EUTROPHICATION AND NUTRIENT CYCLING IN LOMA ALTA SLOUGH, OCEANSIDE, CALIFORNIA

Karen McLaughlin
Martha Sutula
Jaye Cable
Peggy Fong

Southern California Coastal Water Research Project

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Submitted By:

Karen McLaughlin and Martha Sutula

Southern California Coastal Water Research Project

Jaye Cable

Louisiana State University

Peggy Fong

University of California, Los Angeles

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Executive Summary

The purpose of this report is to summarize the findings of a SCCWRP study conducted to support the development of a eutrophication water quality model in Loma Alta Slough. The study included measurement of primary producer biomass, sediment and particulate nitrogen and phosphorus deposition, benthic dissolved oxygen and nitrogen (N) and phosphorus (P) fluxes, and sediment bulk and pore water N and P.

The purpose of this report is two-fold:

- Provide a summary of SCCWRP study data that will be used to develop and calibrate the water quality model for Loma Alta Slough.
- Synthesize study data to inform management actions to address eutrophication and improve the efficiency of nutrient cycling in Loma Alta Slough.

It should be noted that railroad bridge maintenance that occurred during field data collection may have significantly altered conditions within the Slough and produced some artifacts observed in the data during sampling. We recommend redeploying data sondes downstream of the railroad bridge just prior to and during mouth closure and conducting limited analysis of sediment organic matter and nutrients to support TMDL modeling studies.

Following are the major findings of this study:

1. Loma Alta Slough is highly disturbed with respect to eutrophication
   - Primary producers in Loma Alta Slough were dominated by filamentous algae and cyanobacteria mats, indicating that the Slough is on the extreme end of the disturbance gradient with respect to eutrophication. Total algal biomass was extremely high, with peak values of 364 g dry wt m^{-2} during the summer index period when the Slough was closed to oceanic exchange.
   - Chronic hypoxia (dissolved oxygen (DO) < 2 mg l^{-1}) at the segment site (upstream of the railroad bridge) occurred almost immediately with the closure of the Slough ocean inlet and endured throughout early fall until the Slough was opened in preparation for the storm season. Chronic hypoxia is a consequence of the accumulation and decomposition of live and dead algal biomass. However, the configuration of a main channel with a deeper portion occurring just before the closed inlet would tend to trap salty water at the bottom. This trapped layer would extend the residence time of bottom waters, depleting oxygen and compounding potential problems with hypoxia.

2. Terrestrial loads drive the Slough nutrients budget year round, providing an excessive amount of N and P available to fuel biomass growth.
   - The amount of TN from terrestrial sources was 65 times the amount required to support primary producer biomass during the summer. Despite the fact that the Slough is closed during this period, residual N is likely flowing through or under the sand berm, providing a source of N to the coastal ocean. Benthic exchange of N, as well as other N sources such as N fixation and direct atmospheric deposition provided an insignificant direct load to the Slough relative to

terrestrial runoff. The direct input of groundwater to the Slough is unquantified and may potentially be a large source.

- The contribution of benthic P was significant only during the spring and fall periods. During the summer, sediments took up P, so terrestrial loads provided the majority of P supporting macroalgal biomass. A deficit in the P budget residual indicates that external loads are not sufficient to support the high biomass observed. It is likely that internal recycling of P through the microbial loop plays an important part of maintaining high primary producer biomass within the Slough. Because P appears to be a limiting nutrient in the Slough, understanding the sources of P is critical for managing eutrophication.

3. Despite the high biomass and chronic hypoxia, the straight channel and fluvial hydrology of Loma Alta Slough, a river mouth estuary, lends itself toward scouring of sediments during storm events and effectively prevents the interannual accumulation of organic matter that can occur in more depositional environments (such as lagoons) after the growing season. This self-cleansing function thus resetting the eutrophication "clock" each storm season, making the system less susceptible to eutrophication. Sediment oxygen demand, as measured by benthic dissolved oxygen fluxes, was generally low during all periods of the year. Benthic contributions of N and P were likewise low and small relative to terrestrial runoff.

4. Railroad bridge maintenance caused scouring of sediments downstream of the bridge, thus producing an artifact that will affect measurement of benthic dissolved oxygen and nutrient fluxes during the April, July and October index periods. Maintenance involved placement of a berm downstream of the Railroad bridge, causing ponding of the upstream portion of the Slough and providing a course of terrestrial soils and gravel to the downstream portion. It is not clear what cumulative effect this maintenance has on the hydrology, enteric bacteria and patterns of eutrophication measured during the field season.

Loma Alta Slough, as a river mouth estuary, appears to have the advantage that sediments do not appear to accumulate excessive organic matter with depth. Therefore, options for management of eutrophication in Loma Alta Slough are aimed at reducing the availability of nutrients for primary production during the growing season, or removing biomass from the Slough. Three types of options could be considered:

1) Reduce terrestrial loads in order to limit primary productivity. Emphasis should be placed on reducing both P as well as N from the watershed because primary productivity appears to be P limited.
2) Increase flushing during peak periods of primary productivity, particularly when the Slough is closed to surface water exchange with the ocean during the summer. Clearly this is a trade off with a potential increase in sources of pathogens to the beach during summer. Improved circulation during closed condition could help to limit stratification and therefore ameliorate, to

a minor extent, problems with hypoxia. However, limited options exist to increase circulation because of the linear configuration of the Slough.

3) Harvest algal biomass. This option could help to alleviate hypoxia and associated problems. However, the cost-effectiveness of harvesting as a management tool must be carefully considered.

Acknowledgements

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1 Introduction

1.1 Background and Purpose of Report

Loma Alta Slough is a 1.1 hectare estuarine wetland that serves as refuge, foraging areas, and breeding grounds for a number of terrestrial and aquatic species (Loma Alta Creek Watershed Management Plan, MEC Analytical 2003). Land use changes in the Loma Alta Creek watershed resulted in hydrological modifications to the Slough and have led to increased amounts of nutrients, bacteria and other contaminants to the Slough.

Increased nutrient loads are known to fuel the productivity of macroalgal communities in the Slough, in a process known as *eutrophication*. Eutrophication is defined as the increase in the rate of supply and/or *in situ* production of organic matter (from aquatic plants) in a water body. While these primary producers are important in estuarine nutrient cycling and food web dynamics [*Boyer, et al.*, 2004; *Kwak and Zedler*, 1997; *Mayer*, 1967; *McGlathery*, 2001; *Pregnall and Rudy*, 1985], their excessive abundance can reduce the habitat quality of a system. Increased primary production can lead to depletion of O_2 from the water column causing hypoxia (low O_2) or anoxia (no O_2; [*Camargo and Alonso*, 2006; *Diaz and Rosenberg*, 2008; *Valiela, et al.*, 2002]), which can be extremely stressful to resident organisms.

As a result of increased macroalgal blooms, the San Diego Regional Water Quality Control Board (SDRWQCB) placed Loma Alta Slough on the federal 303(d) list of impaired water bodies for eutrophication. The SDRWQCB issued a Monitoring Order (R9-2006-0076) requiring stakeholders to collect data necessary to develop watershed loading and estuarine water quality models. The Southern California Coastal Water Research Project (SCCWRP), Louisiana State University (LSU) and University of California Los Angeles (UCLA), supported by a Prop 50 grant from the State Water Resources Control Board (SWRCB), conducted studies in support of model development including monitoring of primary producer biomass, measurement of sediment and particulate nitrogen and phosphorus deposition, measurement of benthic dissolved oxygen and nutrient fluxes, and sediment bulk and pore water nutrients. During October 2007 through October 2008, SCCWRP and MACTEC Inc., subcontractor to the Carlsbad Hydrological Unit nutrient TMDL stakeholders, conducted monitoring to address the requirements of Investigation Order R9-2006-0076.

The purpose of this report is two-fold:

- Provide a summary of SCCWRP study data that will be used to develop and calibrate the water quality model for Loma Alta Slough.
- Synthesize study data to inform management actions to address eutrophication and improve the efficiency of nutrient cycling in Loma Alta Slough.

Studies were conducted in conjunction with MACTEC, Inc. to address the following research objectives:

- Characterize the seasonal trends in surface water ambient nutrient concentrations, sediment solid phase and pore water nutrients, and primary producer communities.
- Estimate the seasonal deposition of sediments and particulate nutrients to Loma Alta Slough

- Characterize the seasonal trends in nitrogen and phosphorus exchange between the Slough sediments and surface waters (benthic nutrient flux).
- Assess the efficiency of nutrient cycling in Loma Alta Slough by estimating, to the extent possible, nitrogen and phosphorus budgets.

1.2 Report Organization

This report is organized into an executive summary and four chapters:

Executive Summary
Chapter 1: Introduction, purpose, and organization of report, site description, and general study design
Chapter 2: Seasonal trends in Loma Alta Slough surface water and sediment nutrients and primary producer communities
Chapter 3: Seasonal trends in exchange of nutrients between surface waters and sediments
Chapter 4: Loma Alta Slough Nitrogen and Phosphorus Budgets

A summary of quality assurance results is provided in Appendix 1. Appendix 2 provides additional photos and graphics depicting conditions within the Slough. Appendix 3 includes the data tables for summarized SCCWRP study data (as a complement to graphs used to present the data in Chapters 2-4) to facilitate use of data for modeling.

1.3 Site Description

Loma Alta Slough is a small creek mouth estuary at the terminus of the 25 sq. km Loma Alta Creek Watershed (Figure 1.1). The 7 mile long creek flows along Oceanside Boulevard, beginning as rising springs just west of Melrose Drive in the City of Vista and ending at Buccaneer Beach Park where it enters the Pacific Ocean. Approximately 70 percent the watershed is developed. Much of the creek has been modified throughout the years, with the use of fully or partially concrete-lined channels to stabilize the creek-bed slopes [*MEC Analytical Systems*, 2003].

Loma Alta Slough extends from the Ocean to the Coast Highway and includes the beach and the reach adjacent to Buccaneer Park. For the purposes of this study, the lower and upper boundaries of the Slough were defined by the entrance of the Slough at the Ocean and Pacific Coast Highway respectively. The SWRCB 303(d) specifically defines the impairment of the Slough from the ocean to the railroad trestles

The Slough itself is comprised of 0.35 hectares of subtidal area and 0.71 hectares of emergent marsh. The ocean inlet to Loma Alta Slough is intermittently open. The City creates a berm with beach sand to close off the inlet during the summer to avoid contaminating the adjacent beach and ocean with elevated bacteria concentrations. The berm is removed prior to the first rains to allow unimpeded flushing of storm waters from the creek during the winter season.

During the study, construction of a new railroad trestle was initiated and lasted throughout the monitoring period. During various phases of construction, an earthen berm with a plastic corrugated pipe was installed near the segment site and hydrology of the stream was altered. Appendix 2 gives a rough timeline for inlet closure and railroad construction in Loma Alta Slough.

In 2010, after the study was completed, problems were identified with the dry weather mass emission flow data, which appeared to be overestimating dry weather flows in to Loma Alta Slough. New flow data were collected from June -October 2011, and these flow data were utilized in chapter 4 to revise the Loma Alta Slough nutrient budget.

1.4 General Study Design

The general study design for all monitoring conducted to support TMDL modeling is based on a basic conceptual model developed to describe the sources, losses, and transformations of targeted constituents within Loma Alta Slough [*McLaughlin, et al.*, 2007]. The three principal types of monitoring were conducted:

1. Continuous monitoring of hydrodynamic and core water quality parameters (salinity, temperature, etc.);
2. Wet weather monitoring, which was conducted during and immediately following a specified number of storm events at the mass emission (ME) site in the main tributary, targeted locations in the lagoon, and at the ocean inlet; and
3. Dry weather monitoring, which was conducted during "index" periods that were meant to capture representative seasonal cycles of physical forcing and biological activity in the lagoon. During each index period, sampling was conducted at the ME and ocean inlet sites, as well as at the segment site within the Slough. In Loma Alta Slough, the Ocean Inlet site represents the bottom portion of the Slough, while the Segment site represents the upper estuary of the Slough.

In general, stakeholder monitoring was intended to cover: 1) continuous monitoring of hydrodynamic and core water quality parameters, 2) all wet weather monitoring, and 3) dry weather ambient monitoring of surface water nutrient concentrations within the lagoon and at points of exchange between the lagoon and the ocean inlet and watershed freshwater flows (ME site).

SCCWRP studies collected three types of data: 1) estimates of inventories of nutrients within certain pools in Loma Alta Slough (e.g. sediments, primary producer biomass) to complement stakeholder sampling during dry weather index periods, 2) measurements of key rates of exchange or transformation within or among sediments and surface waters, and 3) rates of net sediment and particulate nitrogen and phosphorus deposition to support sediment transport modeling and lagoon water quality modeling.

Sampling to develop the dataset occurred during four index periods in one year (Table 1.1). Each index period represents seasonal variations in each lagoon: Storm season (January 2008), post-storm/pre-algal bloom (March 2008), high algal bloom (July 2008), and post-algal bloom/pre-storm (September 2008). This sampling design aimed to provide a means to examine annual variability in lagoon processes affecting nutrient availability and cycling. SCCWRP sampling was coordinated to coincide with stakeholder monitoring of dry weather ambient water quality [*MACTEC*, 2009].

Table 1.1. Summary of the different sampling activities in Loma Alta Slough by time period, types of sampling event, organization and actual dates sampling occurred.

Period	Event	Organization	Date
Background	Sediment Deposition	LSU	11/15/07
Wet Weather Monitoring	Storm Sampling (3 storm events)	MACTEC	1/5-1/7/08 1/23-1/24/08 2/3-2/4/08
Wet Weather Monitoring	Post Storm Sediment Sampling	MACTEC	1/14/08
Continuous Monitoring	Water Quality Monitoring	MACTEC	1/1/08- 10/21/08
Index Period 1	Ambient Sampling	MACTEC	1/14-1/16/08, 2/7- 2/8, 2/11/08
	Transect Sampling	MACTEC	1/14/08
	Benthic Chamber Study	SCCWRP	1/10/08
	Pore Water Peeper Deployment	SCCWRP	1/7-1/21/08
	Sediment Core	SCCWRP	1/21/08
	Macroalgae Monitoring	UCLA	1/22/08
	Sediment Deposition	LSU	1/21/08
	Sediment Deposition	LSU	2/28/08
Index Period 2	Ambient Sampling	MACTEC	3/24-3/26/08, 3/31-4/1/08, 4/7/08
	Transect Sampling	MACTEC	3/24/08
	Benthic Chamber Study	SCCWRP	3/20/08
	Pore Water Peeper Deployment	SCCWRP	3/18-4/3/08
	Sediment Core	SCCWRP	4/3/08
	Macroalgae Monitoring	UCLA	4/11/08
	Sediment Deposition	LSU	4/3/08
	Sediment Deposition	LSU	5/15/08
Index Period 3	Ambient Sampling	MACTEC	7/7-7/9/08, 7/14-7/16/08
	Transect Sampling	MACTEC	7/8/08
	Benthic Chamber Study	SCCWRP	7/7/08
	Pore Water Peeper Deployment	SCCWRP	7/3-7/23/08
	Sediment Core	SCCWRP	7/23/08
	Macroalgae Monitoring	UCLA	7/21/08
	Sediment Deposition	LSU	7/23/08
	Sediment Deposition	LSU	8/20/08
Index Period 4	Ambient Sampling	MACTEC	10/7-10/9/08, 10/13-10/15/08
	Transect Sampling	MACTEC	10/7/08
	Benthic Chamber Study	SCCWRP	9/15/08
	Pore Water Peeper Deployment	SCCWRP	9/12-9/29/08
	Sediment Core	SCCWRP	9/29/08
	Macroalgae Monitoring	UCLA	9/29/08
	Sediment Deposition	LSU	9/29/08

Figure 1.1 summarizes the sampling locations for each of the different types of monitoring studies in Loma Alta Slough.

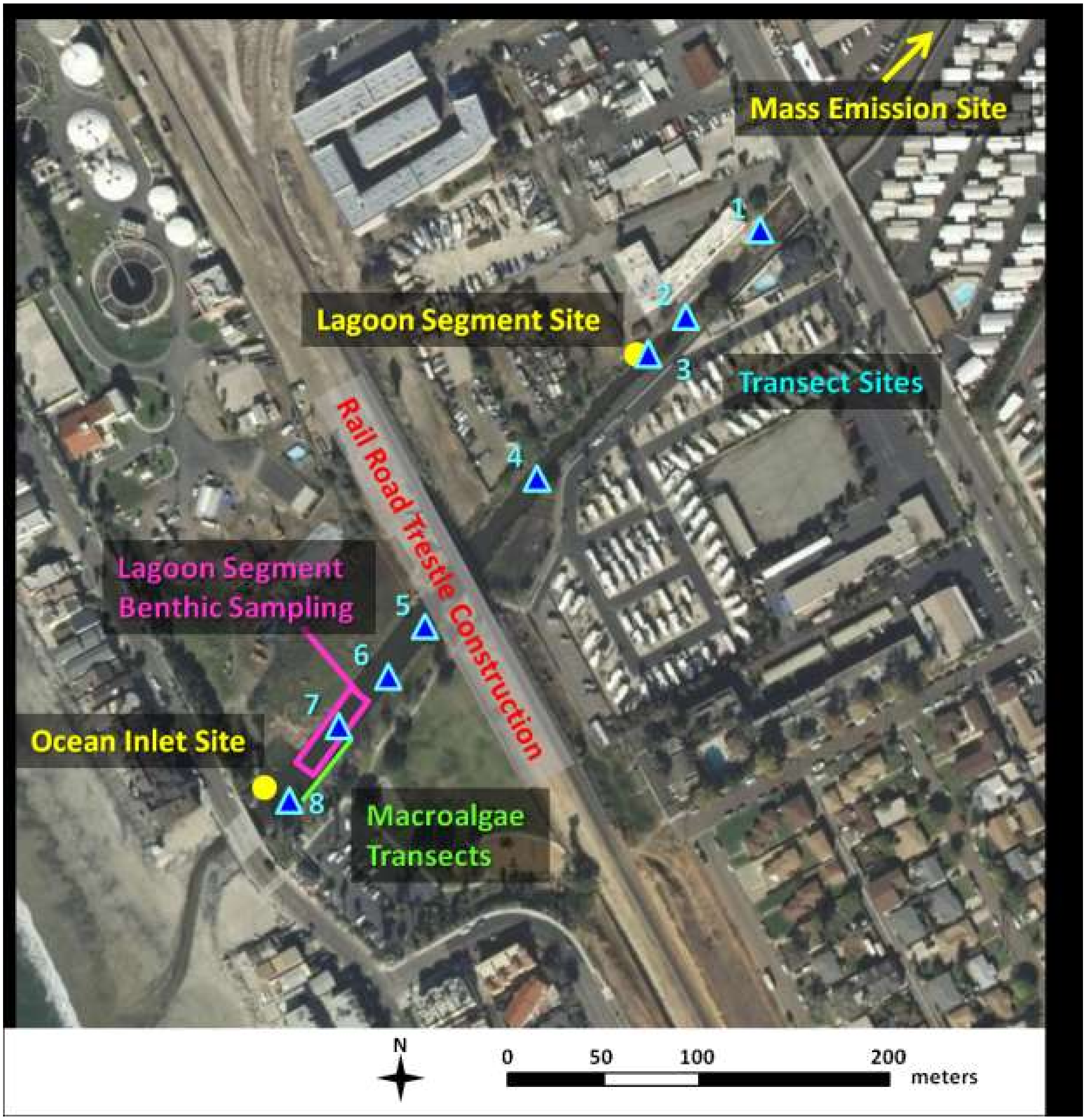


Figure 1.1. Location of sampling activities in Loma Alta Slough.

2 Seasonal Trends in Surface Water and Sediment Nutrients and Primary Producer Communities in Loma Alta Slough

2.1 Introduction

All estuaries exhibit distinct temporal and spatial patterns in hydrology, water quality and biology that, together, are integral to the ecological services and beneficial uses they provide [*Caffrey*, 2004; *Day, et al.*, 1989; *Granek, et al.*, 2010; *Loneragan and Bunn*, 1999; *Rountree and Able*, 2007; *Shervette and Gelwick*, 2008]. Characterization of seasonal and spatial patterns in surface water and sediment nutrient concentrations and aquatic primary producer communities provides valuable information about the sources, dominant transport mechanisms, and fate of nutrients in Loma Alta Slough and helps to generate hypotheses regarding the controls on biological response to nutrients.

The purpose of this chapter is to present a baseline characterization of the patterns in surface water and sediment nutrients and aquatic primary producers in Loma Alta Slough. This work forms the foundation for interpretation of benthic fluxes (Chapter 3) and characterizing the efficiency of nutrient cycling through N and P budgets for the Slough (Chapter 4).

2.2 Methods

This section describes the field methods for the following datasets:

- Longitudinal and seasonal trends in surface water ambient nutrient concentrations, conducted in conjunction with MACTEC Inc.
- Seasonal trends in aquatic primary producer biomass and/or percent cover and tissue nutrient content
- Seasonal variation in sediment bulk characteristics (grain size, solid phase nitrogen and phosphorus content)

Where appropriate, ambient water quality data collected and analyzed by MACTEC are incorporated into the results and discussion. These data are cited when used and for a detailed explanation of methods used to collect these data, please see MACTEC [2009].

2.2.1 Field Methods

2.2.1.1 Surface Water Nitrogen (N) and Phosphorus (P) Along a Longitudinal Gradient

Longitudinal transects of surface water nutrient concentration provide valuable spatial information about how concentrations vary along a gradient from the freshwater source to the ocean end-member.

Surface water samples were collected by MACTEC at 8 sites along a longitudinal gradient from the ocean inlet to upstream of the railroad bridge (Figure 1.1;[*MACTEC*, 2009]). Longitudinal transect sampling occurred on the fourth day of the first week of each index period. Transect sampling was performed using kayaks and grab-sampling techniques. Samples were taken in the tidal channels and were collected once at ebb tide and once at flood tide.

The sample bottle was triple rinsed before filling completely. Sample bottles were open and closed under water to avoid contamination with surface films or stratified water masses. One liter sample bottles were returned to the shore for immediate filtering where appropriate. Ambient water samples were subsampled for a suite of analytes using a clean, 60 mL syringe. Each syringe was triple rinsed with sample water. Mixed cellulose ester (MCE) filters were used for nutrient analysis and total carbon dioxide (TCO_2) and polyethersulfone (PES) filters were used for dissolved organic carbon and metals analysis. Each filter was rinsed with ~20 mL of sample water (discarded) before collection into vials.

