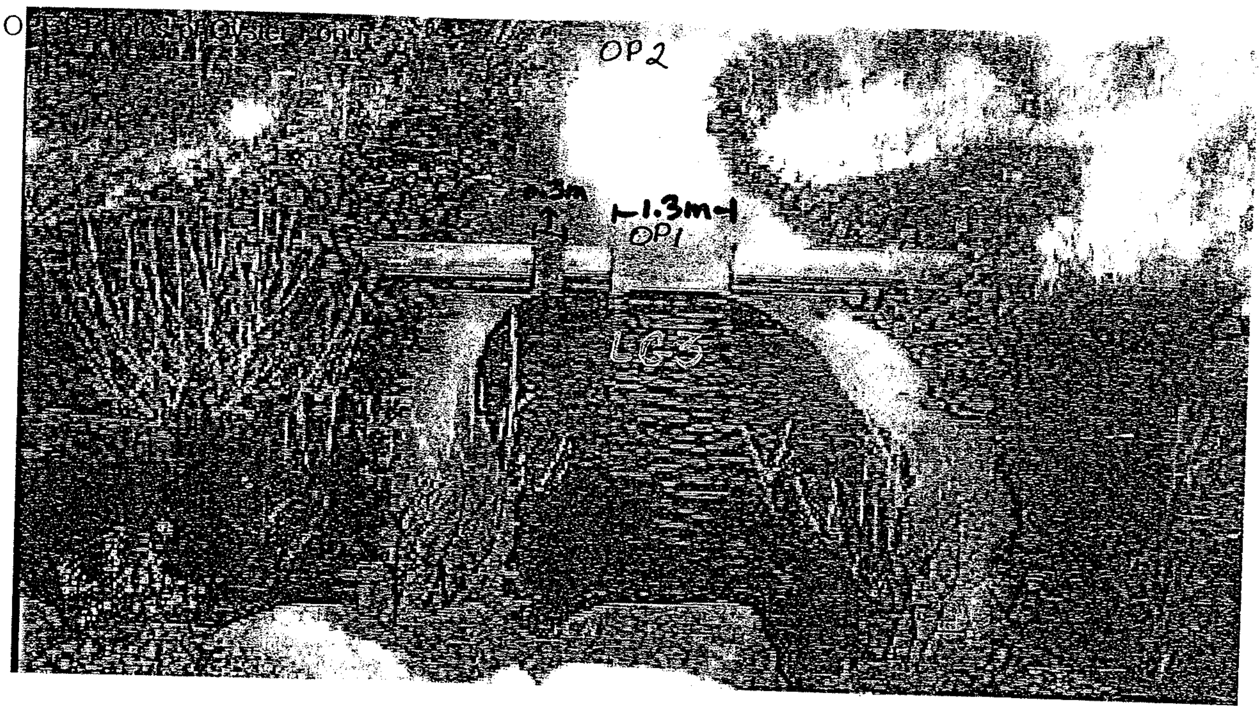
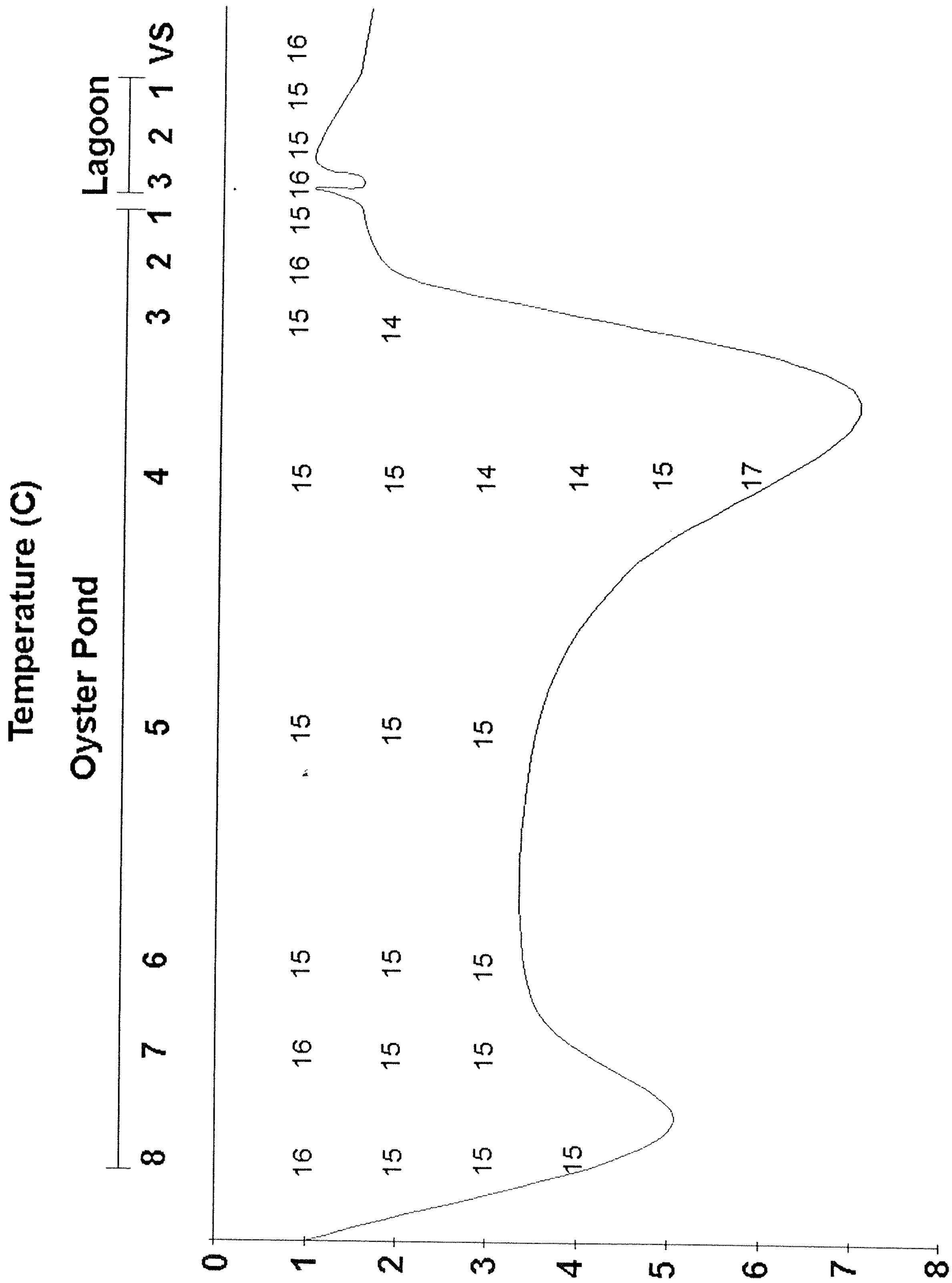


Figure 1 b

Figure 2



Temperature (C)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS
16 16 15 15 15 15 16 15 16 15 15 16
15 15 15 15 15 14
15 15 15 15 14
15 14
15
17
0 1 2 3 4 5 6 7 8