2.2.1.2 Inventory of Aquatic Primary Producer Cover and Tissue Content

Aquatic primary producer communities include macroalgal and cyanobacteria mats, benthic algal mats, and submerged aquatic vegetation. The purpose of this study element was to characterize seasonal variation in the standing biomass, cover, and the tissue nutrient content of these communities. This information will be used to calibrate the component of the eutrophication water quality model that accounts for the storage and transformation of nutrients in primary producer community biomass.

Aquatic primary producer biomass was measured during the four index periods at the within Slough segment site. At the site, intertidal macroalgae were sampled along a 30-m transect parallel to the waterline and one meter down-slope from the vascular vegetation. Macroalgal abundance was determined by measuring percent cover and algal biomass; we included both attached and detached mats. At five randomly chosen points along each transect, a 0.25-m^2 quadrat with 36 evenly spaced intercepts (forming a 6X6 grid) was placed on the benthos. The presence or absence of each macroalgal species in the top layer under each intercept was recorded. When present, algae were collected from a 530.9 cm^2 area circumscribed by a plastic cylinder placed on the benthos in the center of each quadrat. Each sample was placed in an individual ziploc bag in a cooler, transported to the laboratory and refrigerated. Algal samples were transferred to low nutrient seawater where they were cleaned of macroscopic debris, mud and animals. For each sample, algae were placed in a nylon mesh bag, spun in a salad spinner for one minute, wet weighed, rinsed briefly in deinonized water to remove salts, and dried at 60° C to a constant weight. Macroalgal biomass was normalized to area (g wet wt m^{-2}). Fine macroalgal filaments that grow within the sediment may be visible but biomass cannot be collected quantitatively at this early growth stage, making percent cover in this case a more sensitive measurement. In addition, when there is 100% cover, and mats are different thicknesses, biomass will be a more useful measure to make distinctions between sites [*Sfriso, et al.*, 1987]. Thus it is important to use both methods to estimate abundance. Samples were cleaned and weighed to determine wet and dry weights. Dried samples were analyzed for percent organic carbon, percent organic nitrogen and percent phosphorus.

2.2.1.3 Sediment Bulk Characteristics and Solid Phase and Pore Water Nutrients

All sediment loads carry nutrients, either as organic matter or, in the case of phosphorus, associated with particles. When deposited in the estuary, these particulate nutrients may break down to biologically available forms and may build up in high concentrations in sediment pore waters. Sediment bulk characteristics control nutrient content; finer particle size fractions are associated with higher organic carbon, nitrogen and phosphorus content. Temporal trends in sediment solid phase and pore water nutrients provide information about the load and fate of nutrients associated with sediments in Loma Alta Slough.

The purpose of this study element was to better characterize the load and fate of nutrients associated with sediments. Specifically, this involved two types of activities:

1) Measurement of the sediment solid phase bulk characteristics (grain size, porosity, etc.) and sediment N and P concentrations.
2) Measurement of pore water nitrogen and phosphorus concentrations

Sediment bulk characteristics and solid phase nutrient concentrations were estimated for a vertical profile in one sediment core taken from the segment site. For each sampling period, one sediment core was taken (and vertically sectioned on site into 1 cm intervals from the sediment water interface until 6 cm depth and then sectioned every 2 cm down to 12 cm. Sediments were placed in plastic storage bags and stored on ice in the dark until they reached the laboratory. In the lab, sections were wet weighed, dried at 50 °C to a constant weight, and reweighed to determine percent solids and wet bulk density. A subsample of each section (~10 grams dry weight) was removed and ground to a fine powder for percent organic carbon, percent total nitrogen and percent total phosphorus analysis. The remainder of the section was utilized for grain size analysis (percent sand).

Sediment pore waters were sampled from the subtidal area of the southern basin using pore water equilibrators (peepers: [*Hesslein*, 1976]) during each index period (Figure 2.1). When the peepers are placed into the sediment, solutes from the pore waters come into contact with the filter and a concentration gradient is established between the cell water (no solute) and the porewaters. This causes solutes to diffuse into the cells and over time equilibrium is established between the peeper cells and the pore waters and the concentrations on both sides of the filter paper are equal. Each peeper was constructed from a 50 x 18 cm solid plexiglass frame into which cells (0.5 x 3.0 x 13 cm) were milled in at a spacing of approximately 1 cm, which are used to sample a depth profile of the sediment pore waters. Each cell is filled with distilled, deionized water that had been bubbled with nitrogen gas for 24 hours to remove the oxygen and covered with a 0.45 um polycarbonate filter paper. The filter is held in place by an outer plexiglass frame secured with Teflon screws. Peepers are kept under a nitrogen atmosphere until deployment. Peepers were pushed by hand into the subtidal sediment, making sure that the peeper is vertical and the top of the sediment surface was flush with the top well of the peeper. Peepers were secured with a 30 m cable attached to a stake driven into the upper intertidal zone to facilitate recovery and the location was recorded using GPS coordinates. After a two-week equilibration period [*Brandl and Hanselmann*, 1991; *Hesslein*, 1976], the peepers were retrieved. Peeper recovery was coordinated with the collection of the sediment core and a collection of ambient bottom water.

Sediment cores for bulk characteristics and nutrients, described above, were collected within 2 feet of the peeper location.

Immediately following retrieval, the peepers are placed inside large format ziploc bags that were purged with nitrogen gas to minimize artifacts from oxidation of pore water fluids. Pore water samples were extracted from each well using a repeater pipette, dispensed into vials and immediately frozen for analysis. Wells sampled represent porewater depths of: 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 7-8, 10-11, 13-14 cm. Each peeper is processed within 15 minutes of recovery. Following sub-sampling of the peeper, ambient bottom water samples were also filtered, collected into vials and frozen for analysis. All water samples were analyzed for the following: sulfide, ammonium, nitrate, nitrite, soluble reactive phosphate, total dissolved nitrogen, total dissolved phosphorus, dissolved iron, dissolved manganese, total carbon dioxide, and dissolved organic carbon. Before freezing sulfide samples were preserved with zinc acetate. One field blank was collected for each pore water analyte and a field blank and duplicate were collected for each ambient sample. Surface water samples were collected at the time of peeper retrieval.

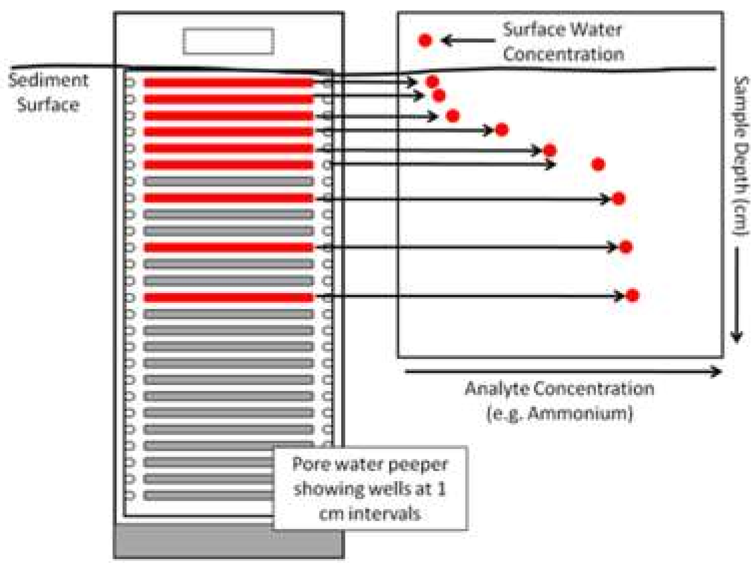


Figure 2.1. Graphic depicting how pore water profiles are generated from pore water peepers.

2.2.1.4 Sediment Berylium-7 Radioisotope Seasonal Inventory

Berylium-7 activity in sediments was measured during the four index periods and three additional periods at the segment site in Loma Alta Slough. One sediment core was taken per segment per site and vertically sectioned down to 12 cm (this was the same core that is used for bulk sediment characteristics – see section above). Radioisotope levels were measured in the core, starting from the top of the core and proceeding downcore until no radioisotopes were detected. Sediments were placed in plastic storage bags and stored on ice in the dark until they reached the laboratory. In the lab, sections were wet weighed, dried at 50 °C to a constant weight, and reweighed to determine percent solids and wet bulk density. A subsample of each section (~10 grams dry weight) was removed and ground to a fine powder for ^{7}Be radioisotope analysis and percent organic carbon, percent total nitrogen and percent total phosphorus analysis. The remainder of the section was utilized for grain size analysis (percent sand).

2.2.2 Analytical Methods

All water samples were assayed by flow injection analysis for dissolved inorganic nutrients using a Lachat Instruments QuikChem 8000 autoanalyzer for the analysis of NH_4, NO_3, NO_2, and SRP. Dissolved Fe and Mn were measured by atomic adsorption spectrophotometry on a Varian Instruments AA400. Water samples were assessed for TDN, TDP, TN and TP via two step process: first water samples undergo a persulfate digest to convert all nitrogen from all N compartments into nitrate and the phosphorus from all P compartments into orthophosphate; then the resulting digests are analyzed by automated colorimetry (Alpkem or Technicon) for nitrate-N and orthophosphate-P [*Koroleff*, 1985]. Water DOC was analyzed on a Shimadzu TOC-5000A Total Organic Carbon Analyzer with ASI-5000A Auto Sampler. Water TCO_2 was analyzed on a UIC instruments carbon dioxide coulometer. Sulfide samples were allowed to react with N,N-dimethyl-p-phenylenediamine and ferric chloride under acidic conditions to yield the product methylene blue, and the concentration of methylene blue was determined spectrophotometrically at 668nm. Concentration of sulfide in the sample was calculated by reference to a standard curve (absorbance vs. sulfide concentration). Inorganic nutrients and trace metals were run by the Marine Science Institute at the University of California, Santa Barbara and total dissolved and total nitrogen and phosphorus and dissolved organic carbon were run at the University of Georgia Analytical Chemistry Laboratory. Sulfide and TCO_2 were measured by SCCWRP.

Dried sediment samples were subsampled and ground for analysis of %OC, %TN, and %TP. Samples for %OC were acidified to remove carbonates; %OC and %TN were measured by high temperature combustion on a Control Equipment Corp CEC 440HA elemental analyzer at the Marine Science Institute, Santa Barbara. Sediment %TP were prepared using and acid persulfate digest to convert all P to orthophosphate, which was then analyzed by automated colorimetry (Technicon) at the University of Georgia Analytical Chemistry Laboratory.

To determine percent sand, a portion of sediment from each interval was weighed dry (total dry weight), then wet sieved through a 63-micron sieve, dried at 50 °C to a constant weight, and reweighed as sand dry weight. Percent sand was calculated as a function of the sand dry weight divided by the total dry weight of the sample.

Seasonal sedimentation rates were determined using radioactive isotopes of ^{7}Be. The activity of ^{7}Be (53-day half-life), was used to document the short term sediment deposition rate. ^{7}Be was determined by gamma spectrometry using a low-energy Germanium (LeGe) planar detector coupled with a low background cryostat and shielding. Samples were counted for 24 hours on an intrinsic germanium detector, and the ^{7}Be radioisotope was measured at the photon peak 477.1 keV.

The analytical methods for grain size, percent organic carbon and total nitrogen, and total phosphorus are given in Section 2.24.

2.2.3 Data Analysis

Analysis of variance (ANOVA) tests were used to test for differences in concentration data by index period and, where relevant, by ebb and flood tide (SAS Proc GLM, 2008). Data were transformed to correct for unequal variance and mean and standard errors were generated from Tukey's pairwise comparisons.

Standing biomass of aquatic primary producers groups (phytoplankton, macroalgae, microphytobenthos, and cyanobacteria mats) were converted to carbon per meter squared in order to make comparisons among the groups. The following assumptions were used in this conversion:

- Phytoplankton- Average 1.5 m depth of water, Chl a: C ratio of 30 [*Cloern, et al.*, 1995]
- MPB – Chl a: C ratio of 30:1 [*Sundbäck and McGlathery*, 2005]
- Cyanobacteria: 50% C by dry wt (study data)
- Macroalgae: 22% C by dry wt (study data)

Porosity, fractions of water and sediment, and wet bulk density were used to estimate seasonal and annual sediment deposition rates and to evaluate changes in sediment nutrient and radioisotope inventories. These values are calculated from parameters measured in the laboratory.

The difference between wet and dry weights was used to calculate the fraction water (f_{wet}) and fraction sediment (f_{dry}):

$$f_{wet} = \frac{W_{wet} - W_{dry}}{W_{wet}}$$

Eq. 2.1, 2.2

$$f_{dry} = 1 - f_{wet}$$

where W_{wet} and W_{dry} are the wet and dry sediment weights, respectively. Subsequently, when enough sample was present, a small known fraction of the initial dried sample was weighed, and dry grain density was determined gravimetrically using Archimedes principle, i.e. by volume displacement. The weighed sediment divided by the displaced volume yielded the dry grain density of each sediment core sample section. The dry grain density and fractions wet and dry were used in turn to calculate the porosity and bulk density. Often the shallowest sections of the cores did not contain enough material for a complete sediment physical properties analysis. We took extra cores near the end of the project to complete any missing sediment physical property data needed for future calculations. Porosity is a measure of the amount of "empty space" in the sediment, defined by the ratio of the volume of voids to the total volume of a rock or unconsolidated material. Porosity was calculated using the following equation:

$$\phi = \frac{\frac{f_{wet}}{\rho_{water}}}{\frac{f_{wet}}{\rho_{water}} - \frac{f_{dry}}{\rho_{drygrain}}}$$ **Eq. 2.3**

where ϕ is the porosity; ρ_{water} and $\rho_{drygrain}$ are the density of ambient water and dry sediment grains, respectively. Bulk density, $\rho_{wetbulk}$ or $\rho_{drybulk}$, was calculated based on the total mass of each core section divided by the core section interval volume. Thus both a wet and a dry bulk sediment density could be determined on deeper samples more often when a larger mass of sample was available for the different analyses. Wet bulk density (ρ in g cm^{-3}) is given by the Equation 2.4.:

$$\rho = \frac{W_{SEDwet\,(i)}}{V_i}$$ **Eq. 2.4.**

Where $W_{SEDwet\,(i)}$ is the wet weight of each sediment core section interval and V is the volume of the sediment core section interval.

Samples were prepared for ^{7}Be analysis by homogenizing about 5 g of dry sediment in a mortar and pestle until the sediment is finely ground. This step ensures the sediment can be densely packed in the sample container to maximize the content being counted and increase the efficiency of the detector. Once the sample was ground, small aliquots were transferred to 1-mL test tube shaped vials and tapped gently for about two to three minutes per transfer to pack the sample down as we filled the vial. When each pre-weighed vial was filled to 33 mm height, the sample and vial were weighed. Each sediment sample was analyzed on a Canberra well germanium detector for 12 hours by measuring the peak gamma ray energy at 477 keV to obtain the ^{7}Be activity. Efficiencies were calculated using an International Atomic Energy Agency (IAEA) reference standard. Net peak area was recorded for each nuclide of interest (^{7}Be), and activities (*A*; dpm/g) were calculated using the following equation:

$$A = \frac{cpm_{sample} - cpm_{background}}{f_{inensity} * f_{eff} * W_{sediment}}$$ **Eq. 2.5**

where *cpm* is count rate per minute of sample or background, $W_{sediment}$ is sample mass in the vial, $f_{intensity}$ is γ-ray intensity, and f_{eff} is system efficiency for a particular photon energy. Activities below detection were reported as zero, and the average background count rate was 0.02 cpm.

From these ^{7}Be activities, down core sediment inventories were quantified using the equation:

$$I_{total} = \sum_{z=0}^{n} (A_z * \rho_z * h_z)$$ **Eq. 2.6**

where I_{total} is total ^{7}Be inventory (dpm/cm^2), A_z is the activity at depth *z*, ρ is sample bulk density, and *h* is sample interval thickness (cm). Total ^{7}Be inventories at each site for each sampling event were corrected for the residual activities remaining from previous events. This residual inventory was estimated by correcting the previous month's total inventory for radioactive decay by the elapsed time between sampling events using the following equation:

$$I_R = I_T e^{-\lambda t}$$ **Eq. 2.7**

where I_R is the residual inventory (dpm/cm^2), I_T is the total inventory from Eq. 2.6, λ is the decay constant for ^{7}Be (0.0130046 d^{-1}), and *t* is the time elapsed between sampling periods (days). New inventory (I_N) for the current sample month was then calculated by subtracting the calculated residual inventory remaining from a previous month from the total inventory via the following:

$$I_N = I_T - I_R$$ **Eq. 2.8**

New inventory physically represents the portion of the total inventory associated with recent sediment deposition or resuspension events. A positive new inventory represents a deposition event while a negative inventory indicates a removal event. Net ^{7}Be flux (dpm/cm^2 d) into or out of the sediments between sampling periods was calculated by dividing the new inventory by the time interval between sampling.

The time-dependent ^{7}Be flux, used here to determine short-term sediment mass accumulation or removal rates, was estimated as

$$\psi = \frac{I_N}{A_{new}}$$ **Eq. 2.9**

where ψ is the short-term sediment deposition or removal rate (g/cm^2 d), and A_{new} is the average activity in the sample after subtracting the decay-corrected activity that existed from the previous sampling period.

Temporal variability in short-term (seasonal) sediment deposition and remobilization was evaluated using the general conceptual model in which the first sediment sampling event (November 2007, before the index periods) sets a baseline of low ^{7}Be activity because of a four-month dry season. Subsequent sampling trips (during wet season and throughout dry season) revealed possible changes occurring at the site in the intervening time period, including: (1) an inventory reflecting recent deposition and/or residual inventory reflecting older deposition events; (2) a small residual inventory associated with decay or partial sediment removal when no recent deposition events had occurred; and (3) no inventory, indicating complete removal of the uppermost sediment layer or complete decay when the sampling interval was sufficiently long (i.e. during the dry season; see [*Giffin and Corbett*, 2003] for in depth discussion on interpretation of ^{7}Be profiles). These time-series inventory comparisons can be used to evaluate the short-term sediment deposition rate, discern whether or not a site is a focal point for sediment deposition or a net-loss site over time, and observe reworking of sediments that may have been caused by bioturbation (birds, burrowing organisms, etc.).

2.3 Results

2.3.1 Seasonal and spatial trends in physiochemical parameters and nutrients

Water quality and primary producers would be expected respond to the opening and closing of the ocean inlet of Loma Alta Slough. During the winter and spring index periods, the Slough was open to tidal exchange (Figure 2.2). DO and salinity were high, though variable during storm period. When the Slough closed in May, DO and salinity dropped. These values remained low throughout the summer index period and most of the fall index period, but had just opened a day prior to sampling the longitudinal transect.

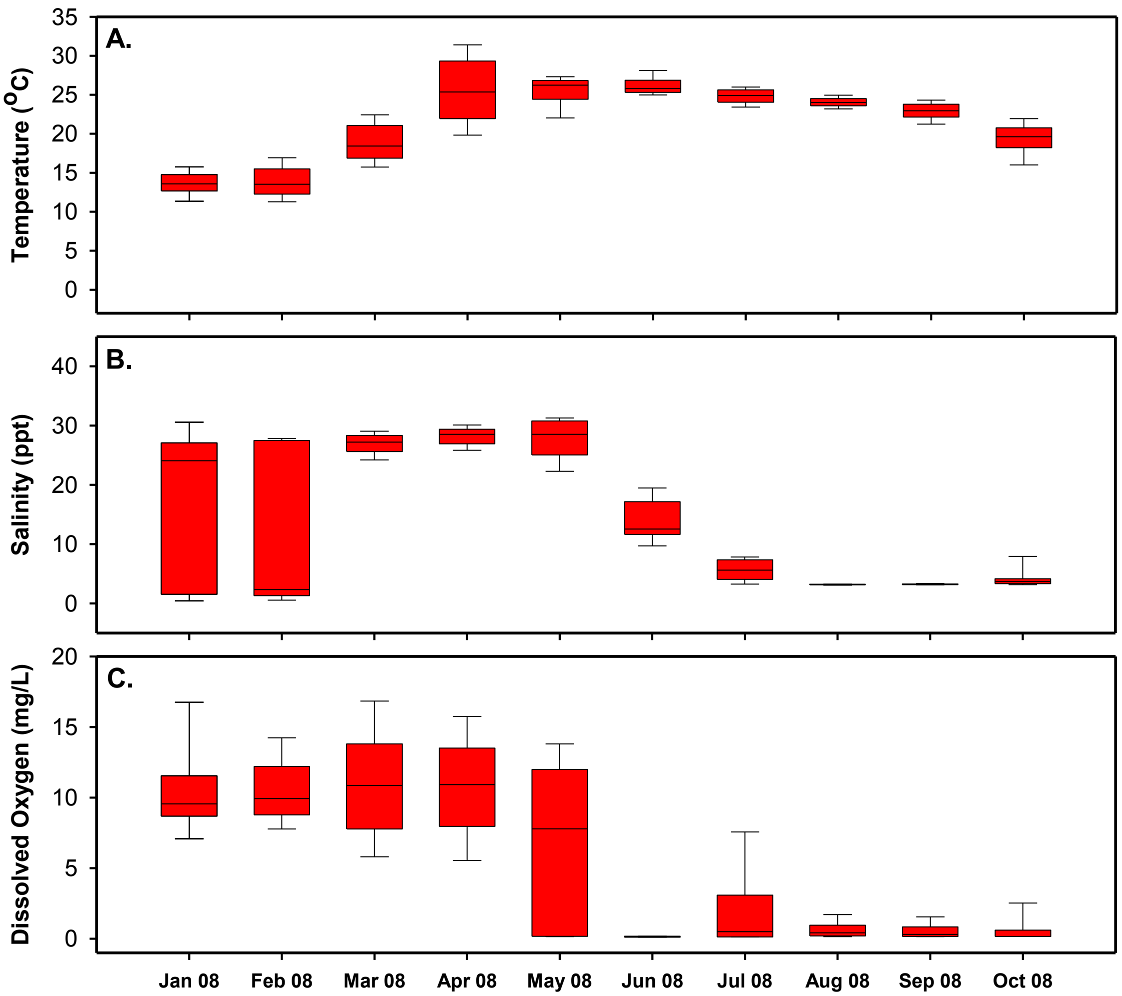


Figure 2.2. Seasonal Variation in (A.) temperature, (B.) salinity, and (C.) dissolved oxygen at the lagoon segment continuous monitoring site. *[MACTEC, 2009]*

Seasonally, surface water TN concentrations were highest in the fall, with peak concentrations of 170 and 130 µM in the Loma Alta Creek and Slough, respectively. Wet weather TN concentrations within the

Slough (60-117 µM) were 30-50% higher than dry weather concentrations during these periods (Figure 2.3, Table 2.1). During all wet and dry weather periods, Slough organic N exceeded dissolved inorganic N. During spring and summer dry weather periods, nitrate, nitrite, and ammonia were less than 10 µM. Mean Slough nitrate+nitrite concentrations peaked in the fall (40 µM).

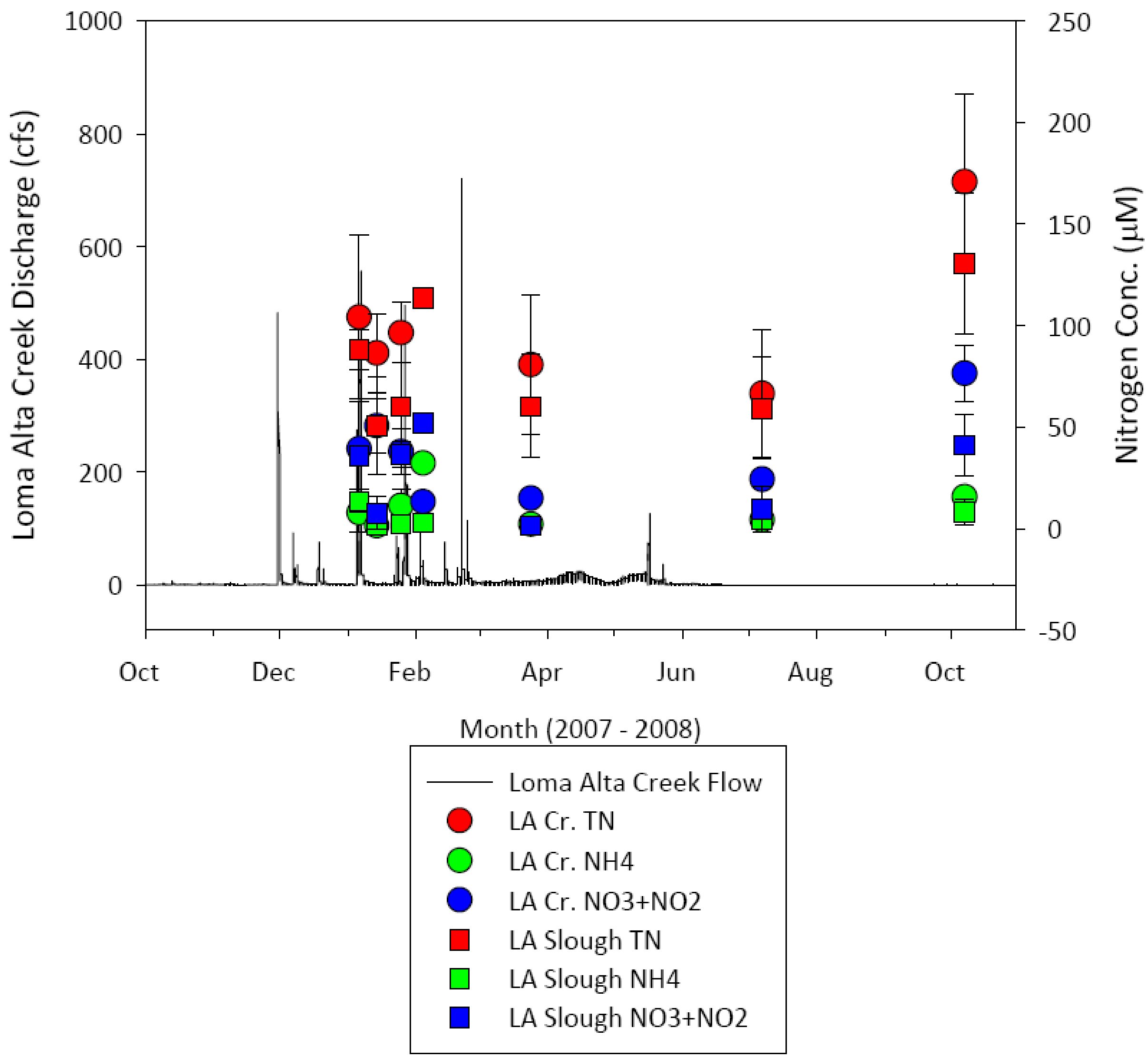


Figure 2.3. Concentrations of TN, ammonia and nitrate in freshwater discharge and ambient slough water as a function of freshwater flow into Loma Alta Slough. Concentrations represent both wet and dry weather sampling periods. Data from MACTEC *[2009]*.

Seasonally, surface water TP concentrations were highest in the winter and spring, with peak concentrations of 3.9 and 6.1 µM in the Loma Alta Creek and Slough, respectively. Wet weather TP concentrations within the Slough (5.2-19.7 µM) were 50-70% higher than dry weather concentrations during these periods (Figure 2.4, Table 2.1). During all dry weather periods, Slough organic P exceeded dissolved inorganic P; though during wet weather events, inorganic P is less than organic P. Inorganic P concentrations are greatest during storm events (5µM), and vary from an average of 0.2 µM and 0.7 µM during dry weather monitoring.

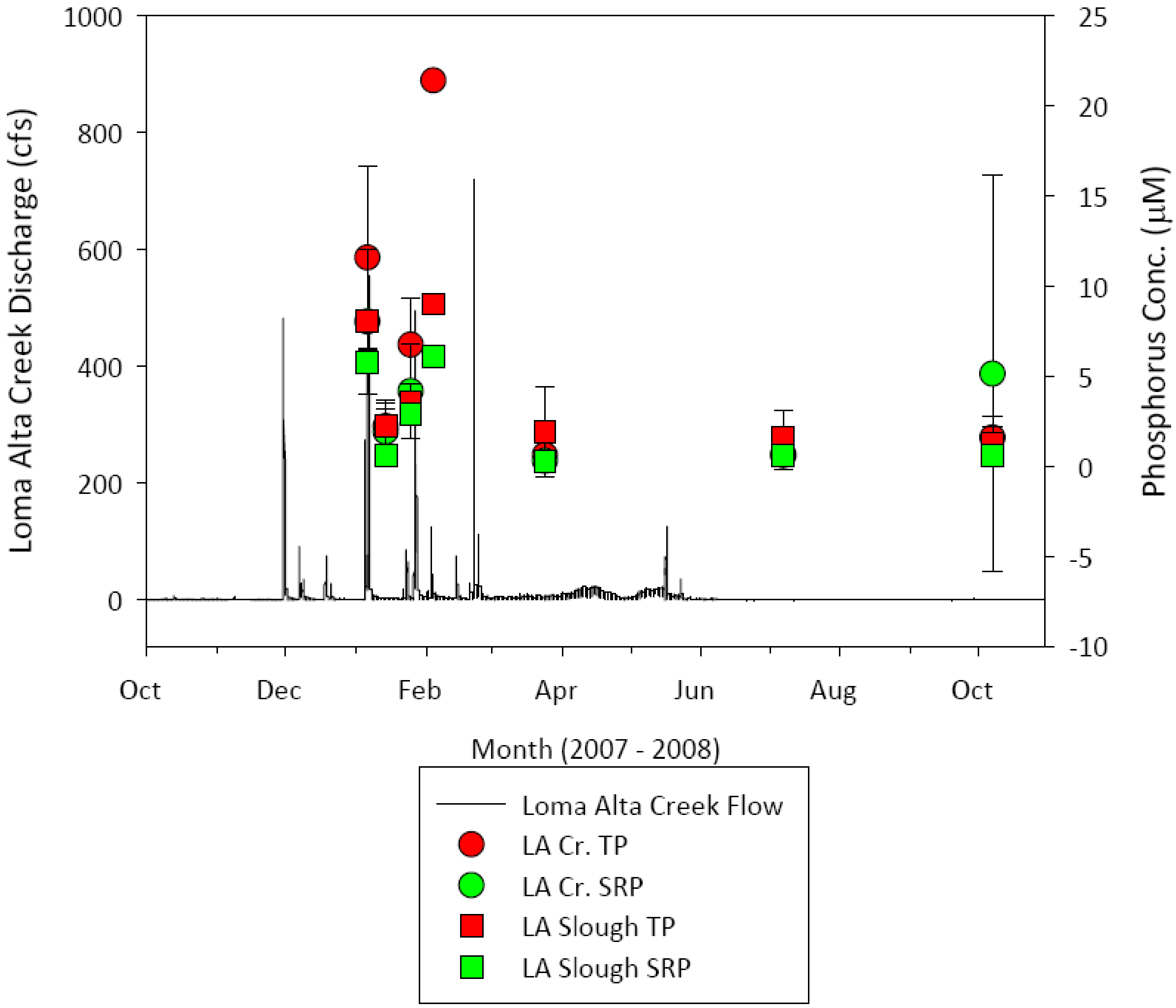


Figure 2.4. Dry weather concentrations of TP and SRP in freshwater discharge and ambient slough water as a function of freshwater flow into Loma Alta Slough. Data from MACTEC *[2009]*.

Table 2.1. Mean Concentrations of nutrients and TSS at segment site of Loma Alta Slough. Data from MACTEC *[2009]*.

Constituent	Wet Weather Mean ± Stdev	Index 1 Mean ± Stdev	Index 2 Mean ± Stdev	Index 3 Mean ± Stdev	Index 4 Mean ± Stdev
TSS	70.3±74.0	13.7±11.2	91.1±121.7	4.9±3.0	5.9±4.0
TN	87.1±26.8	50.5±24.1	60.2±25.5	59.2±25.1	130.5±34.4
TDN	80.7±29.0	36.5±11.3	36.8±6.8	62.2±22.5	126.6±43.0
Ammonia	6.2±6.4	1.8±1.0	1.5±0.7	4.7±2.0	8.3±6.3
Nitrate + Nitrite	41.4±9.3	7.6±8.2	1.4±1.5	9.6±11.2	41.2±15.1
TP	6.9±2.9	2.3±1.1	2.0±1.6	1.6±1.1	1.3±0.6
TDP	7.3±3.8	0.9±0.7	0.4±0.2	1.0±0.5	0.9±0.6
SRP	4.9±1.8	0.6±0.4	0.2±0.1	0.7±0.2	0.5±0.3

Spatially, some trends were visible along a longitudinal gradient in Loma Alta Slough (Figures 2.5 and 2.6). With respect to TN and DIN (combined NH4 and NO3+NO3): during the winter and spring index periods, concentrations decreased towards the ocean during both the ebb and flood transects, with an abrupt shift in DIN concentrations at the railroad bridge. When the Slough was closed during summer or recently opened during the fall, these trends were not visible.

Overall, trends in SRP and TP were not visible from the transect data, regardless of season or inlet status.

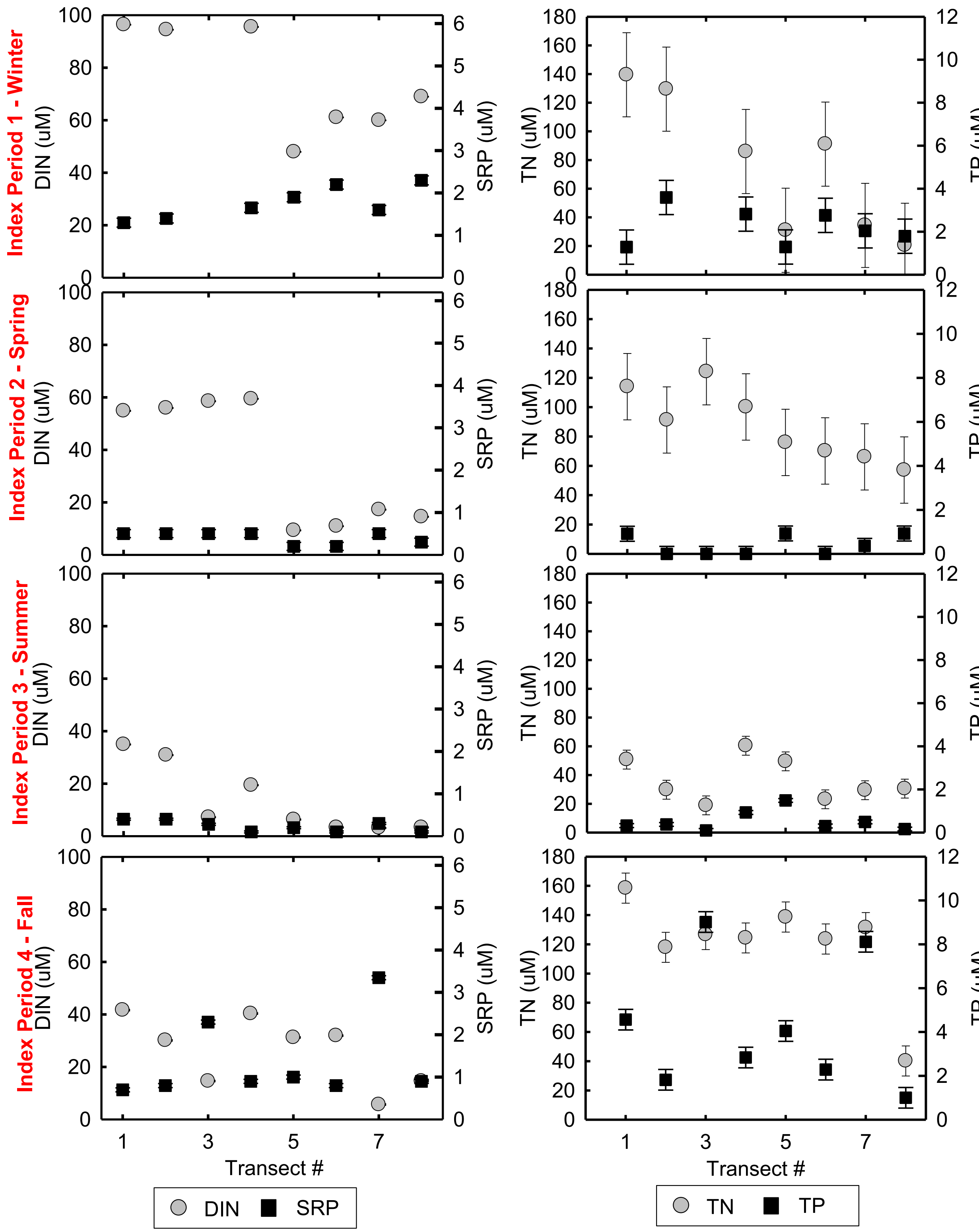


Figure 2.5. Transect data for each index period during ebb tide. ***[MACTEC, 2009]***

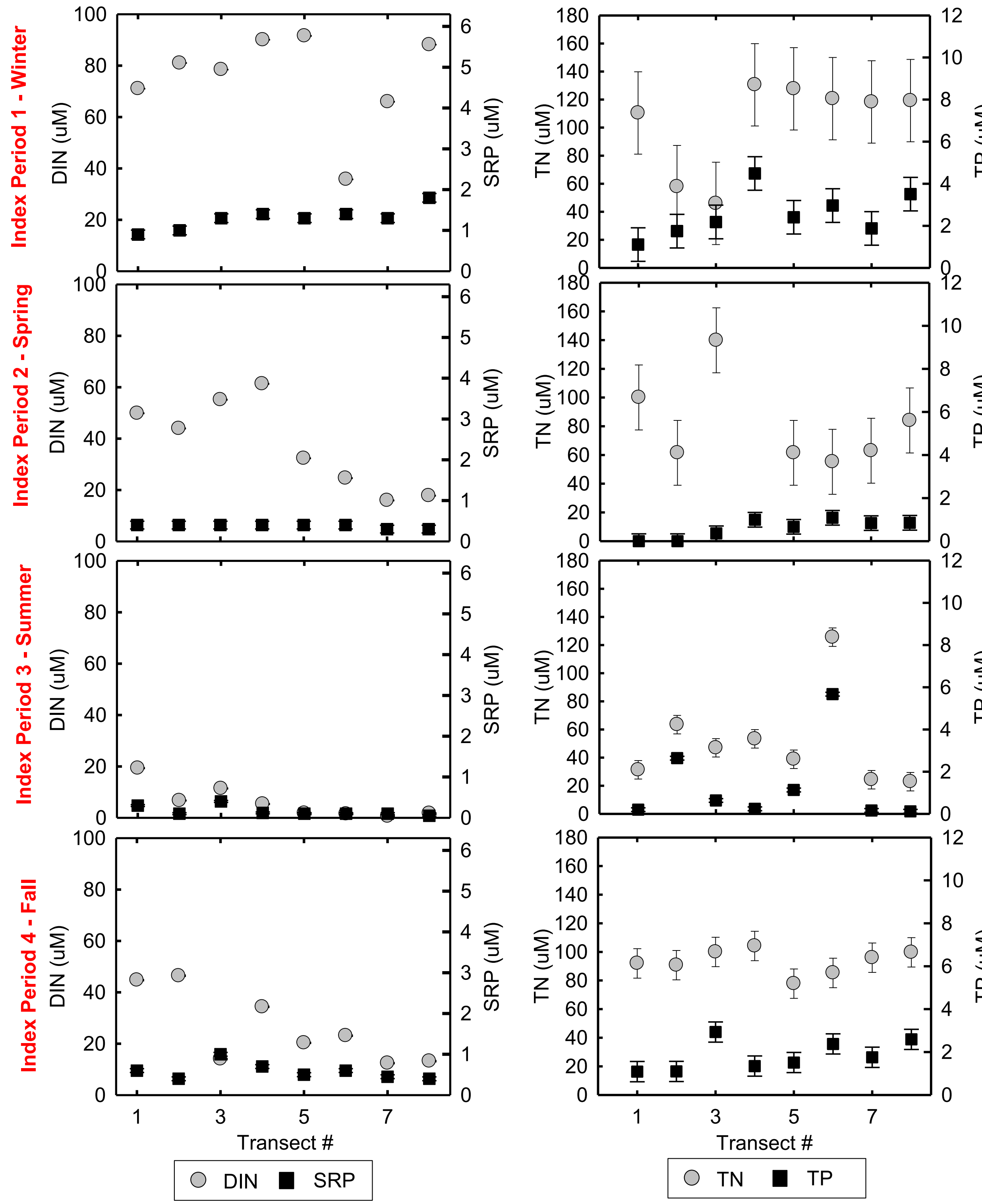


Figure 2.6. Transect data for each index period during flood tide. ***[MACTEC, 2009]***

2.3.2 Seasonal Trends in Primary Producers

This study assessed seasonal trends in biomass and or percent cover of three aquatic primary producer (APP) communities:

- phytoplankton (measured as suspended chlorophyll *a*)
- macroalgae (biomass and percent *c*over)
- microphytobenthos (measured as benthic chlorophyll *a*)

A fourth community, submerged aquatic vegetation, was not observed in Loma Alta Slough.

Figure 2.7 shows the comparative biomass of phytoplankton, macroalgae and microphytobenthos, standardized to mass of carbon (C) per unit area. Macroalgal biomass (*Cladophora sp.* and cyanobacteria mats) dominated the aquatic primary producers during closed Slough conditions during the summer and fall index periods (Figure 2.8), with 100% cover in the summer and fall and extremely high biomass (~350 g C m^{-2}) during the summer. Phytoplankton was seasonally important during the winter and spring index periods, but despite relatively high concentrations throughout the year (~40 µg L^{-1}; Figure 2.9), was an insignificant portion of the APP biomass. Microphytobenthos was insignificant relative to macroalgal biomass (Figure 2.10); benthic chl a was lowest during summer, when the inlet was closed, but, because of high variability, not significantly different from the index periods.

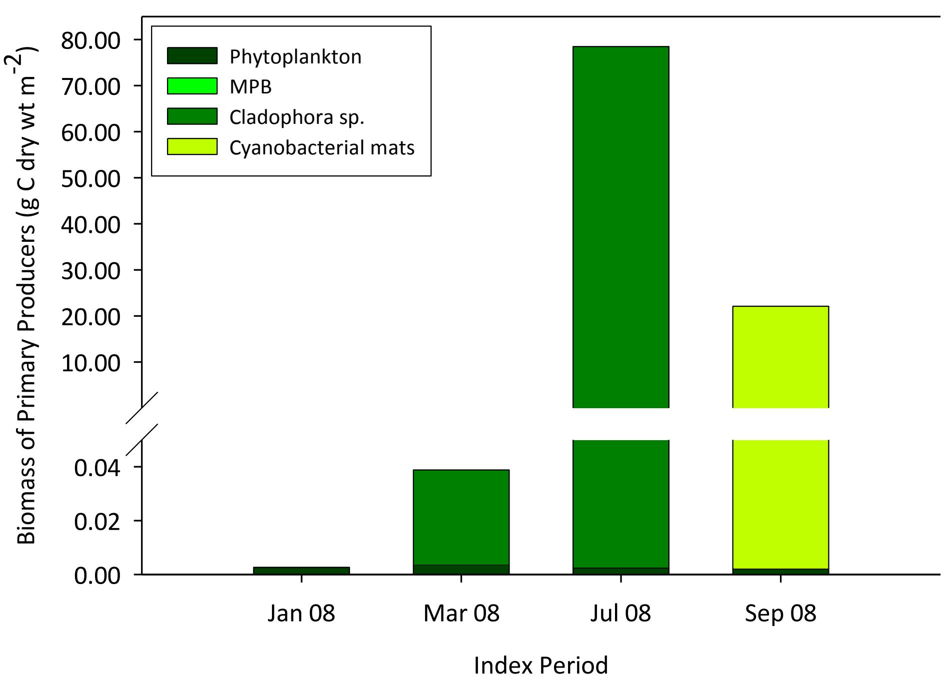


Figure 2.7. Mass of carbon associated with the four types of primary producers observed in Loma Alta Slough from transect data.

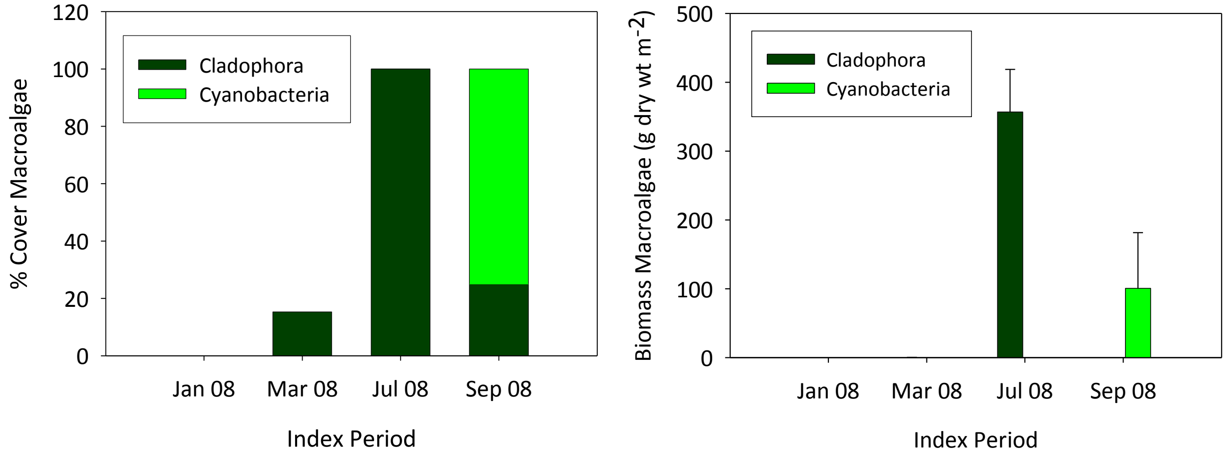


Figure 2.8. Macroalgae % cover by genus (left) and biomass (right panel) for each index period in Loma Alta Slough.