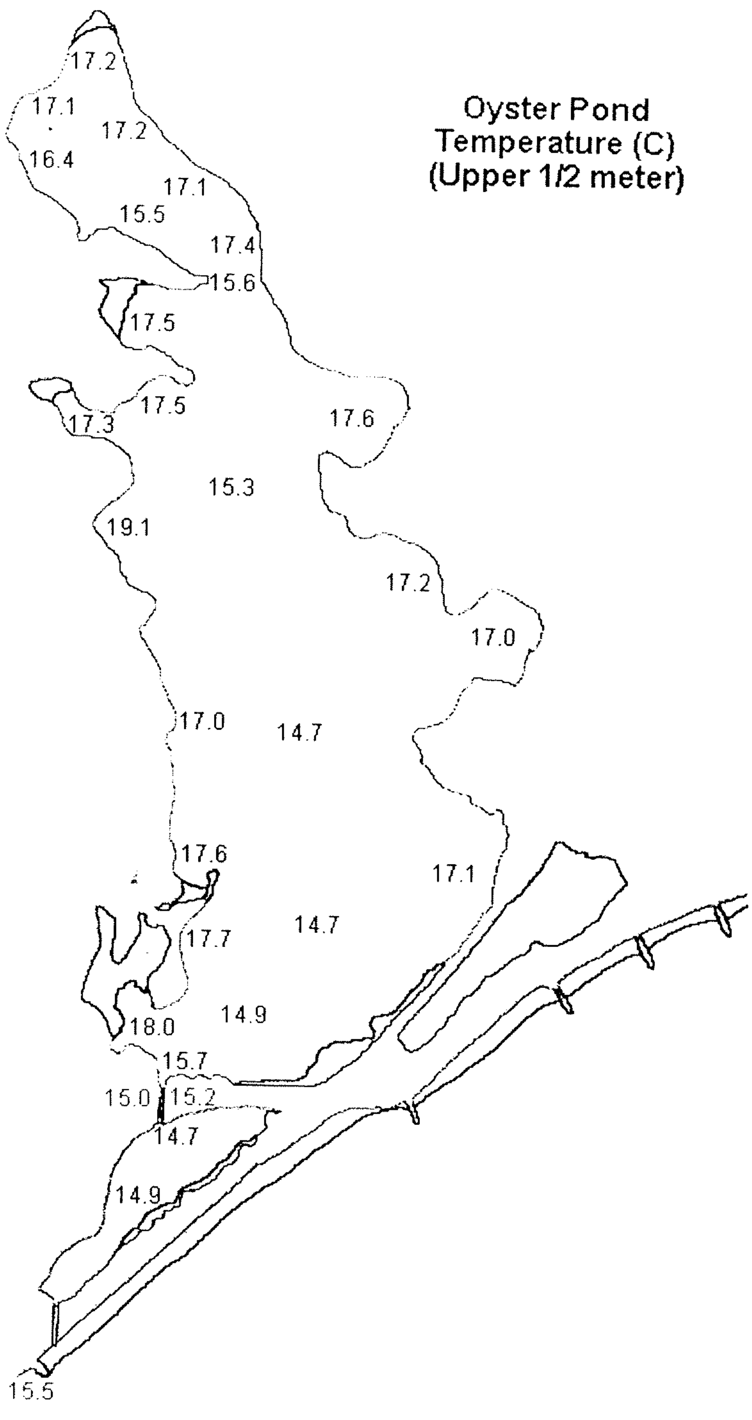
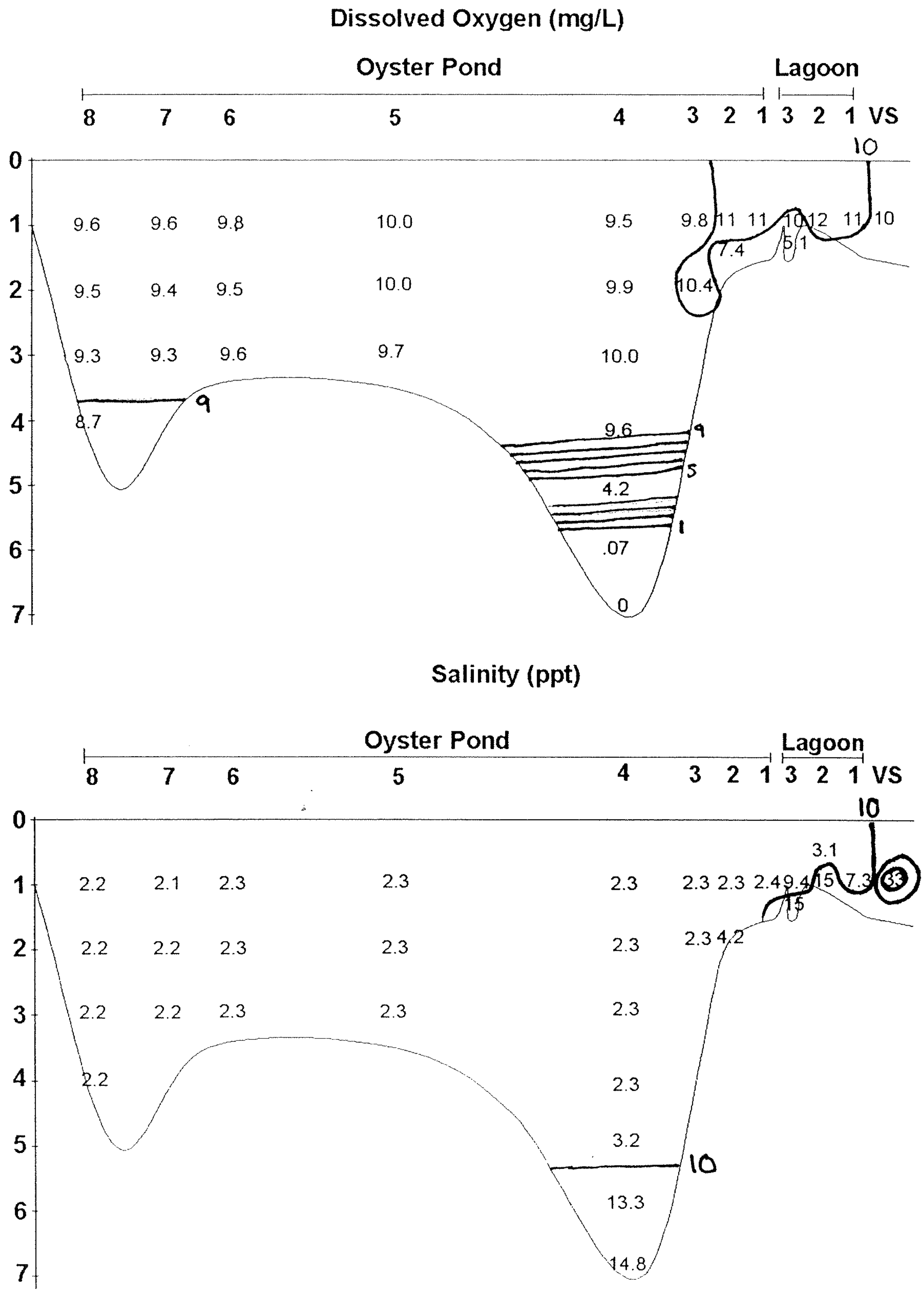

Oyster Pond
Temperature (C)
(Upper 1/2 meter)
17.2
17.1
17.2
16.4
17.1
15.5
17.4
15.6
17.5
17.5
17.3
17.6
15.3
19.1
17.2
17.0
17.0
14.7
17.6
17.1
17.7
14.7
14.9
18.0
15.7
15.0
15.2
14.7
14.9
15.5