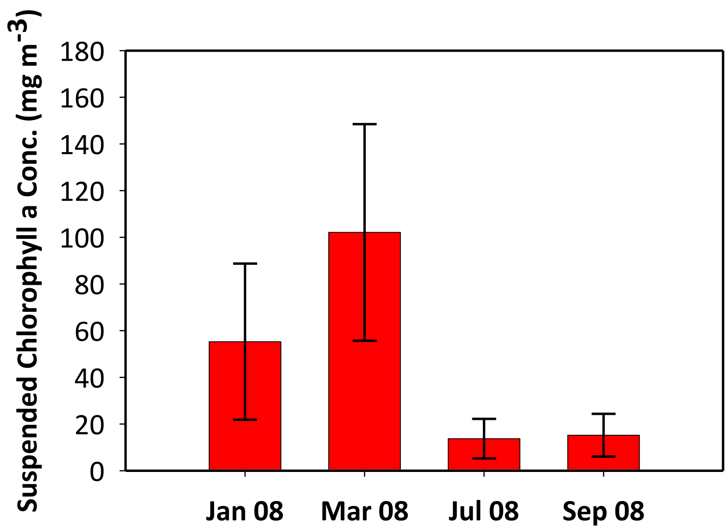


Figure 2.9. Suspended Chlorophyll a concentrations for each index period.

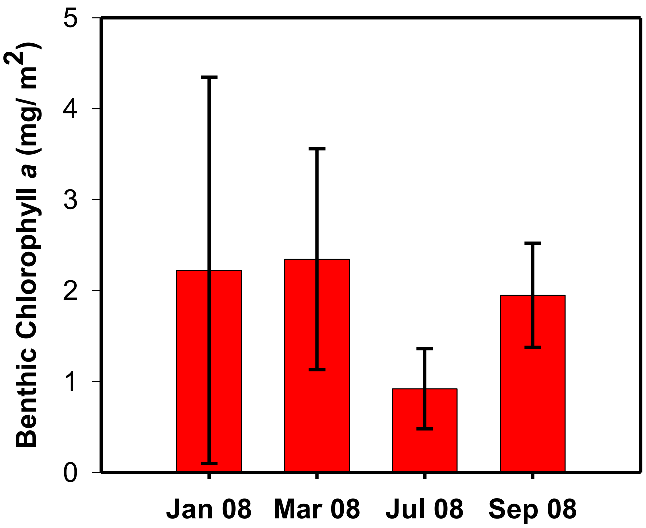


Figure 2.10. Benthic chlorophyll *a* concentrations for each index period

2.3.3 Seasonal Variation in Sediment Grain Size and Total Organic Carbon, Nitrogen and Phosphorus Characteristics by Index Period

Sediment characteristics in Loma Alta Slough were dynamic. Seasonal trends in sediment bulk characteristics were moderate (Figure 2.11). During all index periods, % fines near the top of the core was typically low (~5%), and increased with depth. During spring and fall, percent fines in the first 1 cm of the core was higher (20-40%), then dropped to <5% from 2-4 cm, then increased again below 4 cm (to a maximum of 60% fines). C:N and C:P ratios somewhat mirrored these trends, driven by differences in grain size. During the summer index period, we were unable to find a location to get a significant core depth due to the presence of gravel in the thalweg and thick clay elsewhere and we were unable to push the core tube into these sediment types. This is likely a consequence of the railroad bridge maintenance, which caused scouring of the downstream of the berm placed just below the bridge.

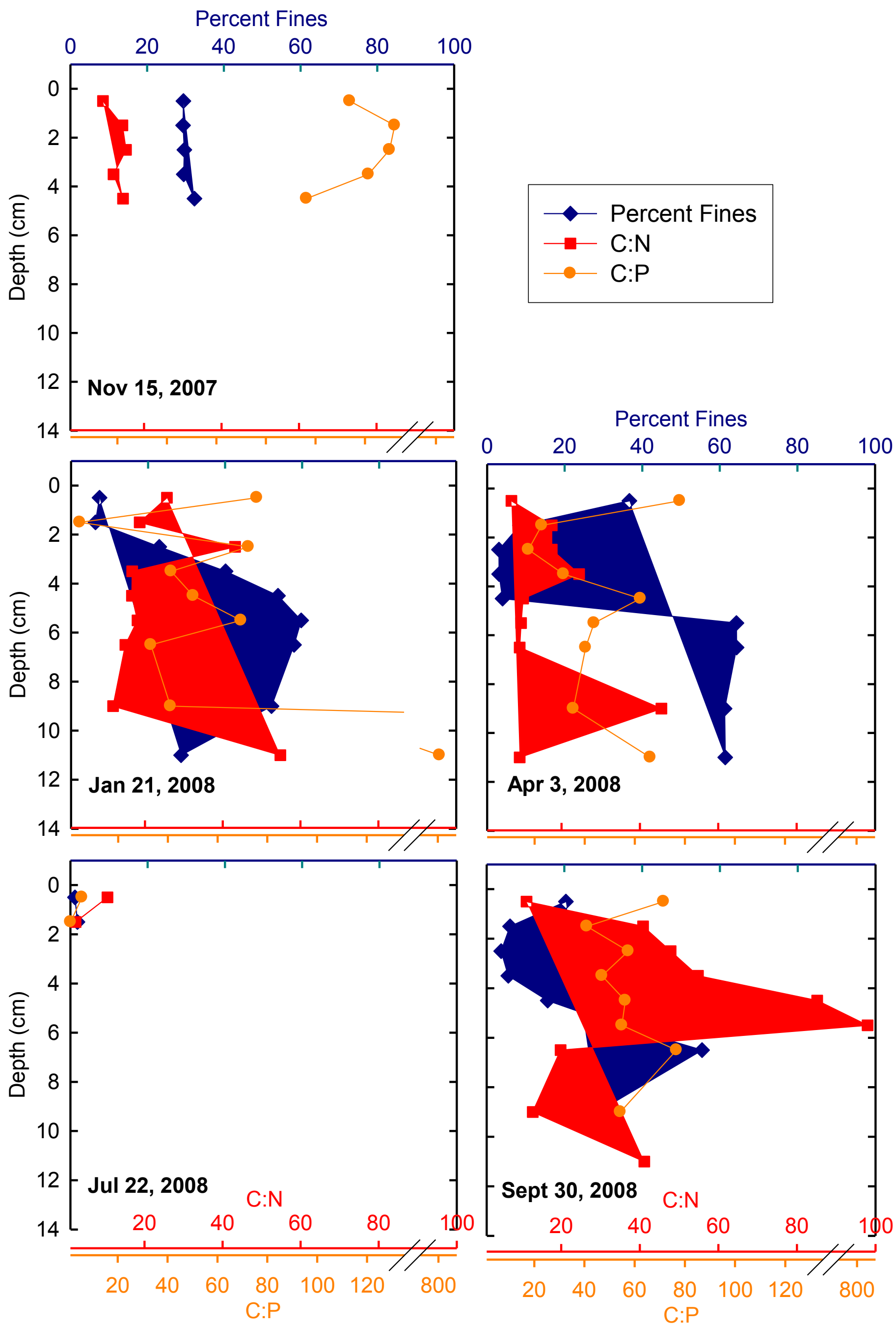


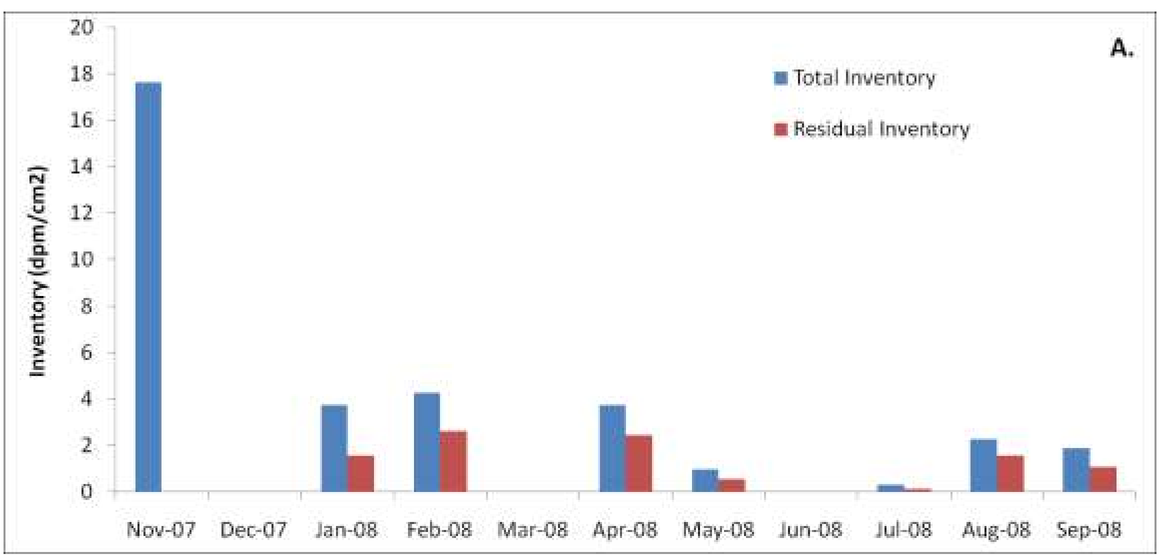
Figure 2.11. Sediment grain size (as percent fines, ♦), carbon: nitrogen (C:N, ■), and carbon: phosphorus (C:P, ●) ratios of cores taken in the southern basin of Loma Alta Slough during each index period.

2.3.4 Seasonal Trends in Sediment Deposition

Sediment deposition and removal events were measured using the particle tracer, ^{7}Be. This cosmogenic radionuclide is produced in the upper atmosphere by spallation of oxygen and nitrogen atoms. Because ^{7}Be is particle reactive, it will adsorb to any aerosols or dust present in the atmosphere at the time of formation. These particles are scrubbed from the atmosphere during rain events or fall out slowly as dry deposition. The ^{7}Be particles can then act as particle tracer proxies for all internal sediment movement, and track the downstream flow of sediment in streams.

Total ^{7}Be inventory versus depth indicates that November 2007 was a high depositional period, but subsequent months were fairly low (Fig. 2.13). All new and residual ^{7}Be appeared in the upper 1 to 2 cm of sediments during the field campaign, indicating sediment transport and deposition/ erosion processes were always recent and ephemeral. Only in the initial sampling period were significant inventories found below the surface sediment layer. When the total inventories are summed with depth, calculated total and residual inventories may be compared. These inventories show a spike (17.6 dpm/cm^2) in Be deposition in the sediments in November 2007, which was the preliminary sample collection from which all subsequent inventory and flux estimates are based (Fig. 2.13 A). The preliminary total inventory was decay corrected to the first index period on 21 Jan 08 in order to estimate the residual and new portions of each inventory. Thereafter, all total inventories were decay corrected for the time between sampling events. Index periods and intervening sample dates were less than 4.5 dpm/cm^2 after November 2007 (Fig 2.13 A).

New inventories versus time indicate that recent depositional periods were small, always less than 2.5 dpm/cm^2 (Fig. 2.13 B). Be deposition to the sediments declined from Index Period 1 steadily to Index Period 3. A slight increase in Be deposition appeared in early fall (Index Period 4). These data were used to calculate a mass flux to/from the sediment surface using the new inventory divided by any new activity present in the sediments.



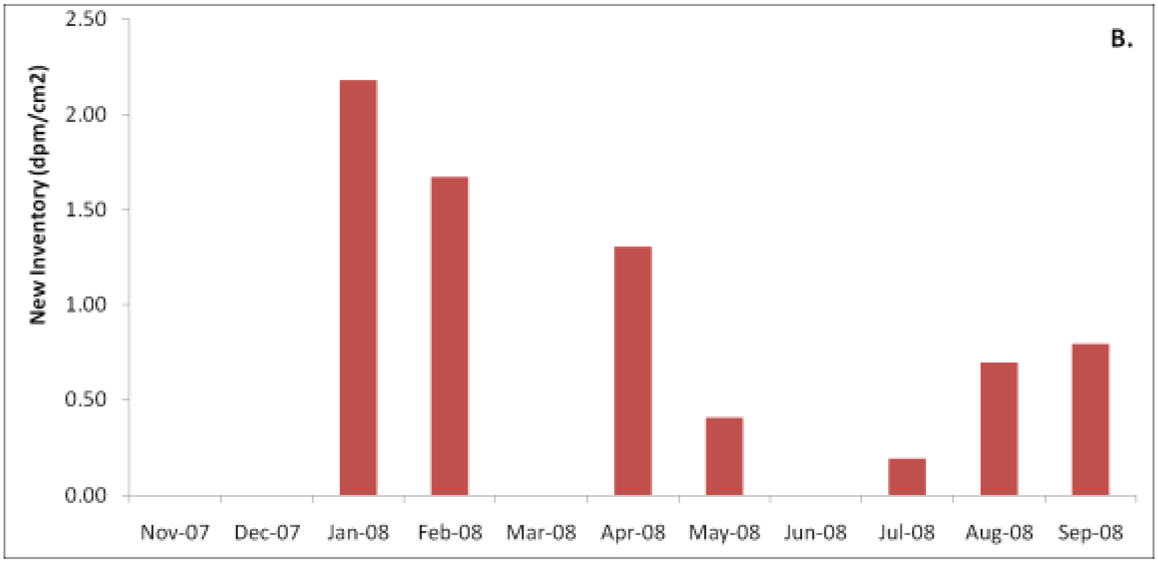


Figure 2.13. (A) Total and residual inventories of ^{7}Be and (B) new ^{7}Be inventories are shown versus time from Novwmber 2007 thru September 2008.

Sediment mass fluxes can be compared to discharge and precipitation events to identify important events. However, Loma Alta Slough was altered by construction during the sampling year and comparisons to discharge and precipitation are not valid. A railroad bridge construction project blocked the downstream movement of water temporarily and restricted flow for most of the sampling period in Loma Alta. In addition, the ocean inlet of Loma Alta was closed in late spring through the fall (Appendix 2). However, we can use mass fluxes to describe the overall deposition/ erosional regime within Loma Alta. Mass fluxes are presented as a material inventory (g/cm^2) (Fig. 2.14) and indicate that sediment was primarily removed between April and July 2008 while slight depositional regimes were present for Index Periods 1 and 4.

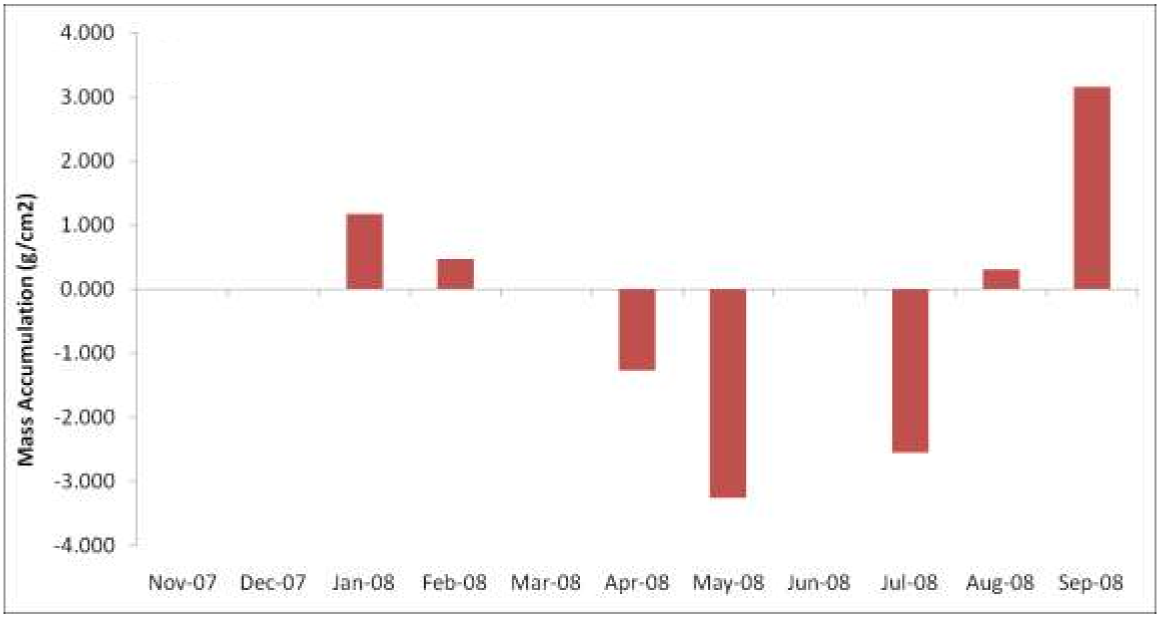


Figure 2.14. Mass flux is given as an inventory of material deposited (+) or removed (-) through time. Most removal occurred during the late spring and summer.

2.3.5 Seasonal Trends in Sediment Pore Water Concentrations

Pore Water Nitrogen and Phosphorus. In all index periods, total dissolved nitrogen in pore waters is chiefly ammonium with only a minor fraction composed of nitrate, and little or no nitrite (Figure 2.15). Pore water ammonium typically increases with depth from low concentration in the surface pore waters and increasing by three to four orders of magnitude with depth. Pore water ammonium concentrations were highest in the deeper pore waters during the summer.

Total dissolved phosphate in pore waters is primarily composed of soluble reactive phosphate and follows a similar depth profile and seasonal trend as TDN and ammonium, where peaks in ammonium and TDN correspond directly with peaks in TDP and SRP.

Pore water nitrate values, though low throughout all sampling periods compared to ammonium, were highest in the spring and summer in the near-surface depths, though profiles in the spring and summer were variable. Thus nitrate tends to follow a pattern opposite to ammonia, SRP, sulfide (concentrations are high when concentrations of these constituents are low). Peaks in nitrate coincided with peaks in iron and, at times, manganese concentrations.

Dissolved organic carbon concentrations in the pore waters were extremely high in the spring and were lower in the winter, summer and fall. Vertically, peaks in DOC tended to coincide with peak Mn or Fe concentrations.

Sulfide and Total Carbon Dioxide. Pore water total carbon dioxide (TCO2) concentrations are indicative of respiration/decomposition of organic matter in the sediments (Figure 2.15). Sulfide concentrations are indicative of the microbially-mediated reduction of sulfate to sulfide in very anoxic sediments.

Sulfate reduction results in the decomposition of organic matter and the production of TCO2. For this reason, these two indicators of decomposition showed similar depth and seasonal trends.

Near surface sediments had low concentrations of TCO_2 and S^{-2} and concentrations typically increased with depth, with the exception of the spring index period. During winter and summer index period, the TCO_2 and S^{-2} concentrations remained low until 7 cm depth when concentrations rose sharply by an order of magnitude. During the spring and fall, S^{-2} and TCO_2 concentrations were low to moderate with little vertical trends visible. The increase in TCO_2 and S^{-2} concentrations with depth correspond with the increase in concentrations of ammonium, TDN, SRP and TDP for each index period.

Iron and Manganese. Pore water Fe and Mn are indicative of iron and manganese redox reactions in which solid-phase oxidized forms are converted via a microbially-mediated reaction to the reduced, soluble forms (Figure 2.15). Iron, manganese reduction and denitrification reactions occur mildly anoxic sediment, so increases in the concentrations of these constituents indicate redox status of the sediments.

In Loma Alta Slough, pore water concentrations of Fe and Mn typically highest in surface sediments before the peaks in of ammonium, TDN, SRP, TDP, TCO_2 and S^{-2} concentrations. Concentrations of Fe and Mn were generally the highest in surficial sediments during spring and summer.

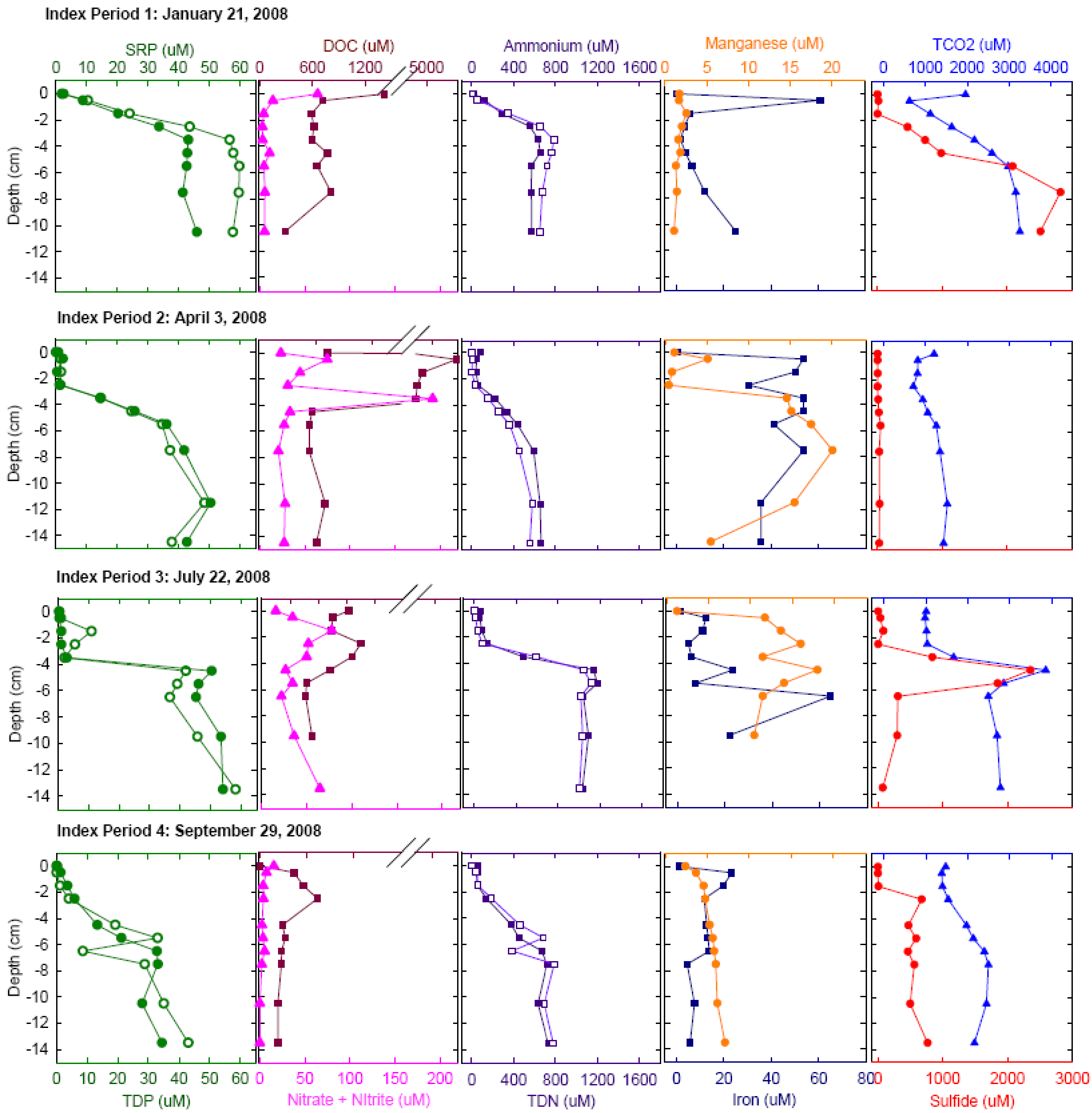


Figure 2.15. Results of sediment pore water sampling in Loma Alta Slough during each index period; each row represents an index period, first column is total dissolved phosphorus (●) and soluble reactive phosphate (○), second column is nitrate + nitrite (▲) and dissolved organic carbon (■), third column is total dissolved nitrogen (■) and ammonium (□), fourth column is iron (■) and manganese (●), fifth column is sulfide (▲) and total carbon dioxide (●). The same scale applies to each column.

2.4 Discussion

2.4.1 Summary of Findings.

Increased eutrophication in estuaries often results in a shift in primary producer communities [*McGlathery, et al.*, 2007], most notably the proliferation of macroalgae within shallow coastal estuaries. During ocean inlet closure, macroalgal biomass in Loma Alta Slough was extremely high (364 g dry wt m^{-2}) and cover was 100% during the summer index period. The high primary productivity is likely a major factor driving hypoxia in the summer and fall. In addition, high cover and biomass of macroalgae was likely responsible for maintaining low dissolved inorganic nutrient concentrations (particularly nitrate) throughout the growing season.

Traditional patterns of sediment deposition and erosion were not observed in Loma Alta Slough, as indicated by Be-7 data, however, these data did indicate net erosion for the year. During the course of construction at the railroad trestle, creek water flow was restricted which appears to have caused erosion of the sediment bed downstream of the railroad bridge.

2.4.2 Significance of Macroalgae in Loma Alta Slough.

Opportunistic macroalgae are highly successful in nutrient–rich freshwater and estuarine systems. These algae typically have filamentous or sheet-like growth forms (e.g., Cladophora or *Ulva* spp.) that can accumulate in extensive, thick mats over the seagrass or sediment surface. Although macroalgae are a natural component of these systems, their proliferation due to nutrient enrichment reduces habitat quality in four ways: 1) increased respiration at night and large oxygen demand from decomposing organic matter, 2) shading and out-competing submerged aquatic vegetation, 3) impacts on the density of benthic infauna, which are a principle food source for birds and fish, and 4) development of poor aesthetics and/or odor [*Fong, et al.*, 1998; *Kamer, et al.*, 2001; *Kennison, et al.*, 2003].

Overall, macroalgae dominated the primary producer community both in terms of total biomass storage and cover. Biomass of macroalgae was extremely high with a peak biomass of 364 g dry wt m^{-2}. However, while primary producer biomass and percent cover are useful for understanding the extent of eutrophication in systems like Loma Alta Slough, there is currently no established assessment framework to determine whether an estuary has become adversely affected by macroalgae. The existing California freshwater nutrient numeric endpoint framework for streams has set a beneficial use risk category (BURC I) threshold at 100 mg Chl a m^{-2}, which defines the lower limit of systems that are sustaining beneficial uses. This limit, converted to g C m^{-2} by assuming a chl a: C ratio of 30:1, would be 3 g C m^{-2}, a number that is an order of magnitude below the peak biomass found in Loma Alta Slough. However, this number was established for periphyton in streams, not soft bodied algae in brackish water estuarine environments.

In Loma Alta Slough, the relative biomass of benthic primary producers followed a seasonal trend typical of eutrophic-hypereutrophic coastal lagoons [*Fong, et al.*, 1998; *Fong, et al.*, 1993; *Kamer, et al.*, 2001].

During the winter index period (January 2008), aquatic primary producers were largely absent at the segment site. Flushing and scouring during storm events act together with low temperatures and light levels to inhibit growth of macroalgae. Phytoplankton and microphytobenthos (MPB) biomass peaked in the spring. By the summer index period, however, microphytobenthos appear to be out-competed by macroalgae *Cladophora* and cyanobacteria mats in the summer and fall, which dominated the primary producer community both in terms of total biomass and cover. By summer, Cladophora sp. dominated APP biomass and percent cover, but the dominance shifted to cyanobacterial mats by the fall index period. This dominance and high standing biomass macroalgae and cyanobacteria during the summer and fall suggest that the Slough is at the extreme end of the disturbance gradient with respect to nutrient over-enrichment [*Fong, et al.*, 1993]. It is possible that the observed deposition in the ^{7}Be data during the fall index period is capturing high organic matter deposition on top of the sediments during the senescence of the high summer APP biomass, rather than sediment transport from upstream.

Macroalgal mats can rapidly deplete dissolved inorganic nutrients from the water column [*McGlathery, et al.*, 2007; *Pedersen and Borum*, 1997]. This depletion of nutrients increases the rate of benthic flux of nutrients from the sediments by creating a concentration gradient, thus diverting nitrogen loss from denitrification and providing a mechanism for nitrogen retention and recycling within the estuary [*Fong and Zedler*, 2000; *Krause-Jensen, et al.*, 1999]. In Loma Alta Slough, the peak in macroalgae productivity coincided with the closure of the Slough ocean inlet. Increased residence time of water during this closure would result in greater nutrient availability that would enhance the productivity of macroalgal blooms.

The presence of macroalgae in estuarine environments can alter dissolved oxygen (DO) concentrations significantly on a diurnal scale. High rates of respiration from elevated biomass may reduce DO content of estuarine waters at night (e.g., Peckol and Rivers [1995]), while decomposition of accumulated organic matter may cause a large microbial O_2 demand both day and night [*Sfriso, et al.*, 1987]. This effect is evident in Loma Alta Slough, where hypoxia was common during the summer and fall (Chapter 4, *[*MACTEC*, 2009]*). Peak biomass in the summer was observed to be associated with a thick layer of decomposing dead organic material at the bottom of the Slough, fueling the chronic hypoxia observed.

2.4.3 Significance of Loma Alta Slough Surface Water and Pore Water Nutrient Concentrations.

Ambient nutrient concentrations within an estuary are the integration of various pathways of sources, sinks and transformations, including both uptake and release [*Bergamasco, et al.*, 2004; *Dalsgaard*, 2003; *Paerl*, 2009; *Valiela, et al.*, 1992; *Valiela, et al.*, 1997]. The relative ratios of the different species can provide some insight into the dominant processes controlling nutrient availability within the estuary. During both wet and dry weather periods, organic N in surface waters exceeded dissolved inorganic N, suggesting that internal recycling of N (algal uptake and release) was probably a dominant process controlling N concentrations in both the creek and Slough. Wet weather TP and SRP concentrations exceeded dry weather concentrations by a factor of 3-4; during wet weather, most TP was SRP; during dry weather, particulate phosphorus and DOP dominated TP (Table 2.1)

Sediment organic matter can be decomposed by microorganisms via a series of biogeochemical reactions which result in the release of mineral forms of nutrients to sediment porewaters. These reactions depend on the oxidative/reducing (redox) potential of the sediment environment (Figure 2.16) and are evidenced by the uptake and release of various pore water constituents (Figure 2.17). For example, measurement of dissolved iron and manganese fluxes provide valuable information about the redox chemistry of the sediments, since these constituents are only released if the environment is of sufficiently low redox potential, which would indicate sediment hypoxia.

Denitrification, the microbially-mediated conversion of nitrate to nitrogen gas, is typically a major pathway through which ambient nitrate concentrations can be lowered (Figures 2.16 and 2.17). Measurements of denitrification in Loma Alta Slough during the study were exceedingly small (0.2 – 5.2 µmol m^{-2} hr^{-1}, T. Kane, UCLA Department of Biology Doctoral Dissertation), three orders of magnitude below the range of published rates in eutrophic estuaries (50 -250 µmol m^{-2} hr^{-1}, Seitzinger 1988). Both nitrate uptake associated with primary production (microphytobenthos or macroalgae) may have limited denitrification through competition for NO_3 (Rysgaard et al. 1995, An & Joye 2001)[*Dalsgaard*, 2003; *McGlathery, et al.*, 2007]. Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because primary producers typically outcompete bacteria for available nitrate [*McGlathery, et al.*, 2007]. Interestingly, pore water nitrate concentrations were relatively high during the spring index period. Peaks were observed in the vertical profiles of nitrate and coincided with elevated manganese and iron pore water concentrations and low sulfide, TCO2, ammonia and SRP concentrations (Figure 2.10), suggesting that the shallow surface sediments were perched at higher redox levels (Figure 2.17) [*Roden and Edmonds*, 1997]. It is likely that nitrification, a process that occurs in relatively aerobic environments and converts ammonia to nitrate, is occurring at these depths. With depth, ammonia increases, with a corresponding decrease in nitrate, signaling the dissimilatory nitrate reduction (conversion of nitrate to ammonium) may be a dominant process [*An and Gardner*, 2002; *Brock*, 2006; *Porubsky, et al.*, 2009]. Summer pore water profiles can not be interpreted with the other index periods due to the fact that the location of the porewater peepers was relocated during this time period. Bed erosion forced us to move away from the thalweg and upstream slightly which created a discrepancy with the other index periods, confounding the data.

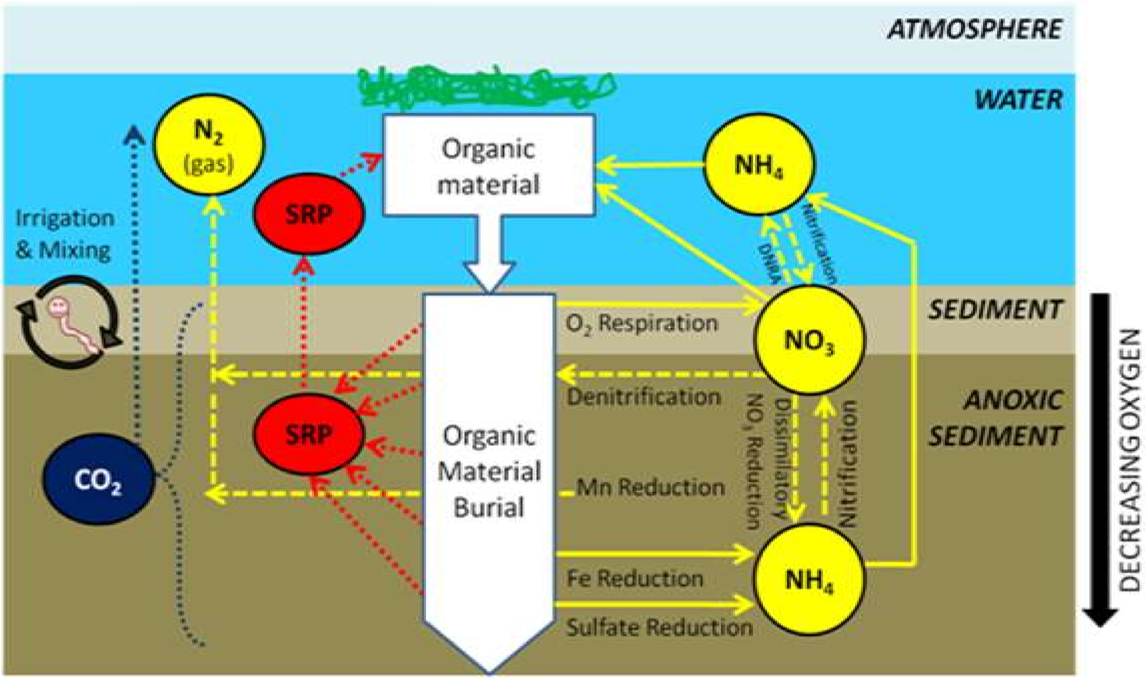


Figure 2.16. Pathways for nutrient cycling and decomposition of organic matter in the sediments

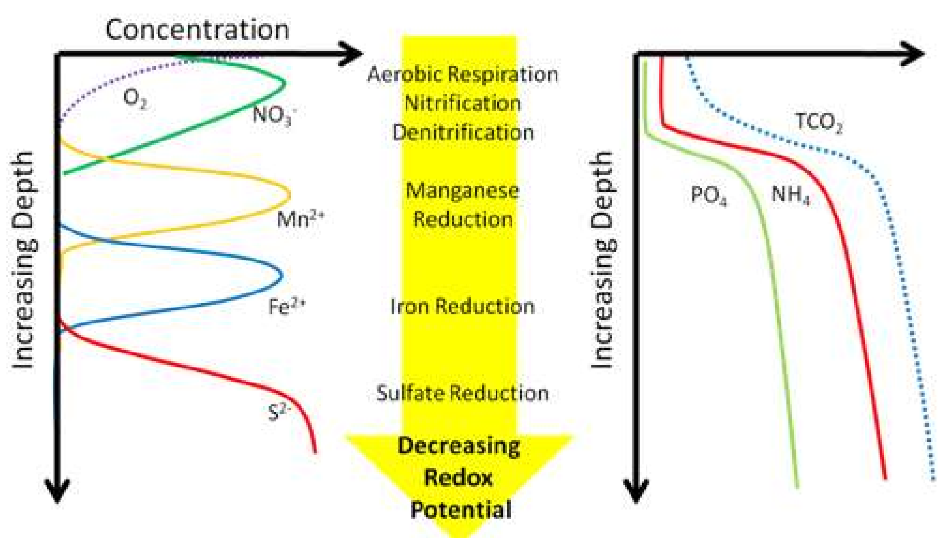


Figure 2.17. Sediment pore water profiles reflect redox status of the sediment.

2.4.4 Significance of Loma Alta Slough Sediment Characteristics and Transport.

As noted above, sedimentary organic matter can serve as a source of remineralized N and P to porewaters and surface waters as the organic matter is decomposed. Sediment grain size typically decreased downcore associated with a decrease in N and P relative to organic C and an increase in porewater ammonium and phosphate. However, the sediments were unlikely to provide a consistent source of remineralized nutrients to the porewaters and surface waters due to the net erosion of sediment over the study period and as evidenced by a lack of seasonality in the sediment C:N and C:P ratios (Table 2.4 and Figure 2.11). It is unclear if this is a regular condition for the Slough, or if it is an artifact of the restriction of flow (and thus deposition) due to the construction of the railroad trestle during the study period (Appendix 2). Mass fluxes indicated the removal of sediment occurred between April and July 2008, while slight depositional regimes were present for Index Periods 1 and 4. Disruptions caused by the construction and diminished tidal exchange for parts of the year make interpretation difficult. When the mass fluxes are summed for the entire year, we find the Loma Alta Slough was a net erosional environment during the 2007-2008 sampling year. Data collected during the summer index period should be qualified due to these activities.

3 Seasonal Trends in Sediment Oxygen Demand and Benthic Nutrient Flux

3.1 Introduction

Sediments are a potentially significant internal source of N and P to surface waters in estuarine systems. Watershed-derived sediments, deposited in estuaries during the wet season, carry an associated particulate N and P load [*Sutula, et al.*, 2004; *Sutula, et al.*, 2006]. When deposited in the estuary, particulate nutrients can be mineralized to biologically-available forms and may build up in high concentrations in sediment pore waters. These pore waters can diffuse into the overlying water column or be released through advective processes such as bioturbation by benthic infauna, forced flow of water through sediments by bioirrigation or tidal pumping, or physical resuspension of sediments through scouring or resuspension during strong tidal currents or storm flows [*Boynton, et al.*, 1980; *Grenz, et al.*, 2000; *Jahnke, et al.*, 2003]. Once released to the water column, these particulate-derived nutrients are available for uptake by primary producers, including macroalgae, microphytobenthos, and submerged aquatic vegetation.

Primary producer abundance is often limited by availability of nutrients [*Howarth*, 1988; *Kamer, et al.*, 2004; *Paerl*, 2009; *Valiela, et al.*, 1997]. Macroalgae generally obtain nutrients directly from the water column, though studies have shown that algae may intercept nutrients fluxing out of sediments [*Lavery and McComb*, 1991; *McGlathery, et al.*, 2007]. In Southern California, wet-season particulate-nutrient loads deposited in lagoons where shown to provide a significant source of nutrients that fueled excessive growth of submerged aquatic vegetation and macroalgae during the dry season [*Boyle, et al.*, 2004; *Sutula, et al.*, 2004; *Sutula, et al.*, 2006]. Thus, sediment-derived nutrients may cause algal blooms to persist even when nutrient loading from the watershed is reduced to levels calculated to limit macroalgal biomass [*Neto, et al.*, 2008; *Sutula, et al.*, 2004].

The principal methods of estimating sediment contribution of nutrients (benthic flux) include benthic chambers [*Berelson, et al.*, 2003; *Clavero, et al.*, 2000; *Hammond, et al.*, 1985], sediment-core incubations [*Risgaard-Petersen and Ottosen*, 2000; *Welsh, et al.*, 2000] and pore water profiles [*Hammond, et al.*, 1999; *Qu, et al.*, 2005]. Vertical fluxes of solutes diffusing between the sediment and overlying waters can be calculated from Fick's law of diffusion (i.e., pore water diffusive fluxes). The major controls on diffusive fluxes are sediment porosity and the diffusive boundary layer (DBL). Benthic chambers and sediment-core incubations are direct measurements and may integrate diffusive and advective transport of porewater by means of bioturbation/or bioirrigation processes [*Berelson, et al.*, 1999]. Additionally, the comparison of computed (diffusive) fluxes with measured (*in situ*) fluxes can provide information about the relation between fluxes at the sediment–water interface and nutrient cycling within sediment column [*Clavero, et al.*, 2000; *Qu, et al.*, 2005].

In addition to nutrients, the fluxes of oxygen and total inorganic carbon (TCO2) and trace metals provide valuable information the biogeochemical functioning of the sediments. In particular, O2 and TCO2 fluxes provide insight on the rates and dominant pathways of organic matter mineralization and benthic community metabolism, which are of primary interest in understanding ecosystem functioning and disturbances caused by eutrophication [*Ferguson, et al.*, 2003; *Ferguson, et al.*, 2004; *Qu, et al.*, 2005]. The production of total inorganic C, measured as the release of TCO2 from the sediment to the overlying water, has been used to interpret the balance between aerobic and anaerobic mineralization since both yield CO_2 as the ultimate oxidation product of carbon [*Berelson, et al.*, 1998; *Hammond, et al.*, 1999]. Measurement of dissolved iron and manganese fluxes provide valuable information about the redox chemistry of the benthic boundary layer, since these constituents are only released if the environment has a sufficiently low redox potential (hypoxic).

The goal of the benthic flux studies in Loma Alta Slough were to estimate the *in situ* flux of nutrients, dissolved oxygen (DO), TCO2, Fe and Mn between sediments and surface waters during four index periods (see Section 1.3 for study design). A combination of techniques was used to estimate these fluxes including:: 1) direct *in situ* measurements of nutrient flux and sediment oxygen demand using benthic flux chambers and 2) calculation of diffusive fluxes based on concentration gradient between surface waters and pore waters. Data were also collected on some of the key factors (sediment characteristics and nutrient content, primary producer biomass) known to control fluxes in order to understand key drivers on the magnitude and direction of flux.

3.2 Methods

Benthic flux chambers were the primary method used to measure the fluxes *in situ* during each of the four index periods. Because the flux of nutrients from the sediments is controlled by a suite of physical, chemical, and biological factors which vary substantially over the course of the year, the sediment grain size, C:N and C:P ratio, the taxa and abundance of benthic infauna, and the biomass of microphytobenthos (benthic chl a) and macroalgae were also measured within each chamber.

3.2.1 Field Methods

3.2.1.1 Measurement of In Situ Benthic Fluxes

In situ sediment nutrient, trace metal, and dissolved organic carbon (DOC) fluxes and sediment oxygen demand were measured using benthic flux chambers [*Berelson, et al.*, 2003; *Burdige, et al.*, 1999; *Elrod, et al.*, 2004]. A minimum of two replicate chamber deployments were conducted in the southern basin of Loma Alta Slough per index period and were incubated for three to five hours during a neap tidal cycle. Water samples were periodically drawn from the chamber as oxygen levels within the chamber decline (Figure 3.1). These samples, when analyzed, yield the change in concentration of the targeted analyte over time. The surface area of the chamber is known and the volume of water contained with the chamber can be calculated, therefore, a flux rate can be derived.

Four identical benthic flux chambers were built based on a modified design from Webb and Eyre [*Webb and Eyre*, 2004]. The chamber is made of clear acrylic measuring 25 cm x 25 cm x 26 cm (l x w x h) mounted to an aluminum frame and is designed such that 10 cm of the chamber height is submerged in the sediment (leaving a height of 16 cm above the sediments) (Figures 3.2 and 3.3). The chamber frame is placed on top of an acrylic “skirt”, a thin sheet of acrylic measuring 24” x 36” with a hole cut in the center. This "skirt" allowed for the acrylic chamber to sink into the sediments but prevented the frame from also sinking into the sediments and thus changing the chamber height over the deployment time. When properly deployed the total chamber volume is 10 liters. Two of the chambers were left clear and open to variations in ambient light throughout the deployment (light chambers, Figure 3.4); the other two chambers were covered in aluminum foil to prevent ambient light from penetrating the chambers (dark chambers).