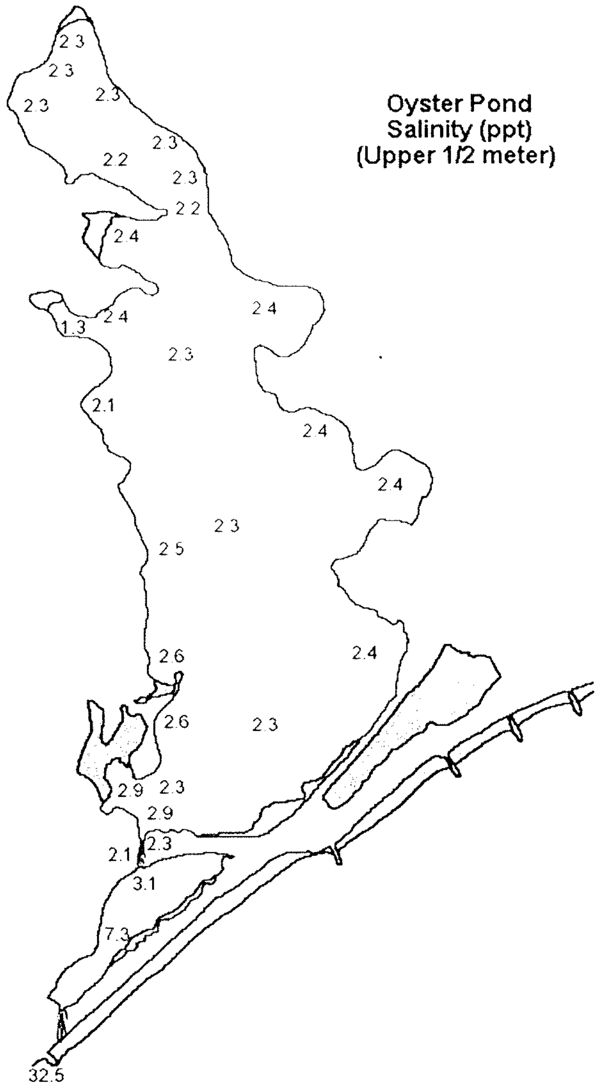
Figure 3

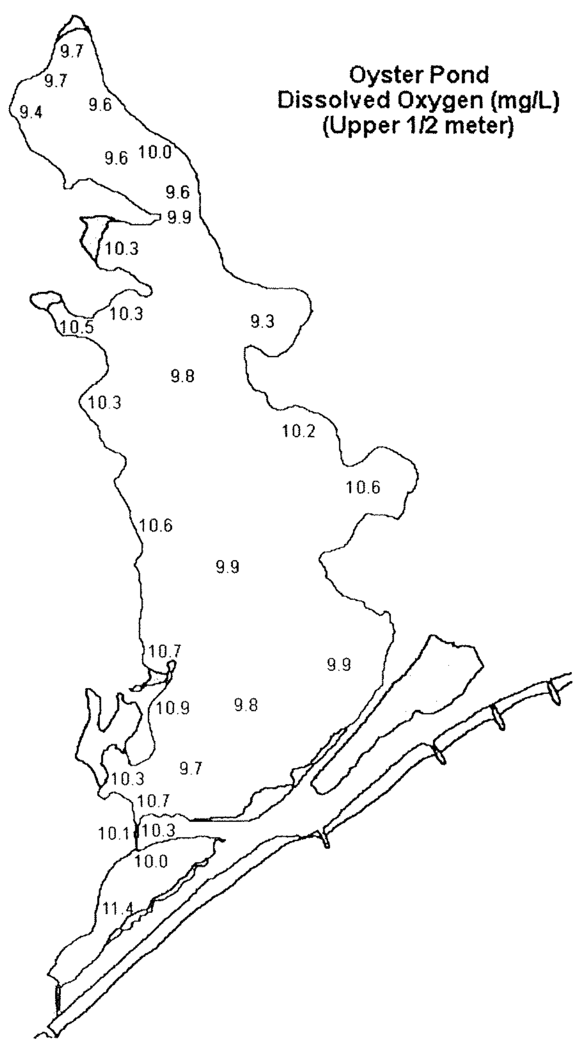


Dissolved Oxygen (mg/L)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS
Salinity (ppt)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS

Figure 4

Figure 5


Oyster Pond
Salinity (ppt)
(Upper 1/2 meter)
2.3
2.3
2.3
2.3
2.3
2.2
2.3
2.2
2.4
2.4
1.3
2.4
2.3
2.1
2.4
2.4
2.3
2.5
2.6
2.4
2.6
2.3
2.9
2.3
2.9
2.1
2.3
3.1
7.3
32.5


Oyster Pond
Dissolved Oxygen (mg/L)
(Upper 1/2 meter)
9.7
9.7
9.4
9.6
9.6
10.0
9.6
9.9
10.3
10.3
10.5
9.3
9.8
10.3
10.2
10.6
10.6
9.9
10.7
9.9
10.9
9.8
10.3
9.7
10.7
10.1
10.3
10.0
11.4

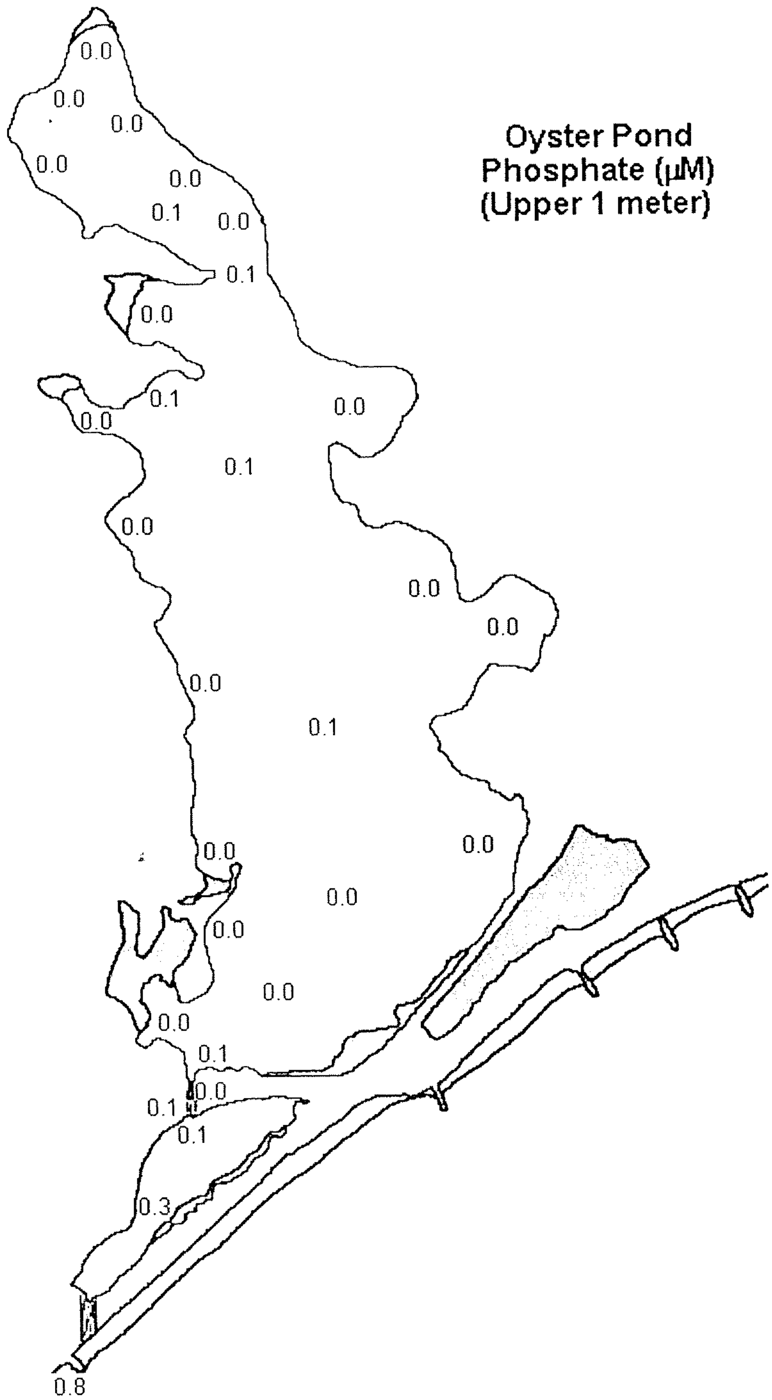

Oyster Pond
Phosphate (µM)
(Upper 1 meter)
0.0
0.0
0.0
0.0
0.0
0.1
0.0
0.1
0.0
0.1
0.0
0.0
0.1
0.0
0.0
0.0
0.0
0.1
0.0
0.0
0.0
0.0
0.0
0.0
0.1
0.0
0.1
0.1
0.3
0.8

Figure 6

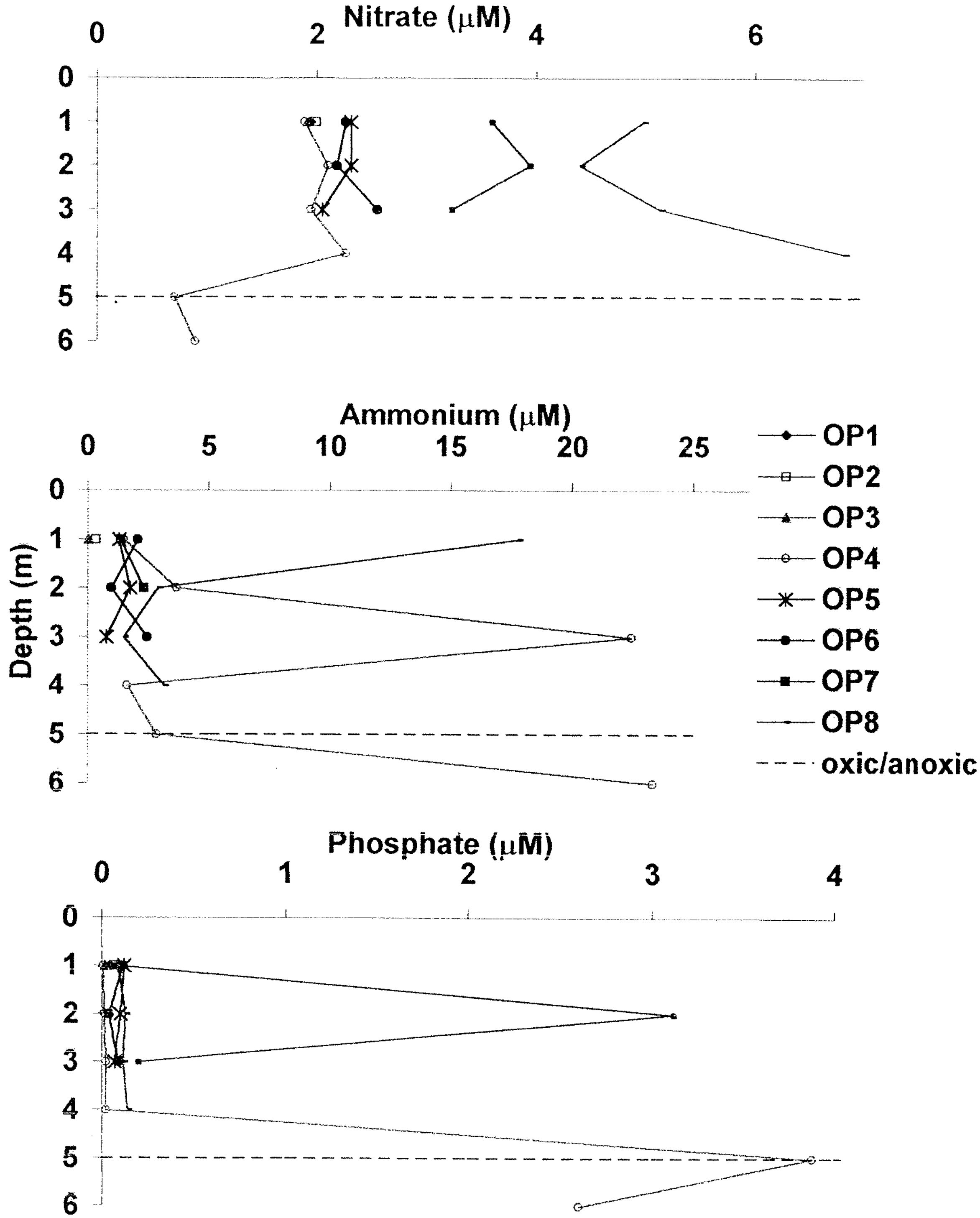
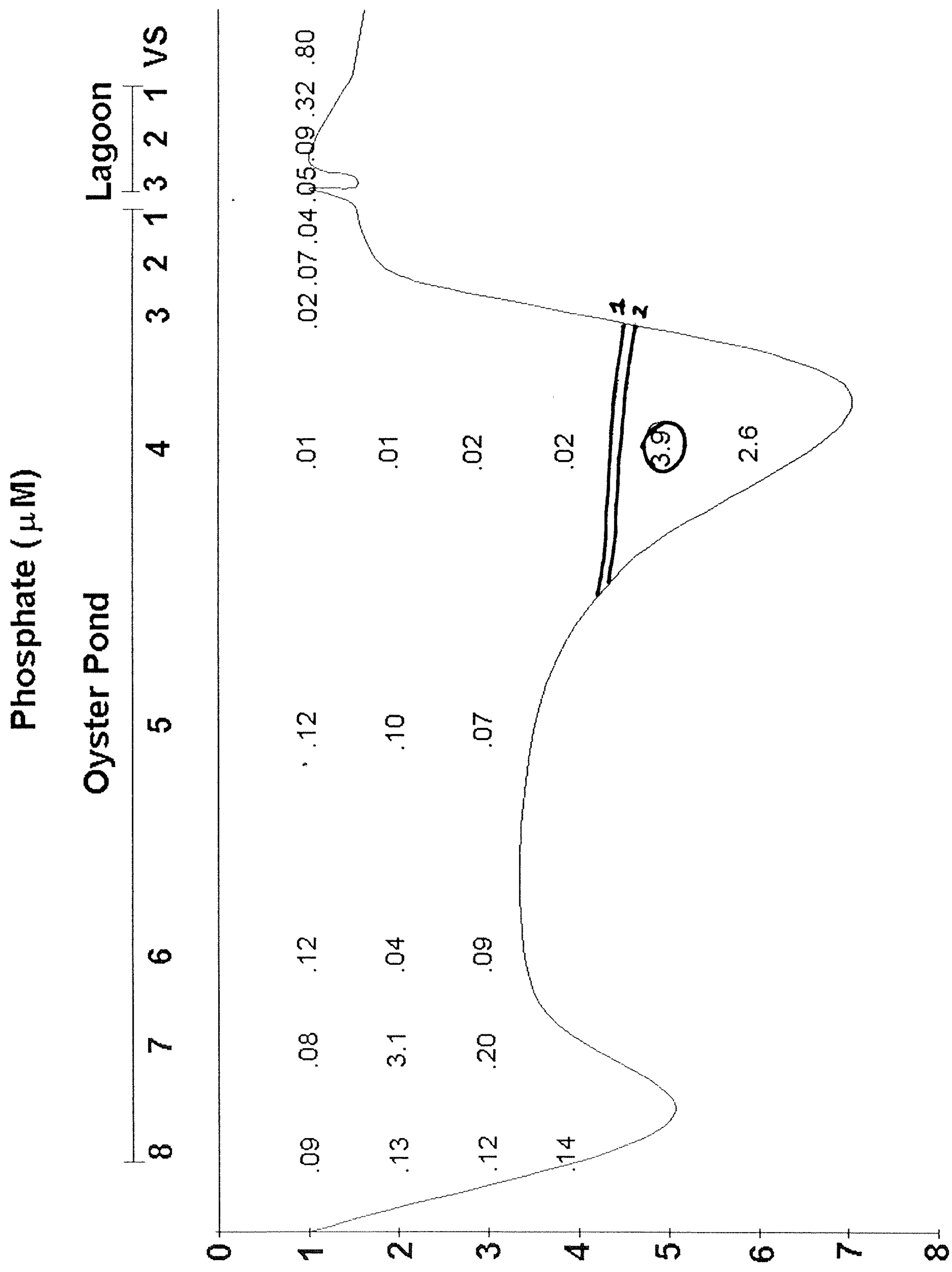

Nitrate (μM)
0
2
4
6
0
1
2
3
4
5
6
Ammonium (μM)
0
5
10
15
20
25
0
1
2
3
4
5
6
Depth (m)
OP1
OP2
OP3
OP4
OP5
OP6
OP7
OP8
oxic/anoxic
Phosphate (μM)
0
1
2
3
4
0
1
2
3
4
5
6

Figure 7

Figure 8



Phosphate (μM)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS
.09 .08 .12 .12 .01 .02 .07 .04 .05 .05 .09 .32 .80
.13 3.1 .04 .10 .01
.12 .20 .09 .07 .02
.14 .02
3.9
2.6
1
2
0 1 2 3 4 5 6 7 8