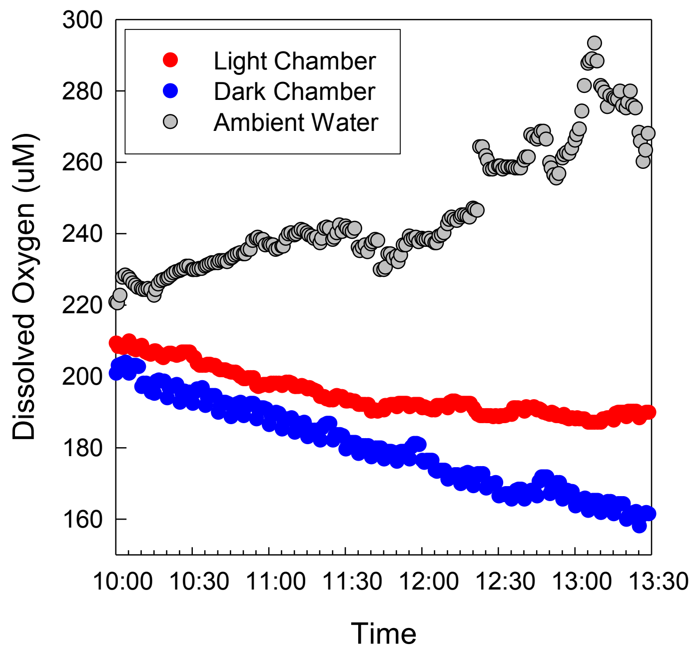


Figure 3.1. Typical chamber time series of dissolved oxygen concentration within the light and dark chambers relative to ambient surface water (September 2008). Oxygen concentrations in both the light and dark chambers steadily decreased over the incubation. Flux calculations were made during the most linear part of the curve

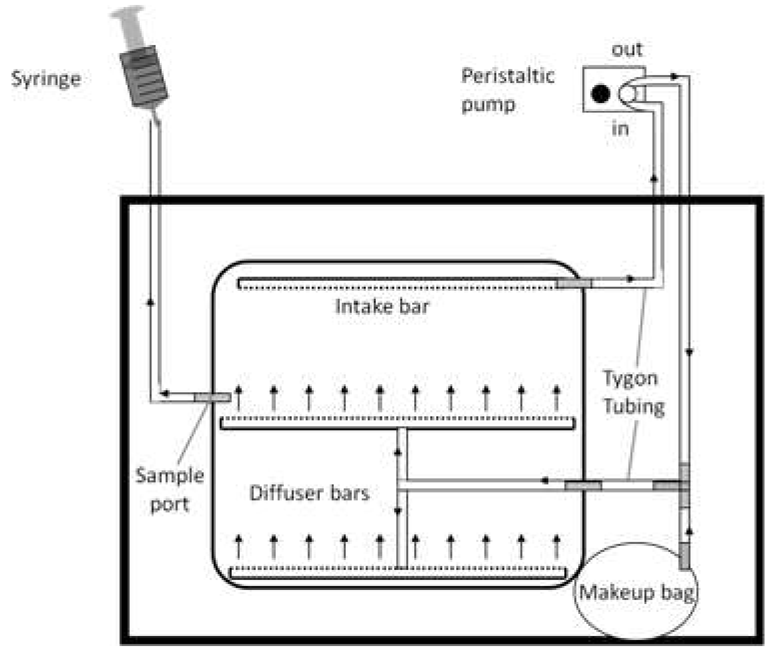


Figure 3.2. Schematic of benthic chamber design as viewed from above.

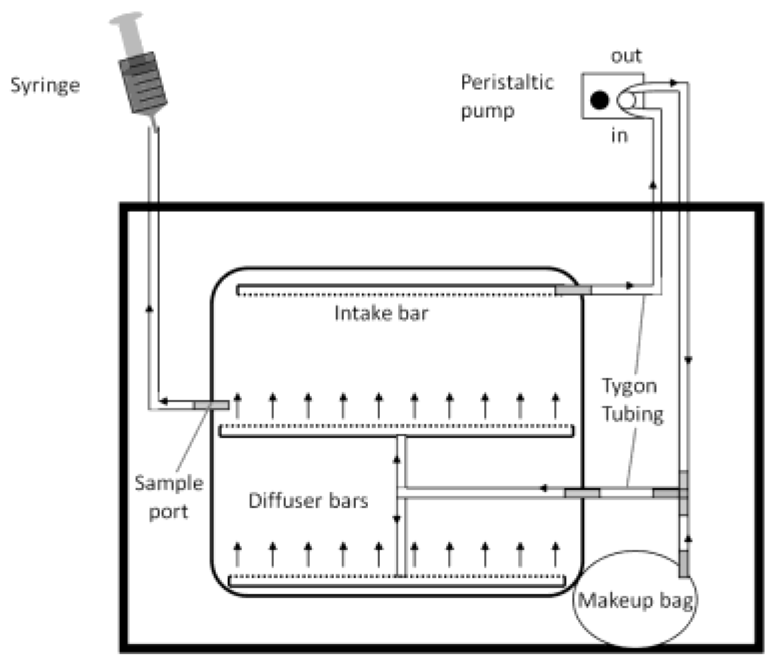


Figure 3.3. Schematic of benthic chamber design as viewed from side

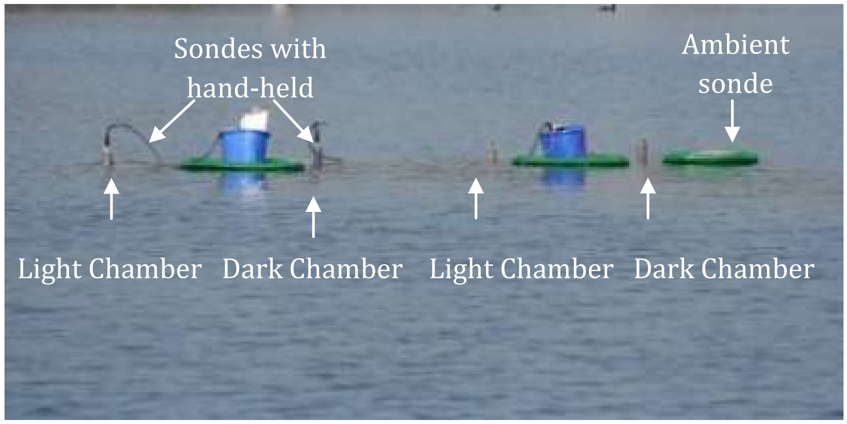


Figure 3.4. Orientation of flux chambers during deployment.

Each chamber is equipped with a YSI 6920 data sonde containing a temperature/conductivity probe, optical dissolved oxygen probe, and pH probe allowing for continuous measurements within each chamber and of ambient water every minute. All probes were calibrated in the laboratory before deployment. Two of the chamber probes were connected to a YSI 650 hand-held data display unit allowing for real-time monitoring of dissolved oxygen levels within each chamber. Such a set up allowed the field team to set the timing of chamber samplings to insure that all five samplings were evenly spaced in time and that no sampling would occur after the chamber DO levels fell below 2 mg/L.

The chamber is "plumbed" with tygon tubing leading to a peristaltic pump which keeps water circulating through the chamber, preventing the development of a benthic boundary layer which would alter the benthic-flux rate [*Webb and Eyre*, 2004]. An additional tube is connected to a clean 60 mL syringe which is used to pull water samples from the chamber at the designated intervals. There were five sample draws from each chamber and each sample draw removed approximately 130 mL of water from the chamber (two syringes plus 10 mL of rinse). In order to maintain consistent chamber volume, water from a "make-up" bag is drawn into the chamber as the sample water is withdrawn. The two syringes used to draw chamber water at each sampling port are immediately taken to the shoreline for processing.

Sediments were mildly disturbed during deployment, so chambers were allowed to equilibrate with their surroundings before the tops were closed. Chambers were closed when the turbidity measurement in chamber 1 returned to baseline. Dissolved oxygen, temperature, salinity and pH were measured continuously in each chamber and the surface water directly adjacent to the chambers with data sondes. Dissolved oxygen concentrations in the chambers were monitored during the incubation and observed to steadily decline in both the light and dark chambers over the course of the experiment relative the ambient DO concentration (Figure 3.1). Samples were pulled from the chamber at evenly spaced intervals to measure the change in concentration within the chambers as a function of time; these data were used to calculate the flux from the sediments. The interval between samplings was determined based on the rate at which the real-time measurements of DO decreased; the aim of the experiments was to collect five distinct samplings before the DO levels fell below 2 mg/L (62 µM).

Chamber water and ambient surface water samples were analyzed for TDN, TDP, ammonia, SRP, nitrate, nitrate, DOC, iron, manganese and TCO_2. One unfiltered split was collected for TN and TP, and then the syringe was fitted with an MCE filter, which was rinsed with 10 mL of sample water, and splits were collected for dissolved nutrients (NO_2, NO_3, NH_4, and SRP), and total dissolved nitrogen and phosphorus (TDN/TDP). The second syringe was fitted with a PES filter, which was rinsed with 10mL of sample water, and splits collected for DOC, dissolved metals (iron and manganese), and TCO_2. All samples were placed in the dark on ice while in the field. Total carbon dioxide samples were analyzed in the laboratory within 6 hours of collection. The remaining samples were frozen upon return to the laboratory until analysis within their respective holding times.

After the deployment was completed, surface sediment samples were collected and analyzed for grain size, organic carbon, organic nitrogen, and TP content, and sediment chlorophyll a. Algal biomass and SAV biomass were comprehensively harvested from the chamber whenever applicable, sorted, cleaned and weighed.

Ambient water samples were collected by SCCWRP during both the benthic chamber deployment (surface waters) and the pore water peeper extraction (bottom waters). The protocol for sampling and processing was the same as given above for the transect sampling (Section 2.3.1).

During the first two index periods (winter and spring), the benthic flux chambers were placed in a similar location, near the thalweg. However, a result of the scour of the sediment bed after the spring index was that the thalweg was composed primarily of clay and gravel, which made it impossible to redeploy the chambers and pore water peepers in this area. As a result the chambers were moved up to a submerged and sandy berm area that was not eroded due to the presence of a rock wall and the peepers were moved to a position near the opposite bank from the chambers in deeper water (to prevent vandalization) and upstream slightly. The summer and fall benthic chambers were maintained at the new location, but the fall peepers were returned to their winter/spring location.

3.2.1.2 Benthic Infauna.

Benthic infauna cores (5 cm diameter, 10 cm deep) were collected from each benthic flux chamber following deployment in each index period. Individuals were identified and counted by genus and extrapolated to estimate the number of infauna of each genus in the top 10 cm of each square meter of subtidal sediment.

3.2.2 Analytical Methods

Analytical methods for nutrients, TCO2, trace metals, and chlorophyll a are identical to those given in Section 2.2.2.

3.2.3 Data Analysis

3.2.3.1 In Situ Benthic Flux

Flux rates (F) for each constituent (dissolved nutrients, metals, TCO_2, and O_2) are calculated from the chamber height (h) and the change in constituent concentration within the chamber over time (dC/dt):

$$F = h * (dC/dt). \quad \textbf{Eq. 3.1.}$$

Concentration versus time was platted as a linear gradient using all data that passed a quality assurance check. Use of the linear portion of the incubation curve assumes that the flux of a constituent is constant during the incubation interval (Figure 3.1).

3.2.3.2 Diffusive Flux

Instantaneous diffusive-flux rates were calculated for each species of nutrient using Fick's law given in Equation 3.2.:

$$J = -\phi * D_{aq} * \theta^{-2} * (dC/dz) \quad \textbf{Eq. 3.2.}$$

where J is the rate of flux of species (mol m^{-2} s^{-1}), Φ is the porosity (dimensionless), D_{aq} is the aqueous diffusion coefficient, θ is the tortuosity, and dC/dz is the change in pore water concentration (dC) over the distance from the overlying water to the sediments (dz). θ^{-2} was estimated from Boudreau's law (Boudreau 1997) given in Equation 3.3.:

$$\theta^{-2} = \frac{1}{(1-ln(\phi^2))} \quad \textbf{Eq. 3.3.}$$

D_{aq} for each nutrient species were obtained from Boudreau (1997) and are given in Table 3.1 below. The constant selected was that closest to the ambient water temperature at time of field sampling:

Table 3.1. Aqueous diffusion coefficients (D_{aq}) for each nutrient species by temperature.

Species	10 °C	15 °C	20 °C	25 °C
NO_3^-	1.26 E -09	1.44 E -09	1.62 E -09	1.79 E -09
NH_4^+	1.45 E -09	1.68 E -09	1.90 E -09	2.12 E -09
HPO_4^{-2}	4.75 E -10	5.56 E -10	6.37 E -10	7.16 E -10
Lactate (proxy for DON and DOP)	6.44 E -10	7.54 E -10	8.64 E -10	9.72 E -10

Diffusive flux rates were predicted using the following assumptions:

- Exchange between the sediments and surface waters occur at steady state;
- Advective transport processes in Loma Alta Slough (groundwater, pumping from tidal currents, and bioturbation) are minor relative to diffusive transport; and
- Chemical or biological processes that can modify chemical fluxes at the sediment water interface (O_2 content, benthic diatoms, sediment redox chemistry, etc.) have a negligible impact relative to diffusion on exchange rates.

3.3 Results

3.3.1 Seasonal Trends and Factors Influencing Dissolved Oxygen and Carbon Dioxide Fluxes.

Loma Alta Slough sediments showed a net release of TCO2 and a net uptake of O2 during the winter index period, indicating that the sediments were net heterotrophic (respiration exceeds primary production). During the spring index period, the net fluxes of TCO2 and O2 yielded a small net release of TCO2 and O2. The ratio of TCO2:O2, which at 1.3:1 is indicative of aerobic decomposition of organic matter, was 0.04:1 during this period, indicative of a dominance of autotrophic processes. During summer and fall index periods, when the ocean inlet was closed, the Slough showed strong but highly variable net uptake of TCO2 and production of O2, indicating that the system was net autotrophic during this period. Dark O2 fluxes were greatest in the fall and winter, indicating enhanced rates of respiration during these periods.

Productivity at the sediment/water interface can be estimated from the fluxes of TCO2 and O2 as carbon fixation and gross primary productivity (GPP) respectively. Carbon fixation is a measure of the amount of inorganic carbon (carbon dioxide) converted to autotrophic biomass and is calculated from the difference between light (with photosynthesis) and dark (without photosynthesis) TCO2 fluxes:

$$\text{Carbon Fixation} = \text{Flux TCO2}_{light} - \text{Flux TCO2}_{dark}$$

Gross Primary Productivity is the rate at which primary producers capture and store chemical energy as biomass and can be calculated from the difference between light (with photosynthesis) and dark (without photosynthesis) O2 fluxes:

$$\text{GPP} = \text{Flux O2}_{light} - \text{Flux O2}_{dark}$$

Carbon fixation ranged from 30-60 mmol C $m^{-}2$ d^{-1} during the winter and spring. Rates of gross primary productivity (GPP) during these index periods were similar in magnitude to carbon fixation (20-58 mmol O2 $m^{-}2$ d^{-1}). During the summer and fall, coincident with the highest observed biomass in the slough (Chapter 2), C fixation rates were highly variable, ranging from 45 – 165 mmol C $m^{-}2$ d^{-1}. and GPP rates were extremely high during these periods, ranging from 140-400 mmol O2 $m^{-}2$ d^{-1}. Of the co-factors measured, temperature, salinity, pH and macroalgae had significant correlations with TCO_2 flux; none of the measured factors were significantly correlated with DO flux (Table 3.2).

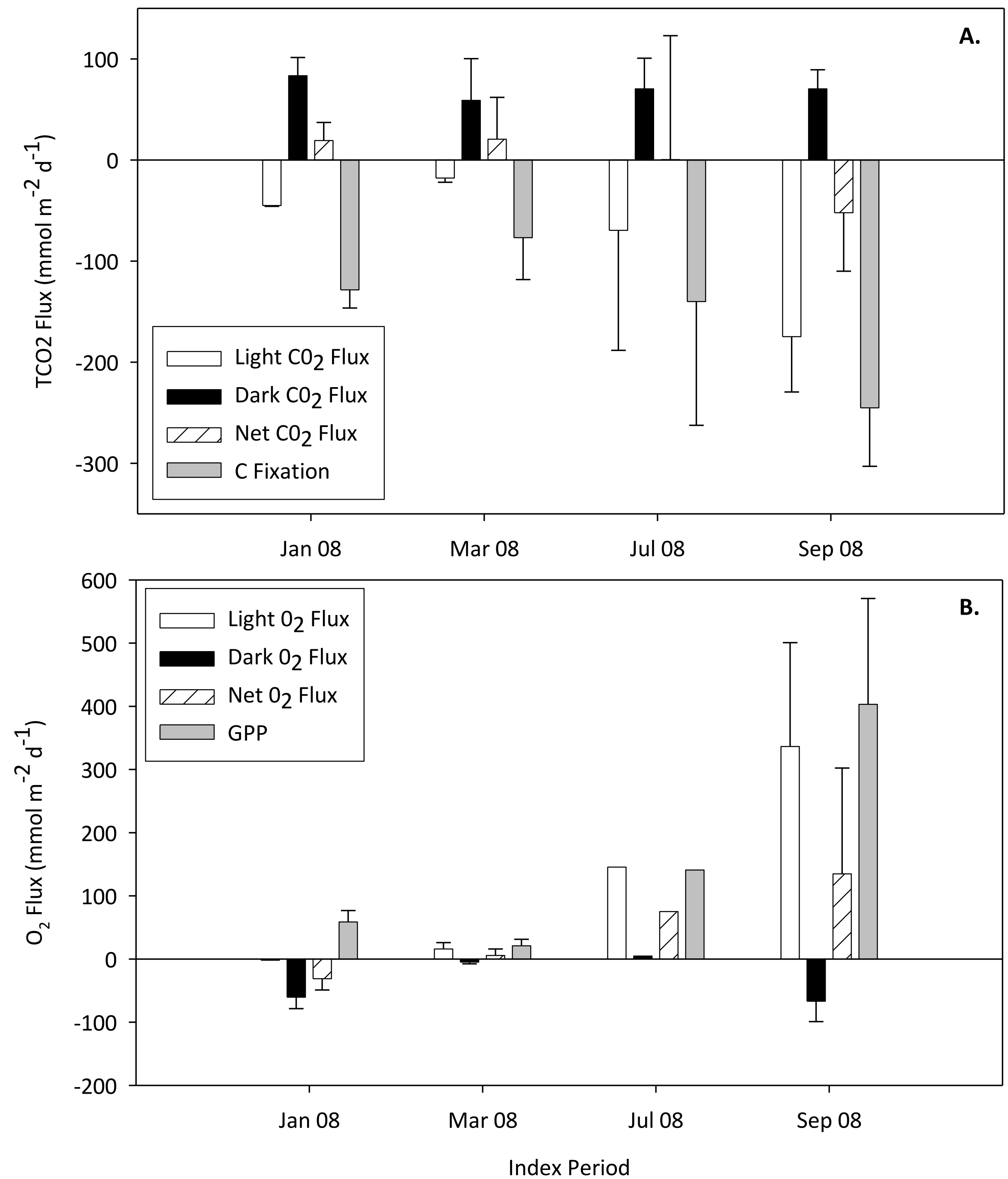


Figure 3.5. Light (white bands), dark (black bands), net (white hashed band; 24 hr average of light and dark) A.) TCO2 fluxes and estimated C fixation (grey bands;) and B.) O2 fluxes and Gross Primary Productivity (GPP). Error bars represent the standard deviation between replicates.

Table 3.2. Spearman's Rank Correlation Between DO, TCO2 and factors known to influence benthic flux (Temperature – Temp, Salinity (Sal), pH, sediment C:N Ratio, total infaunal abundance, sediment % fines, benthic chl a and macroalgal biomass within chambers). Table gives correlation (r) and p-value (for α=0.05).

Variable	DO	TCO_2	Temp	Sal	pH	C:N Ratio	Tot. Infauna Abund.	% Fines	Benthic Chla	Macro algae
TCO2 Corr. (r)	**-0.54**	1	**-0.69**	**0.56**	**0.81**	0.21	0.02	0.28	0.01	**-0.66**
TCO2 (p-val)	**0.03**		**0.01**	**0.04**	**0.007**	0.42	0.93	0.28	0.97	**0.004**
O2 Corr.(r)	1	**-0.54**	0.37	-0.09	-0.17	0.11	0.23	0.10	-0.37	0.48
O2 (p-val)		**0.03**	0.21	0.74	0.57	0.72	0.43	0.73	0.21	0.09

Continuous monitoring data in the slough was collected at two sites: the "segment" site (Figure 3.6 A.), upstream of the railroad trestle and the "ocean-inlet" site (Figure 3.6 B.), just upstream of the S. Pacific Street Bridge. The ocean inlet site was physically closer to the chamber deployment area. Both sites show similar patterns in when hypoxia develops; however hypoxic periods at the inlet are generally of longer duration compared to the segment site. Periods of low dissolved oxygen concentration (<5 mg/L) commenced in the spring, with fluctuations occurring from 0 to 18 mg DO L^{-1}, with the lowest DO concentrations occurring in the early morning and the highest concentrations during the evening at the ocean-inlet site (the continuous monitoring site closest to the chamber deployments). Hypoxia at the segment site seems to be related to tidal changes at this location with low DO concentrations coincident with the ebbing tide. At the ocean inlet, hypoxic periods extend for most of the diurnal cycle with the exception of the late afternoon flood tide when DO levels are typically greater than 8 mg/L. The benthic chamber O2 and TCO2 data show a diurnal pattern during all index periods where the dark chamber O2 flux (representing night) is near zero or into the sediments and a light chamber O2 flux (representing day) is near zero or out of the sediments, and vice versa for TCO2. Such fluxes would be expected to contribute to low DO levels in ambient waters during the night and higher DO levels during the day. Based on observed fluxes, this influence would be expected to be mild during the winter and spring and much stronger during the summer and fall. Indeed, these fluxes may contribute to the low (<5 mg/L) DO levels at night and early morning observed at the ocean inlet sonde site from mid-March through May, but does not account for the continual hypoxia observed in the summer and fall, when there are no strong diurnal patterns emerging until late October, when the ocean inlet was open again [*MACTEC*, 2009].