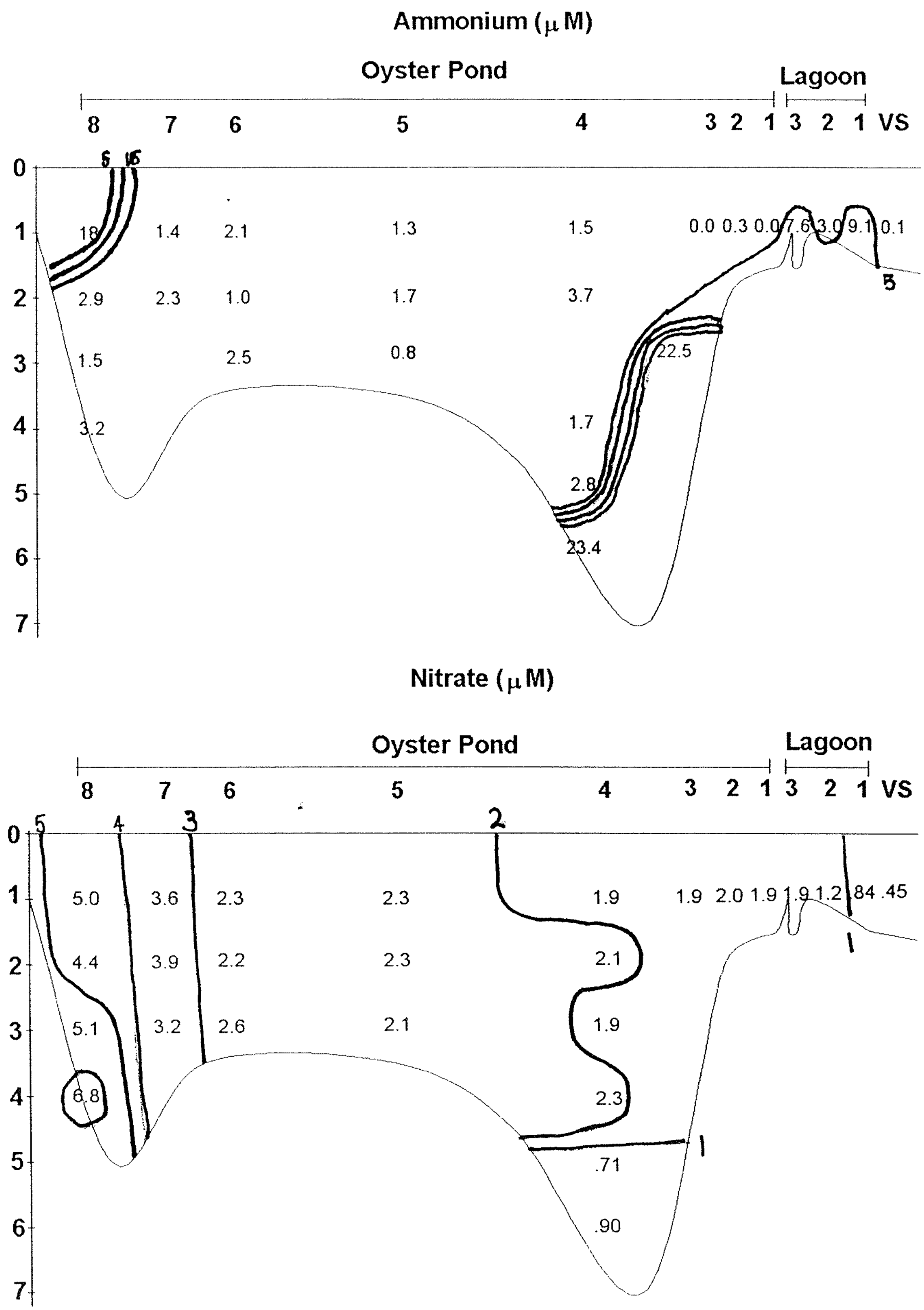
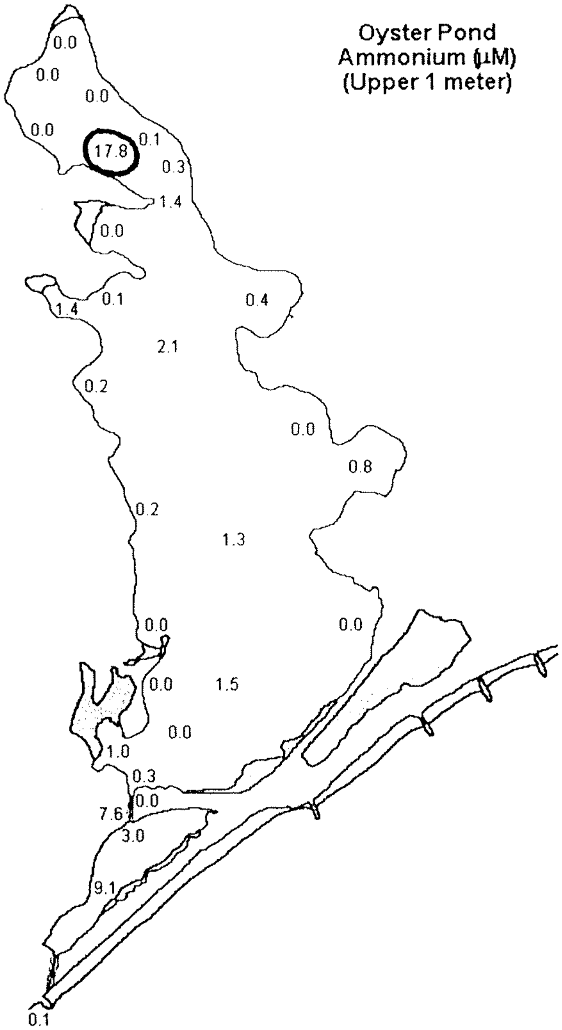
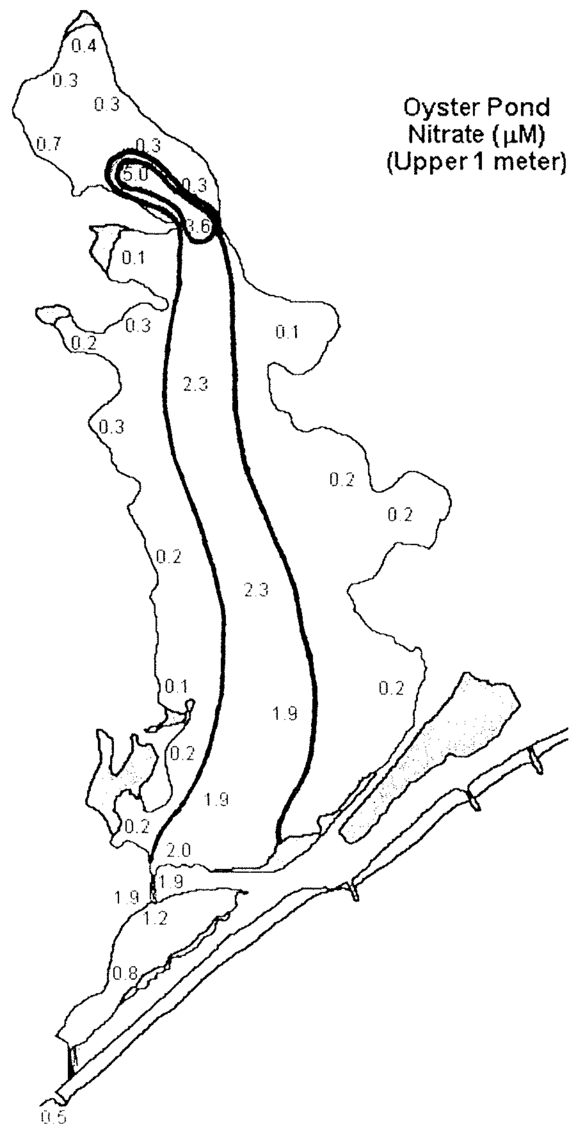
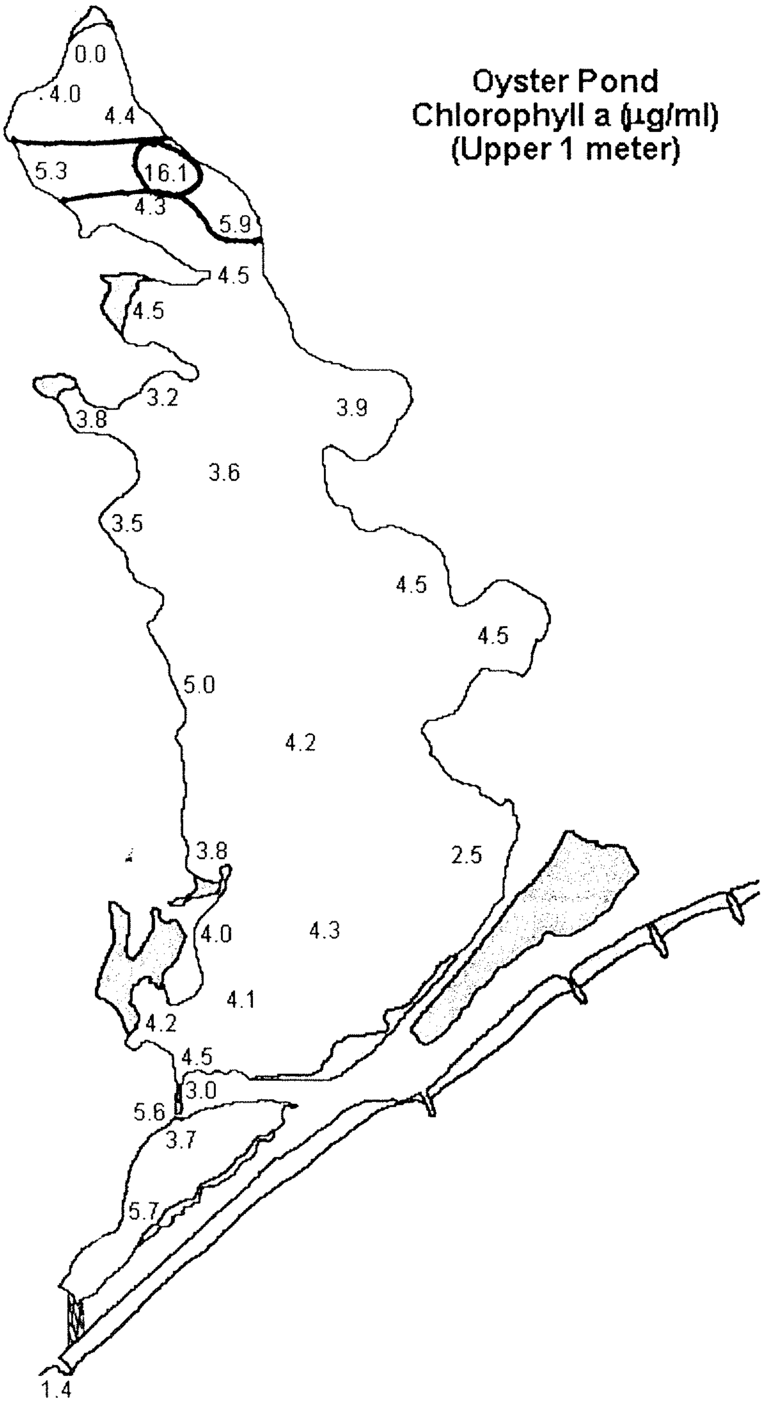

Ammonium (μM)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS
18 1.4 2.1 1.3 1.5 0.0 0.3 0.0 7.6 3.0 9.1 0.1
2.9 2.3 1.0 1.7 3.7
1.5 2.5 0.8 22.5
3.2 1.7
2.8
23.4
Nitrate (μM)
Oyster Pond
Lagoon
8 7 6 5 4 3 2 1 3 2 1 VS
5.0 3.6 2.3 2.3 1.9 1.9 2.0 1.9 1.9 1.2 .84 .45
4.4 3.9 2.2 2.3 2.1
5.1 3.2 2.6 2.1 1.9
6.8 2.3
.71
.90

Figure 9

Figure 10


Oyster Pond
Ammonium (µM)
(Upper 1 meter)
0.0
0.0
0.0
0.0
17.8
0.1
0.3
1.4
0.0
1.4
0.1
0.4
2.1
0.2
0.0
0.8
0.2
1.3
0.0
0.0
0.0
1.5
0.0
1.0
0.3
7.6
0.0
3.0
9.1
0.1


Oyster Pond
Nitrate (µM)
(Upper 1 meter)
0.4
0.3
0.3
0.7
0.3
5.0
0.3
3.6
0.1
0.3
0.2
0.1
2.3
0.3
0.2
0.2
0.2
2.3
0.1
0.2
1.9
0.2
0.2
1.9
0.2
2.0
1.9
1.9
1.2
0.8
0.5



Oyster Pond
Chlorophyll a (µg/ml)
(Upper 1 meter)
0.0
4.0
4.4
5.3
16.1
4.3
5.9
4.5
4.5
3.2
3.8
3.9
3.6
3.5
4.5
4.5
5.0
4.2
3.8
2.5
4.0
4.3
4.1
4.2
4.5
3.0
5.6
3.7
5.7
1.4

Figure 11

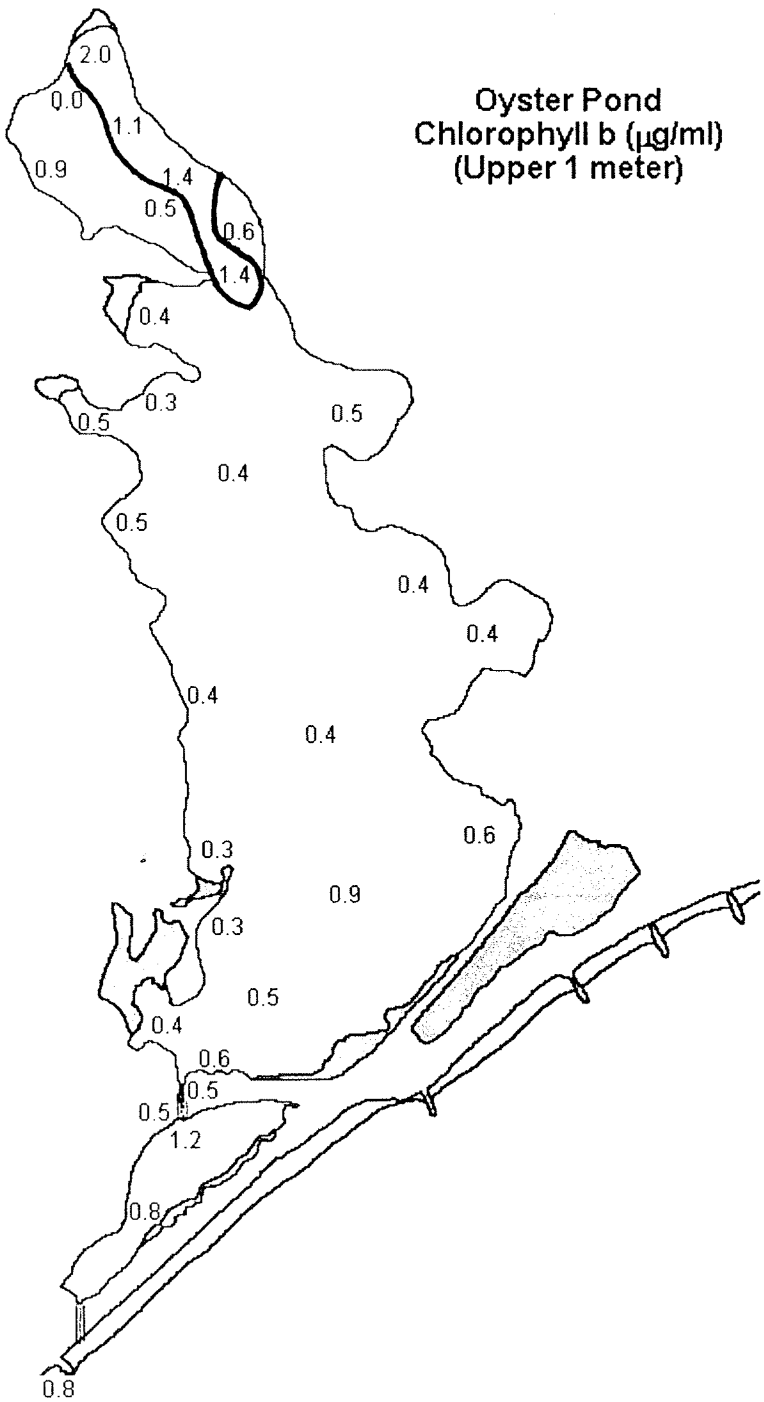

Oyster Pond
Chlorophyll b (µg/ml)
(Upper 1 meter)
2.0
0.0
1.1
0.9
1.4
0.5
0.6
1.4
0.4
0.3
0.5
0.5
0.4
0.5
0.4
0.4
0.4
0.4
0.3
0.6
0.9
0.3
0.5
0.4
0.6
0.5
0.5
1.2
0.8
0.8