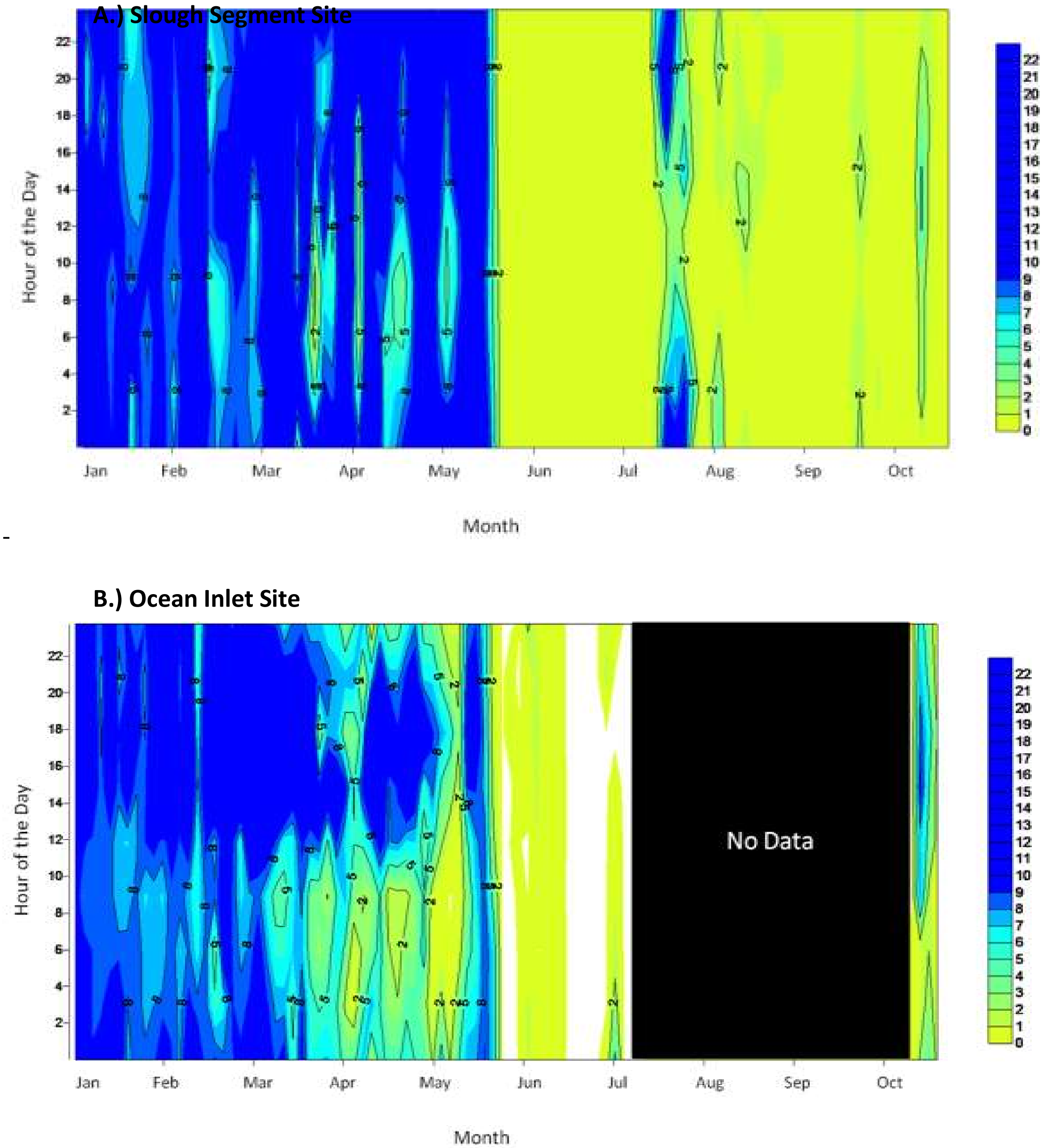


Figure 3.6. Dissolved oxygen in Loma Alta Slough at the: A.) Slough Segment Site and B.) Ocean Inlet Site, as a function of month and time of day. 2, 5, and 10 mg L^{-1} contour lines are shown (data from *[*MACTEC*, 2009]*).

3.3.2 Seasonal Trends and Factors Influencing Nitrogen Fluxes

Fluxes of nitrogen (ammonia, nitrate and DON) exhibited high variability. No significant differences were found based on chamber light regime for any of the three forms (p-value>0.05; Figure 3.7, top two panels) and only nitrate and ammonia were significantly different by index period. Of the total dissolved nitrogen flux, approximately 5% was comprised of dissolved inorganic nitrogen species (nitrate, nitrite, and ammonium). Nitrite was typically non-detectable.

Nitrate fluxes generally tended to be into the sediments for index periods except the winter. Nitrate fluxes during the spring and summer index periods were nearly non-detectable. Fluxes during the fall index period were more strongly negative, with a larger negative flux during light (-6.7±2.0 mmol N-NO3 $m^{-2}d^{-1}$) versus dark conditions (-2.7±0.5 mmol N-NO3 m^{-2} d^{-1}). Nitrate fluxes during the winter index period were on average positive for both light and dark (3-6 mmol N-NO3 m^{-2} d^{-1}).

Ammonium followed a similar pattern to nitrate (Figure 3.6, first panel). During the winter index period, average ammonium fluxes were typically positive (out of the sediments) in both light and dark chambers (5-13 mmol NH4-N m^{-2} d^{-1}). Ammonium fluxes in both light and dark chambers were nearly non-detectable during spring and summer. Fall index period fluxes were negative in both light and dark chambers, ranging from -2 to -3 mmol NH4-N m^{-2} d^{-1}. DON fluxes were generally positive for all index periods, with the largest fluxes occurring in the winter period (41-42 mmol DON m^{-2} d^{-1}) and the lowest fluxes occurring during the summer index period (0.3 to 3 mmol DON m^{-2} d^{-1}). Of the co-factors measured that could affect nitrate and ammonia flux, only salinity was positively correlated with both these forms (r=-0.5, p-value<0.05), while temperature was negatively correlated (r=-0.7 to 0.8, p-value<0.05). None of the measured co-factors were significantly correlated with DON flux.

3.3.3 Seasonal Trends and Factors Influencing Phosphorus Fluxes

DOP and SRP fluxes were highly variable and not significantly different by index period or chamber light regime (p-value <0.05, Figure 3.7, third panel). On average, 99% of TDP flux was DOP. In general, the largest DOP and SRP fluxes were during the winter index period. Mean DOP fluxes ranged from a high of 1.9 mmol m^{-2} d^{-1} to -1.0 mmol m^{-2} d^{-1}. SRP ranged from 0.5 mmol m^{-2} d^{-1}, measured in the summer, to 0.07 mmol m^{-2} d^{-1}, with many individual flux measures at or below detection levels in the spring and summer. Of the co-factors measured (Table 3.2), the only significant correlation was between SRP flux and Mn flux (r=-0.50, p-value = 0.04). DOP flux was not significantly correlated with any of the co-factors.

3.3.4 Seasonal Trends and Factors Influencing Organic Carbon Fluxes.

As with N and P species, DOC fluxes were highly variable among the benthic chambers during each index period and mean fluxes among replicate chambers were typically not significantly different from zero, with the exception of the spring sampling period (Figure 3.7, second panel). DOC values ranged from a high of 440 mmol m^{-2} d^{-1} measured during the spring to a low of -700 mmol m^{-2} d^{-1} measured fall. There were no significant differences by index period nor by chamber light regime (p-value>0.05).

Of those factors measured which could impact DOC flux, total infaunal abundance was significantly positively correlated to DOC flux (r=+0.66, p-value<0.05).

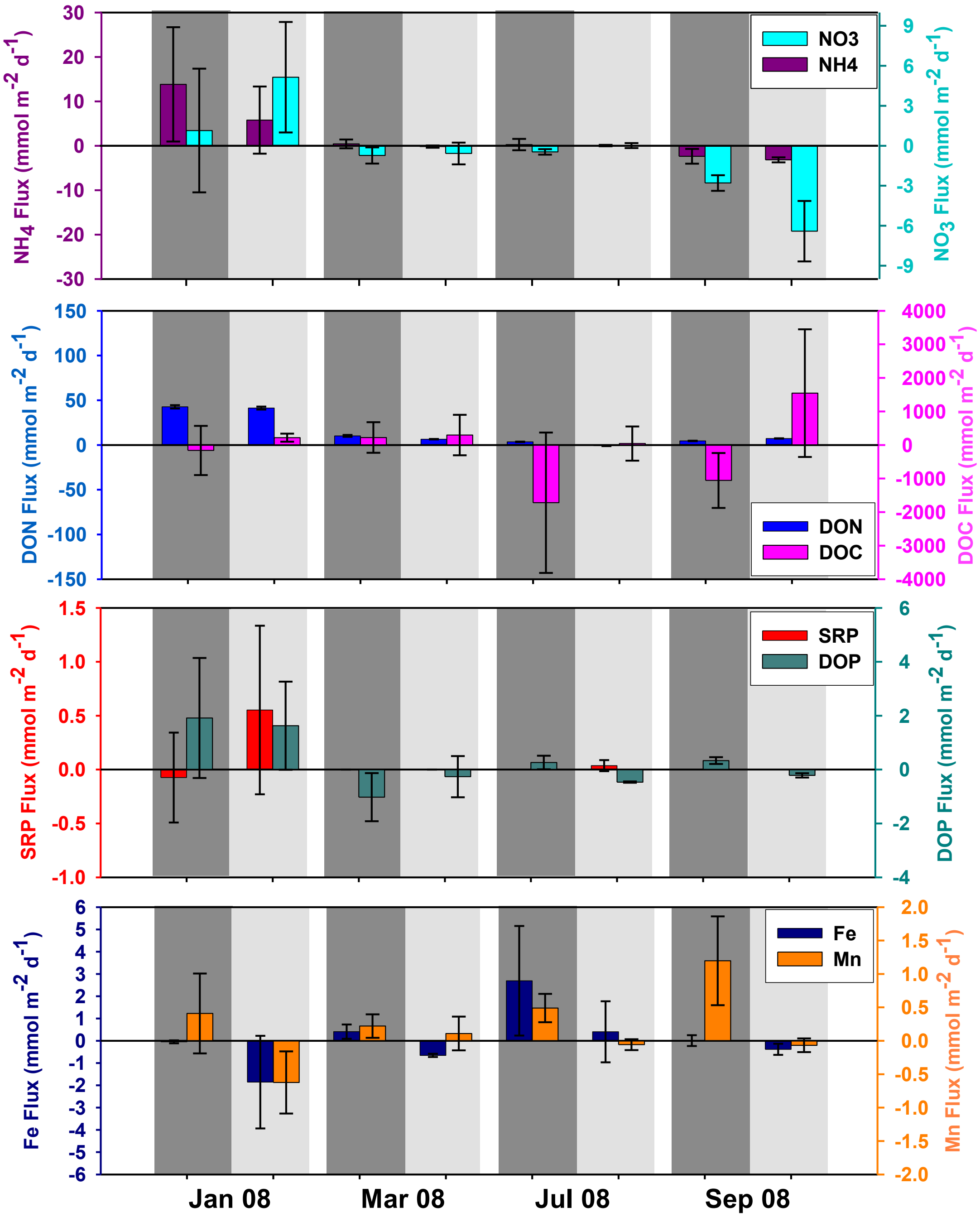


Figure 3.7. Benthic fluxes for dark (dark grey bands) and light (light grey bands) for each of the index periods. Error bars represent the standard deviation between replicate chambers.

3.3.5 Seasonal Trends and Factors Influencing Trace Metal Fluxes.

Trace metal fluxes (dissolved iron and manganese) were also highly variable (Figure 3.7, bottom panel). Iron fluxes ranged from a high of 2.7 mmol m^{-2} d^{-1}, measured during the summer to -1.8 mmol m^{-2} d^{-1}, measured during the winter, but mean values were not significantly different by index period nor by light chamber regime (p-value >0.05). Mn fluxes were not significantly different by index period (p-value>0.05), but dark Mn fluxes were on average generally twice as great as light fluxes (p-value<0.05). These differences were most noticeable during the fall and winter index periods.

Of those factors measured which could impact trace metal flux, Fe flux was significantly correlated with pH (-0.60, p-value=0.02).

3.3.6 Benthic Infaunal Diversity and Abundance

In Loma Alta Slough, the benthic infauna community appears to be low in diversity, dominated by polychaetes with low abundances (0 – 3000 individuals m^{-2}) in both the winter and spring when the Slough was fully tidal (Figure 3.8). Few large burrowing infauna were present, suggesting that the depth of bioturbation in this system is limited. The lack of infauna in the January index period may have been caused by storm event, which could have scoured out the creek and depleted infaunal populations. Infaunal abundances peak in March, but then decline during the July and September index periods, coincident with oligohaline salinities, peak temperatures and macroalgal biomass, and chronic hypoxia.

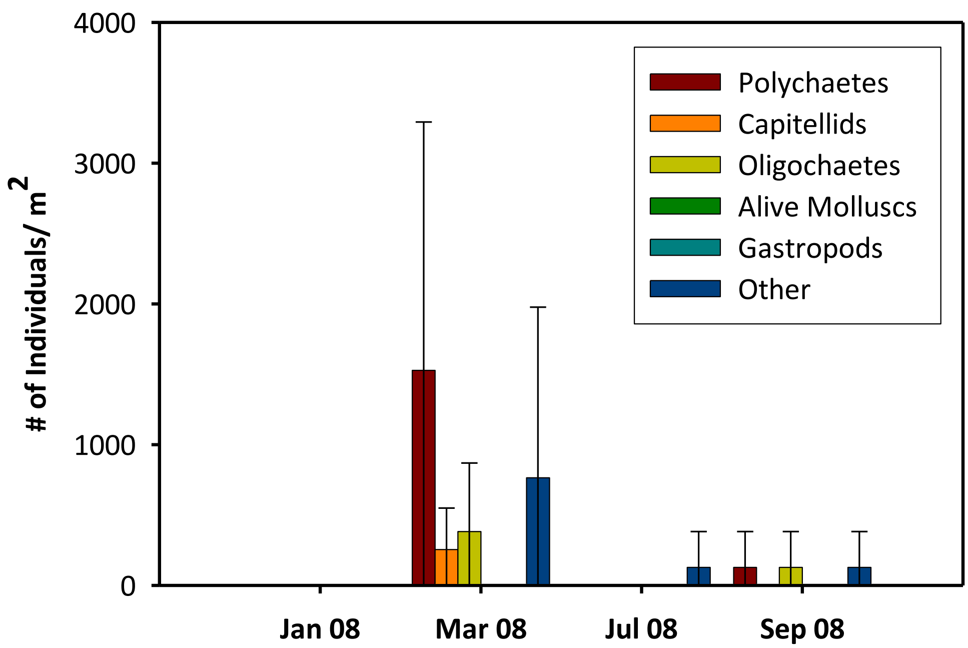


Figure 3.8. Mean and standard deviation of the abundance of infauna taxa in Loma Alta Slough benthic chambers by index period.

3.3.7 Relationship between In Situ and Diffusive Fluxes

Of the constituents modeled, SRP diffusive fluxes were the only estimates that can be considered predictive of *in situ* chamber fluxes, although diffusive fluxes tended to over-predict chamber fluxes by a factor of 20 (Tables 3.3 and 3.4). Diffusive flux estimates for other constituents were not significant predictors of *in situ* fluxes.

Table 3.3. Predicted Diffusive Fluxes by index period for each constituent of interest.

Index Period	Predicted Diffusive Fluxes (mmol m^{-2} d^{-1})					
	NH4	NO3	DON	SRP	DOP	DOC
Winter	0.43	-0.05	-3.62E-02	1.15E-02	-5.93E-04	-0.68
Spring	0.10	0.01	-8.60E-02	-1.90E-04	-2.68E-04	8.26
Summer	0.48	0.08	-4.60E-02	4.48E-03	1.76E-04	-0.33
Fall	0.29	-0.01	-2.05E-01	7.20E-04	1.49E-03	0.80

Table 3.4. Summary of linear regression relationship between predicted diffusive fluxes and in situ chamber flux data.

Constituent	In Situ Flux Data Used For Regression	Regression Equation	R^2 and Pr>F
NH4	Dark Chambers	$NH4_{IS}$ = 2.6+17.5*$NH4_{DF}$	R^2 = 0.17, Pr>F : 0.60
	Light Chambers	$NH4_{IS}$ =-2.3 + 9.0*$NH4_{DF}$	R^2 = 0.17 Pr>F : 0.58
	All	$NH4_{IS}$ =-2.4 + 13.3*$NH4_{DF}$	R^2 = 0.17, Pr>F : 0.59
NO3	Dark Chambers	$NO3_{IS}$ =-1.8 +21.5*$NO3_{DF}$	R^2 = 0.26, Pr>F : 0.41
	Light Chambers	$NO3_{IS}$ =-3.7 +58.9*$NO3_{DF}$	R^2 = 0.22, Pr>F : 0.43
	All	$NO3_{IS}$ =-2.8 + 40.23*$NO3_{DF}$	R^2 = 0.23, Pr>F : 0.42
DON	Dark Chambers	DON_{IS} = 26.4 + 119.9*DON_{DF}	R^2 = 0.25, Pr>F : 0.49
	Light Chambers	DON_{IS} = 21.5 + 85.8*DON_{DF}	R^2 = 0.12, Pr>F : 0.64
	All	DON_{IS} = 24.0 + 102*DON_{DF}	R^2 = 0.18, Pr>F : 0.57
SRP	Dark Chambers	SRP_{IS} = - 3E-36 + 3E-31*SRP_{DF}	R^2 = 0.02, Pr>F : 0.89
	Light Chambers	SRP_{IS} =-0.05 +48.1 * SRP_{DF}	**R^2 = 0.84, Pr>F : 0.05**
	All	SRP_{IS} =-0.02 + 20.9* SRP_{DF}	**R^2 = 0.855, Pr>F : 0.04**
DOP	Dark Chambers	DOP_{IS} = -0.43 +610*DOP_{DF}	R^2 = 0.53, Pr>F : 0.48
	Light Chambers	DOP_{IS} = 0.34 +64.5*DOP_{DF}	R^2 = 0.19, Pr>F : 070
	All	DOP_{IS} = -0.38 +337*DOP_{DF}	R^2 = 0.70, Pr>F : 0.37

3.4 Discussion

3.4.1 Significance of Rates of Benthic O2 and TCO2 Flux in Loma Alta Slough.

Eutrophication produces excess organic matter that fuels the development of hypoxia (i.e. low surface water DO concentration) as the organic matter is respired [*Diaz*, 2001]. When the supply of oxygen from the surface waters is cut off (via stratification), or the consumption of oxygen exceeds the rate of resupply (decomposition of excessive amounts of organic matter exceeds diffusion/mixing of oxygen to bottom waters), oxygen concentrations can decline below the limit for survival and reproduction of organisms [*Borsuk, et al.*, 2001; *Diaz*, 2001; *Stanley and Nixon*, 1992]. The consequence of this is often a cascade of effects including loss of habitat and biological diversity, development of foul odors and taste, and altered food webs [*Sutula, et al.*, 2007]. Dissolved oxygen levels that fall below 5 mg/L can be a stressor to aquatic life and levels below 1-2 mg/L for more than a few hours can be lethal to both fish and benthic invertebrates [*USEPA*, 2000; 2003]. The basin plan water quality objective for Loma Alta Slough states that DO shall be greater than or equal to 5 mg/L.

Shallow estuaries such as Loma Alta Slough can develop hypoxia typically through one of two main processes: 1) as episodic events driven by primary producer blooms (net autotrophic- greater production than decomposition) and decomposition (net heterotrophic- greater decomposition than production) [*McGlathery, et al.*, 2007] or 2) during density-driven stratification which develops during intermittent closure to tidal exchange when the estuaries "trap salt" and preclude diffusion and mixing of oxygen to bottom waters [*Largier, et al.*, 1991]. In Loma Alta Slough, both of these processes appear to contribute to the observed seasonal hypoxia. Loma Alta Slough was mildly net heterotrophic during the winter index period, indicating that the Slough at this time was decomposing more organic matter than producing it at the time of sampling [*Eyre and Ferguson*, 2002a; b]. By summer, the continuous data show that hypoxia was chronic, with extended periods below 2 mg L^{-1} from late May through October, when the ocean inlet closed, water column temperatures were highest and macroalgae exhibited the greatest biomass. In contrast, net benthic O2 and TCO2 data suggest that during the summer and fall time period, the Slough appears to be net autotrophic with extremely high rates of C-fixation and GPP. Based on these data, one would expect to see, at minimum, large diurnal swings in surface water DO concentration. The lack of diurnal variability in DO concentrations, particularly during the May – July period, suggesting that Loma Alta Slough may have become stratified when the ocean inlet closed, trapping a wedge of higher salinity water under freshwater.

It should be noted that both the continuous monitoring and benthic flux datasets captured conditions at incomparable locations within the Slough. Because the data sonde is located in the deeper part of the Slough where waters were likely to be stratified, and the chambers were set in shallower water that was more likely to be susceptible to mixing (and the fact that the installation of the chambers was likely to mix the water column) the observed discrepancies between the datasets are not unexpected. It was not possible to set the chambers in the channel bed adjacent to the sonde because conditions were not ideal for deployment: the sediment bed had eroded away to gravel as a conseqeuence of construction activities and inlet closure had made the water column too deep. Furthermore, benthic flux incubations were generally conducted in the late morning during peak periods of photosynthesis and generally not of sufficient duration to fully capture "dark conditions", thus underestimating dark O2 and TCO2 fluxes.

Continuous DO data is likely overestimating the extent of hypoxia if the Slough was stratified during inlet closure because the data was only collected at a single depth at the bottom of the water column.

Interestingly, comparison of oxygen and TCO2 fluxes with *in situ* measurements in other systems indicate that Loma Alta Slough fluxes are generally lower than those found in most eutrophic estuaries (Table 3.5). High net TCO2 fluxes are typically driven by respiration of accumulated dead or decaying biomass (organic matter accumulation) in the sediments rather than respiration of live biomass. While Loma Alta Slough had among the highest biomass of macroalgae documented, this biomass does not appear to accumulate in Slough sediments from season to season. Surficial sediments have low C:N values, indicating sediments enriched with algal carbon, but these values increase dramatically with depth, indicating that organic matter burial and accumulation is not occurring with depth. During our sampling year, this sediment scour may have been stronger than in other years due to the presence of the earthen dam near the railroad construction (see Appendix 2). This restriction coupled with an open Slough mouth would have resulted in tidal scour of the slough channel. The only place that did not scour was the sandy "bench" where the chambers were placed during the summer and fall because the bench was protected by a submerged rock wall. Whether this scour would occur in the absence of the dam is unknown, though some degree of storm driven scour would be expected. In fluvially-dominated river mouth estuaries such as Loma Alta Slough, this lack of interannual organic matter accumulation would make them less susceptible to eutrophication [*Bate, et al.*, 2004; *Paerl, et al.*, 1998; *Schubel and Kennedy*, 1984].