Figure 12

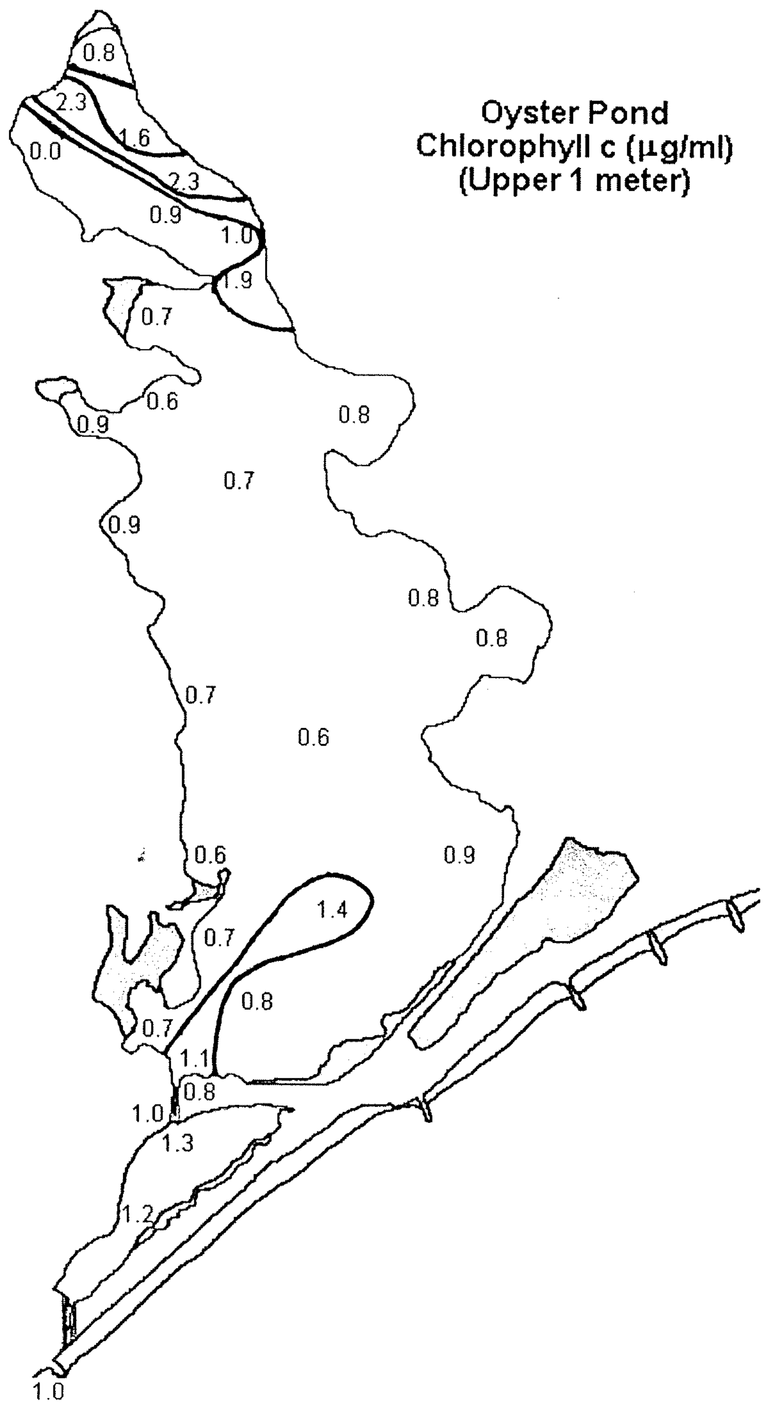

Oyster Pond
Chlorophyll c (µg/ml)
(Upper 1 meter)
0.8
2.3
1.6
0.0
2.3
0.9
1.0
1.9
0.7
0.6
0.9
0.8
0.7
0.9
0.8
0.8
0.7
0.6
0.6
0.9
1.4
0.7
0.8
0.7
1.1
0.8
1.0
1.3
1.2
1.0

Figure 13

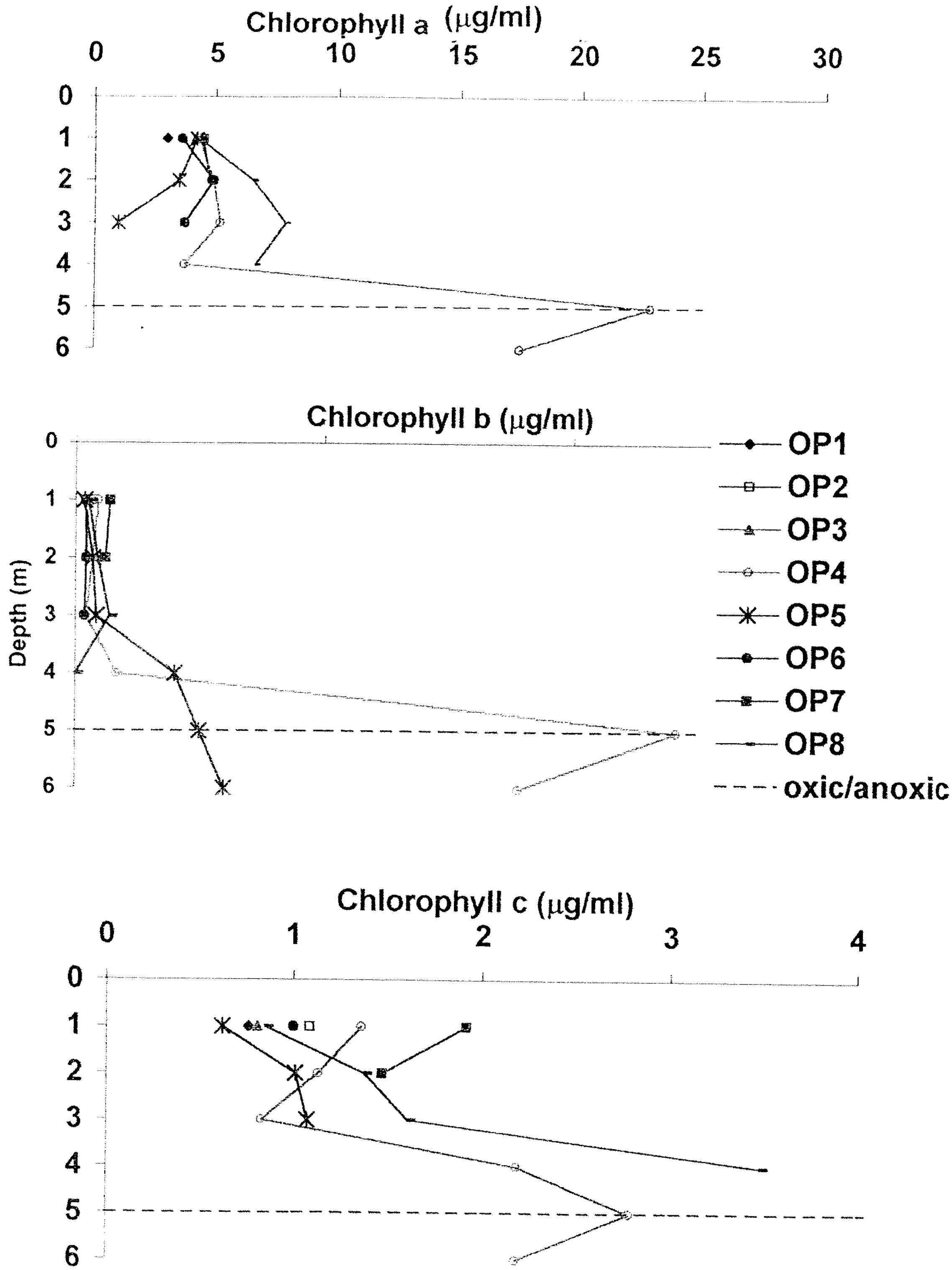
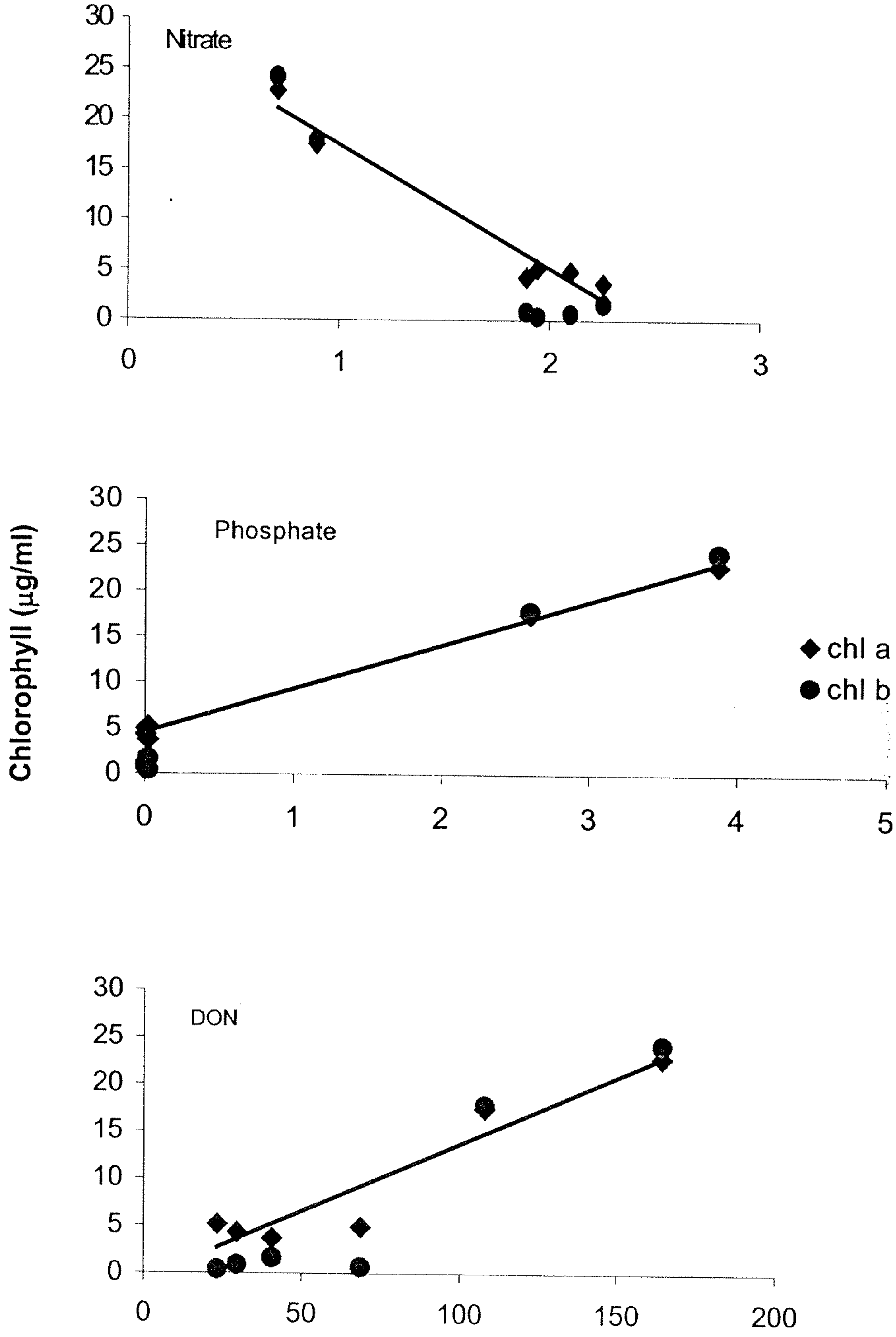

Chlorophyll a (μg/ml)
0 5 10 15 20 25 30
0 1 2 3 4 5 6
Chlorophyll b (μg/ml)
0 1 2 3 4 5 6
Depth (m)
OP1
OP2
OP3
OP4
OP5
OP6
OP7
OP8
oxic/anoxic
Chlorophyll c (μg/ml)
0 1 2 3 4
0 1 2 3 4 5 6

Figure 14



Nitrate
Phosphate
DON
Chlorophyll (µg/ml)
chl a
chl b
30
25
20
15
10
5
0
0
1
2
3
4
5
50
100
150
200

Figure 15

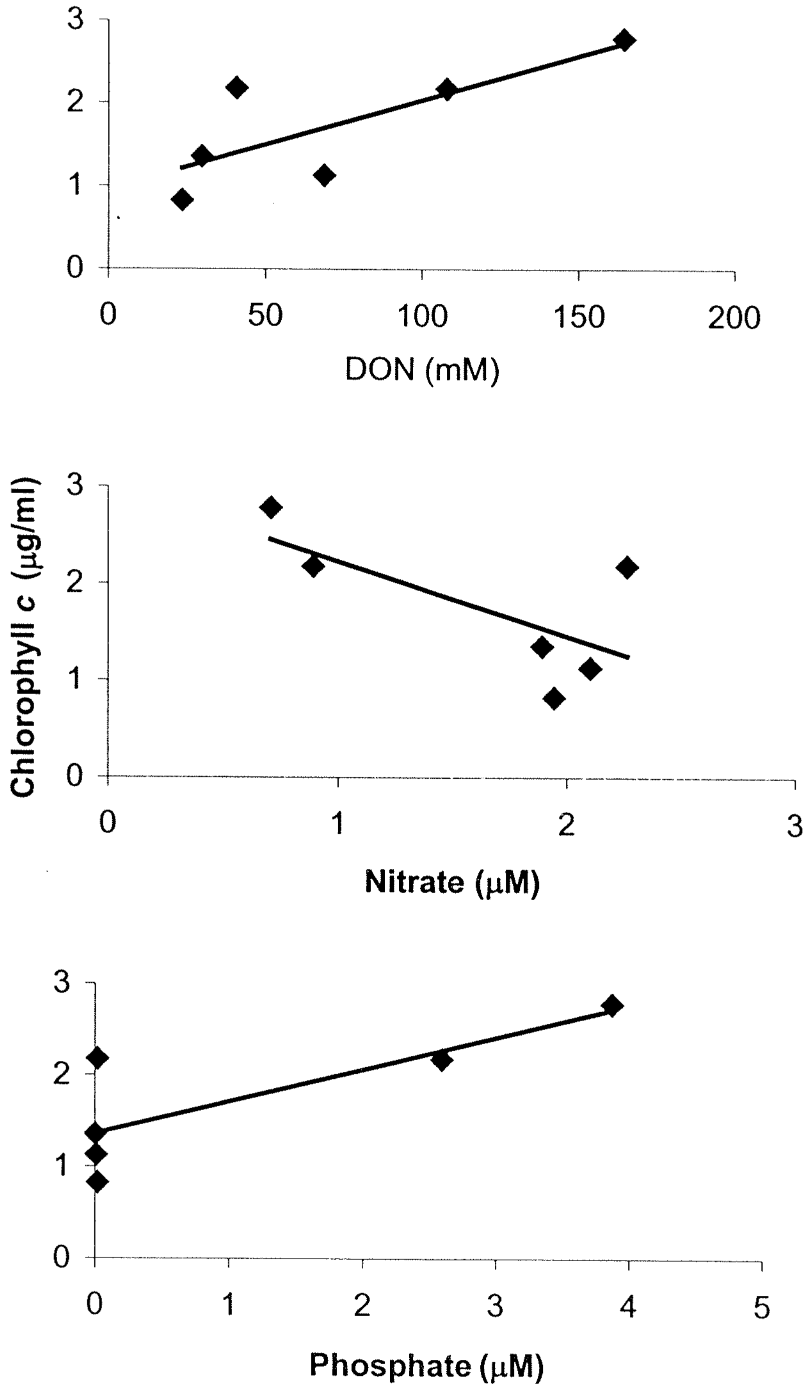

3
2
1
0
0
50
100
150
200
DON (mM)
Chlorophyll c (µg/ml)
3
2
1
0
0
1
2
3
Nitrate (µM)
3
2
1
0
0
1
2
3
4
5
Phosphate (µM)

Figure 16