Table 3.5. Comparison of fluxes from Loma Alta Slough to other estuarine environments

Site	O_2	TCO_2	SRP	NH_4	NO_3	Mn	Fe
Loma Alta Slough (this study)	-62.9 ± 36.8	104.4 ± 66.8	-0.17 ± 0.17	0.98 ± 1.49	-0.18 ± 0.47	-0.24 ± 0.45	0.02 ± 1.2
Shallow SE Australian Lagoons (Eyre and Ferguson 2002)	-50 to 0	10 to 100		-3.4 to 0.3	0 to -60		
Hog Island Bay (Tyler et al. 2003)	-0.003 to +0.012			-0.33 to + 0.42	-0.12 to +0.009		
Shallow NE Australian Lagoons (Ferguson et al 2004)				-0.2±0.3	-0.4 ± 0.3		
Newport Bay [*Sutula, et al.*, 2006]	-43 ± 20	107 ± 81	0.36 ± 0.52	5.7 ± 2.7	-3.0 ± 5.3	0.38 ±0.35	30±100
Los Angeles Harbor (Berelson unpublished)	-18.9 ± 6.3	39 ± 29	0.33 ± 0.40	3.9 ± 2.9	-0.19 ± 0.18	0.25± 0.13	-4.0±3.4
San Francisco Bay [*Hammond, et al.*, 1985]	-30 ± 7	24 ± 8	0.10 ± 0.50	1.1 ± 0.1	-0.5 ± 0.6		
Monterey Bay [*Berelson, et al.*, 2003]	-9.1 ± 2.4	9.9 ± 2.7	0.113 ± 0.073	0.56 ± 0.24	-0.57 ± 0.48	0.010± 0.006	5.2±3.2

Chesapeake Bay [*Callender and Hammond*, 1982; *Cowan and Boynton*, 1996]	-49		0.8	10.2	-2.9 – 0.2		
San Quentin Bay, Baja CA [*Ibarra-Obando, et al.*, 2004]	-23.4 ± 10.7	31 ± 22.9	0.114 ± 0.140	2.15 ± 1.39			
Tomales Bay [*Dollar, et al.*, 1991]	-9.37 ± 9.56	20.7 ± 24.4	0.24 ± 0.40	1.96 ± 2.39	-0.01 ± 0.17		
Plum Island Sound [*Hopkinson, et al.*, 1999]	-33 – -170	23 – 167	-0.25 – 1.5	4.8 – 21.2			

3.4.2 Seasonal Patterns of Nutrient Flux and Benthic Metabolism in Loma Alta Slough.

Estuaries, at the terminus of watersheds, are typically subject to eutrophication due to high inputs of anthropogenic nutrient loads and hydromodification. Shallow coastal lagoons with natural or anthropogenic muting of the tidal regime are particularly susceptible, because restricted exchange increases the residence time of water and thus the amount of time nutrients are available for uptake by primary producers [*Sundbäck and McGlathery*, 2005]. Primary production in these tidally restricted estuaries can be fueled by either "new" nutrients entering the system from the watershed or from "recycled" nutrients from the remineralization of particulate and dissolved organic matter. As such, the seasonality of ocean inlet closure played a large role in regulating primary producer biomass and benthic metabolism in Loma Alta Slough. These factors in turn drove the seasonal variation in the magnitude and direction of benthic fluxes observed in this system.

Peak flows during storm events in the winter index period would be expected to provide a subsidy of nutrients and particle-bound nutrients as well as an environment dominated by physical mixing of the surface waters and sediments [*Correll, et al.*, 1999; *Paerl*, 2006; *Smith, et al.*, 1996]. As evidence of this, surface sediments during this period contained low percent fines. Denitrification rates, though in general low, were at their peak during this period (5.2 µmol m^{-2} hr^{-1}, T. Kane, UCLA Ph.D. Dissertation). Ammonia, nitrate, and SRP fluxes were the highest of any index period and for the most part, consistently out of the sediment, and primary producer biomass was low, indicating that fluxes were likely controlled to a greater extent by sediment organic matter decomposition and physical transport processes rather than biological uptake. Sediment TCO2 and O2 fluxes corroborate these data, showing a system that is mildly net heterotrophic (consuming O2 and producing TCO2; [*Eyre and Ferguson*, 2002b; *Sutula, et al.*, 2006]).

During the spring sampling period, the Slough was still open to tidal exchange and therefore well flushed, but with less freshwater flow, though as noted above, the presence of the earthen dam at the railroad trestle may have resulted in the start of tidal scouring of the sediment bed during this period. Filamentous macroalgae began to be established in a benthic form. Surface sediments showed moderate percent fines (~40%) and low C:N ratios, indicating enrichment with algal carbon, but sediments were highly coarse with depth with little %OC indicating little sedimentary organic matter, thus deeper sediments cannot act as a major source of recycled nutrients for algal uptake. Sediment O2 light and dark fluxes were small and nearly balanced, with a small positive O2 flux measured over the chamber deployment period, indicating very slight autotrophy. Ammonia fluxes were near non-detect, while nitrate and SRP fluxes were small and negative, indicating uptake. Since denitrification rates were non-detectable during this period, it's likely that these small in fluxes of nitrate and SRP represent algal uptake. Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because these primary producers can typically outcompete bacteria for available N [*Dalsgaard*, 2003; *McGlathery, et al.*, 2007]. Benthic algae can act to decouple nutrient turnover in the sediments from the overlying water column by acting as a "filter" for nutrient efflux from the sediments, at times completely intercepting nutrient fluxes across the sediment-water interface [*McGlathery, et al.*, 2004]. Low fluxes of dissolved inorganic nitrogen compared to other eutrophic systems (Table 3.5), coupled with balanced TCO2 and O2 fluxes, are an indication that this phenomenon may be occurring.

During the summer index period, macroalgae continued to be the dominant primary producer, but biomass peaked during this period at 364 g dry wt m^{-2}. Macraolgae have been shown to control the biomass of other primary producer communities, including benthic microalgae, because of a competitive advantage in nutrient uptake rate [*Fong, et al.*, 2003; *Fong, et al.*, 1993]. Surface water DIN was extremely low and DIN and SRP fluxes near non-detect. Previous studies have suggested that macroalgae can drive an increased efflux of dissolved inorganic nutrients from sediments by drawing down surface water concentration, thereby increasing the concentration gradient [*Sutula, et al.*, 2006; *Tyler, et al.*, 2003], though these effluxes would presumably not be measured by benthic chambers. As these nutrients are trapped as biomass, macroalgae become an effective mechanism to retain and recycle nutrients within an estuary, diverting loss from denitrification or tidal outflow (though no open tidal exchange occurred during this index period due to inlet closure). This concept is supported by non-detectable rates of denitrification in the Slough during this index period.

The extremely large accumulation of biomass during the summer also appears to control the magnitude of TCO2, O2 and nutrient fluxes during this index period. Though as noted previously, interpretation of data taken during this the summer index period is hampered because of the need to move the location of the chambers. Large differences in the magnitude and direction of TCO2 and O2 flux were observed between light and dark incubations and TCO2 and O2 fluxes were highly correlated, indicating that live biomass was likely driving these fluxes to a greater extent than sediment metabolism. Porewater sulfide reached peak concentrations in surficial sediments (0-4 cm) and coincided with high ammonia, SRP and declining nitrate with depth, indicating the predominance of sulfate reduction and dissimilatory nitrate reduction pathways. Benthic infaunal abundance and diversity declined from spring index period levels, possibly due the relocation in the chambers but could also be attributed to the dramatic decline in salinity, chronic nighttime hypoxia and elevated sulfide concentrations. This decline would result in reduced bioirrigation of the sediments and less oxygen penetration, further exacerbating hypoxic conditions.

During the fall, the dominant primary producer community shifted from filamentous macroalgae to cyanobacteria mats, with a lower total biomass (24 g C m^{-2}) than the peak observed in July. As with the summer index period, the live cyanobacterial biomass rather than sediment metabolism appeared to drive the light and dark O2 and TCO2 fluxes. Chronic hypoxia continued during this period and benthic infaunal abundance and diversity was at its lowest point. DON fluxes were slightly positive and water column TN was at its highest (despite low DIN), indicating recycling of algal N to surface waters. Ammonia and nitrate fluxes were low, but negative, indicating measurable uptake of slightly higher concentrations of these constituents in the surface waters. Denitrification was very low, but detectable (0.2 µmol m^{-2} hr^{-1}). Seasonal scour of the sediment bed seems to have stripped Loma Alta Slough of accumulated sedimentary organic matter and thus, sediment remineralization of nutrients and subsequent efflux into the water column is not the main source of nutrients driving primary production in Loma Alta Slough. During the times of peak macroalgal biomass, inorganic N and P fluxes are small, particularly compared to watershed sources. Thus, eutrophication and co-occurring hypoxia in Loma Alta Slough seems to be driven primarily by “new” nutrients rather than “recycled” nutrient efflux from the sediments.

4 Loma Alta Slough Nitrogen and Phosphorus Budgets

4.1 Introduction

Nutrient cycling is one of the critical functions of estuaries [*Day, et al.*, 1989]. The net balance of nutrient sources, transformations and losses from the estuary dictate the biomass and community structure of primary producers and bacteria, which forms the foundation for the estuarine food webs and dictates the habitat quality for benthic and pelagic fauna. One means of evaluating the efficiency of nutrient cycling within an estuary is to estimate its nitrogen and phosphorus budgets [*Sutula, et al.*, 2001]. Budgets are a useful method to assess the relative importance of allochthonous inputs ("new" nutrients) versus internal recycling ("recycled" nutrients) on primary productivity [*Mitsch and Gosselink*, 1993] – the main symptom of eutrophication.

The purpose of this section is to estimate Loma Alta Slough nitrogen and phosphorus sources, losses, and change in storage for those terms which are readily estimated. The estuarine hydrodynamic and water quality models will be used in the future to develop refined nutrient budgets for Loma Alta Slough. However, in the interim, coarse estimates of nutrient budgets can be derived. This information, in conjunction with data estimating the change in storage, can shed light on the efficiency of nutrient cycling and inform potential management actions in Loma Alta Slough.

4.2 Methods

Budgets are estimated by determining the sum of source and loss terms from an estuary during the time period of interest (Figure 4.1). The sum of the source and loss terms, plus the change in "storage" of nutrients within specific compartments within the estuary (e.g. sediments, surface water, primary producers), should be equal to zero (equation 4.1). Table 4.1 gives a summary of all the possible nutrient source, loss, and change in storage terms for an estuary and which of these were measured in Loma Alta Slough.

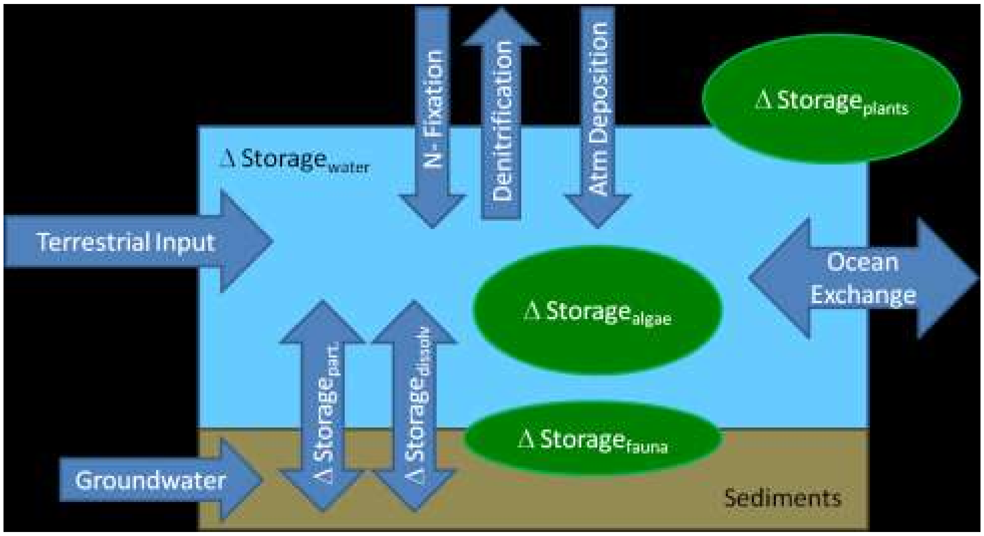


Figure 4.1. Conceptual model for development of budget estimates.

Nutrient sources to Loma Alta Slough include: terrestrial runoff (wet and dry weather from creeks and storm drains), groundwater efflux, atmospheric deposition, tidal surface water inflow, and benthic nitrogen fixation (Table 4.1). Nutrient losses to include: groundwater recharge, tidal surface water outflow, sediment burial, and benthic denitrification. Change in storage includes benthic exchange with surface waters, aquatic primary producer biomass, sediment mass accumulation or loss, and faunal uptake and release.

$$Load_{watershed} \pm Load_{ocean} \pm Load_{groundwater} + \text{Atmospheric Deposition} - \text{Denitrification} + \text{N fixation} - \Delta Storage_{algae} - \Delta Storage_{plants} - \Delta Storage_{fauna} + \Delta Storage_{part} + \Delta Storage_{dissolv} - \Delta Storage_{water} + \text{Residual} = 0 \quad \text{Eq. 4.1}$$

Terrestrial runoff was estimated from wet and dry weather runoff monitoring conducted by MACTEC, Inc. *[2009]*. In 2010, after the study was completed, problems were identified with the dry weather mass emission flow data, which appeared to be overestimating dry weather flows in to Loma Alta Slough. New flow data were collected from June -October 2011, and these flow data were utilized to revise the dry weather terrestrial loads to Loma Alta Slough.

Benthic nitrogen fixation and denitrification were measured during each of the index periods at the segment site (personal communication, T. Kane, UCLA Department of Biological Sciences Doctoral Dissertation). Atmospheric deposition rates were not estimated in this study and no local data were available. Atmospheric deposition rates are estimated from a National Atmospheric Deposition Program site in the San Bernadino Mountains during 2007. Dry deposition for ammonia and nitrate for this site was 2.6 kg ha^{-1} $year^{-1}$ while wet deposition was 1.5 kg ha^{-1} $year^{-1}$. Fewer data are available for atmospheric deposition of phosphorus; data from south Florida indicate total (wet+dry) P fluxes ranging from 0.1 to 0.4 kg/ha/year, with an average of 0.3 kg ha^{-1} $year^{-1}$ [*Ahn and James*, 2001; *Redfield*, 2000]. Typically ratios of dry:wet P deposition are 3:1. These numbers were used to estimate annual atmospheric loads for Loma Alta Slough, but are acknowledged to be highly uncertain. Sediment mass accumulation and loss was estimated from long-term annual deposition rates measured by Louisiana State University (see Chapter 2). These terms were estimated from monitoring data or from literature values for the period of November 1, 2007- October 31, 2008.

Table 4.1. Summary of nutrient budget terms: sources, losses and change in storage.

Budget Term	Nitrogen	Phosphorus
Sources		
Terrestrial Runoff (wet and dry weather)	MACTEC	MACTEC
Groundwater efflux	Unquantified	Unquantified
Atmospheric Deposition	Literature values	Literature values
Tidal surface water inflow	MACTEC[1]	MACTEC
Benthic nitrogen fixation	UCLA Study	N/A
Losses		
Tidal surface water outflow[1]	MACTEC	MACTEC
Grounwater influx	Unquantified	Unquantified
Denitrification	UCLA Study	N/A
Change in Storage		
Benthic exchange of nutrients with surface waters	SCCWRP	SCCWRP
Plant/algal uptake/ release	Residual of Sum of Sources, Losses and Change in Storage Terms	
Sediment deposition/resuspension of particulate nutrients	LSU	LSU
Faunal uptake and release	Assumed negligible	Assumed negligible

Groundwater interactions and the change in storage associated with faunal and emergent vegetation contributions were not quantified. Tidal surface water inflow and outflow were measured by MACTEC, but at a location within the Slough that does not represent concentrations of ocean water entering the Slough. Ocean inlet concentrations and influx were therefore assumed to be negligible for this calculation during open and closed conditions. Table 4.2 presents the literature and assumptions were used to convert primary producer biomass to N and P.

Table 4.2. Literature values for Chla:C and C:N:P ratios of primary producer communities and assumptions to convert biomass to areal estimates of N and P associated with biomass.

Community	Stoichiometry (C:N:P)	Reference
Phytoplankton, assumed 1.5 m water depth	Chl a: C Ratio of 30:1 C:N:P = 106:16:1	[*Cloern, et al.*, 1995], Redfield Ratio [*Anderson and Sarmiento*, 1994; *Redfield*, 1958]
Cyanobacteria mats	50% C by dry wt	Study data

[1] Tidal surface water inflow and outflow were measured by MACTEC, but at a location within the Slough that does not represent concentrations of ocean water entering the Slough. Ocean inlet concentrations and infux were therefore assumed to be negligible for this calculation.

	C:N:P = 550:30:1	[*Atkinson and Smith*, 1983]
Macroalgae	22% C by dry wt C:N:P = 80:5:1	Study data, [*Eyre and McKee*, 2002]
Benthic microalgae	Chl a: C ratio of 30:1 C:N:P = 90:15:1	[*Sundbäck and McGlathery*, 2005] [*Eyre and McKee*, 2002]

4.3 Results and Discussion

Coarse seasonal nitrogen and phosphorus budgets for Loma Alta Slough provide order of magnitude estimates of nutrients available for primary productivity and can be used interpret the importance of external loads versus internal biological recycling in supporting it.

Overall, budget estimates show a net annual TN export from the Slough of 6730 kg (Table 4.3). The pattern of net export is consistent for all index periods. Annually, wet weather TN loads were 90% of the total terrestrial loads to the Slough and thus far more important than dry weather loads. Peak dry season export occurred in the spring and summer (209 and 309 kg TN respectively).

Table 4.3. Comparison of estimated nitrogen source, loss and change in storage terms in Loma Alta Slough during dry weather periods (kg N). Positive and negative under "source and loss" terms indicates source and loss to Slough respectively. Positive and negative numbers in change of storage terms indicate gain and loss from compartment respectively. Residual is the sum of source and loss terms, minus the change in storage.

Budget Term	Wet Weather	Dry Weather Nov-Jan	Dry Weather Feb-Apr	Dry Weather May-Jul	Dry Weather Aug-Oct	Annual (Wet +Dry)
Source and Loss Terms						
Terrestrial runoff	5,991	138	82	209	309	6730
N - Fixation	--	1.4	0.8	1.0	0.0	3.1
Atmos. Deposition	0.5	0.7	0.7	0.7	0.7	3.4
Denitrification	--	-0.02	0.00	0.00	0.00	-0.02
Source + Loss Terms	5991.5	140.3	83.9	211.0	309.6	6736.3
Change in Storage						
Benthic N Flux	--	246	35	6	-7	280
1^0 Producer N	--	0	0	-20	14	-6
Residual	5992	386	119	197	317	7010

With respect to quantified sources[2], the contribution of benthic flux was largest in the winter and declined through the summer (from 63% to 3% of total sources). Thus terrestrial inputs were the

[2] The net exchange of groundwater is unknown.

primary source of N to the Slough during the period of peak primary producer biomass. Estimates of benthic flux may be an underestimate; macroalgae has been shown to intercept benthic nutrient effluxes and can even increase the net flux by increasing the concentration gradient between sediments and surface waters [*Sutula, et al.*, 2006; *Tyler, et al.*, 2003]. A significant amount of macroalgae was present in chambers during the benthic flux measurements during the summer and fall index periods, thus drawing down N and P concentrations and potentially intercepting any efflux from the chambers. However, even an underestimate of benthic flux are not likely to change the relative importance of external loads versus internal recycling; terrestrial loads far outstrip internal recycling in Loma Alta Slough during the peak period of primary production; the net exchange of groundwater is unknown.

Nitrogen fixation and atmospheric deposition together contribute an insignificant amount of TN to Loma Alta Slough. Collectively, they represent ~0.1% of the terrestrial runoff during any index period. Likewise, denitrification was negligible. Denitrification is thought to be an unimportant sink for N in shallow coastal lagoons because primary producers typically outcompete bacteria for available N, and partitioning of nitrate reduction will shift to dissimilatory nitrate reduction to ammonium in later stages of eutrophication [*An and Gardner*, 2002; *Dalsgaard*, 2003; *McGlathery, et al.*, 2007; *Risgaard-Petersen and Ottosen*, 2000].

Table 4.4. Comparison of loads from watershed versus benthic nutrient flux (kg).

kg	Wet Weather	Index Period 1		Index Period 2		Index Period 3		Index Period 4		Annual (Wet+ Dry)	
		Water-shed	Benthic Flux	Water-shed	Benthic Flux	Water -shed	Benthic Flux	Water -shed	Benthic Flux	Water -shed	Benthic Flux
TN	**5,991**	138.2	--	82.4		209.3		308.9		6,730	--
TDN			246		35		6		-7		280
NH_4	**576**	2.2	44	1.6	1	8.3	1	26.9	-12	615	33
NO_3	**2,303**	72.3	14	33.9	-3	97.9	-1	138.3	-21	2,645	-10
TP	**1,215**	6.5	--	1.5	--	3.3	--	6.2	--	1,233	--
TDP			20		-6		-1		1		13
SRP	**810**	5.3	2	0.7	0	2.6	0	4.6	0	823	3

Table 4.5. Comparison of estimated phosphorus source and loss terms in Loma Alta Slough during dry weather periods (kg P). Positive and negative under "source and loss" terms indicates source and loss to Slough respectively. Positive and negative numbers in change of storage terms indicate gain and loss from compartment respectively. Residual is the sum of source and loss terms, minus the change in storage.

P Budget Term	Wet Weather	Dry Weather Nov-Jan	Dry Weather Feb-Apr	Dry Weather May-Jul	Dry Weather Aug-Oct	Annual (Dry Weather Only)
Source and Loss Terms						
Terrestrial runoff	1,215	7	1	3	6	1233
Atmos. deposition	0.03	0.06	0.06	0.06	0.06	0.3
Source + Loss Terms	1,215	7	2	3	6	1233
Change in Storage						
Benthic N Flux	--	19.9	-6.4	-0.8	0.6	13
1^0 Producer P	--	0.0	0.0	-8.9	2.9	11.8
Residual	1,215	26	-5	-6	10	1,258

Overall, budget estimates show a net annual TP export from the Slough of 1233 kg (Table 4.5). This annual export is driven mostly by export during the wet weather, which represented 98% of total annual TP load. Most of the dry weather TP export occurred during winter, when the Slough was open. Net TP loads to the ocean during the spring through summer were insignificant. Terrestrial TP runoff was mostly SRP, ranging from 70% during wet weather to 80% during dry weather.

Unlike the N budget, benthic recycling and uptake played a larger role in controlling P availability for primary production. During the spring periods, P contributions from benthic flux were 75% that of the total sources. During the summer, benthic flux represented a sink of P, so terrestrial loads provided the majority of P supporting macroalgal biomass. A deficit in the P budget residual indicates that external loads are not sufficient to support the high biomass observed; it is likely that internal recycling of P through the microbial loop plays an important part of maintaining high primary producer biomass within the Slough. It is also possible that additional sources of P to the Slough are unquantified (e.g. grounwater). Because P appears to be a limiting nutrient in the Slough, understanding the sources of P is critical for managing eutrophication. The cycling of P is likely to be significant as water column data show that Loma Alta Slough is primarily phosphorus limited (Figure 4.2). Recycling of P within the macroalgal and cyanobacterial mats is likely to play an important role in supporting observed levels of biomass. As with N, atmospheric sources of P appear to be insignificant.

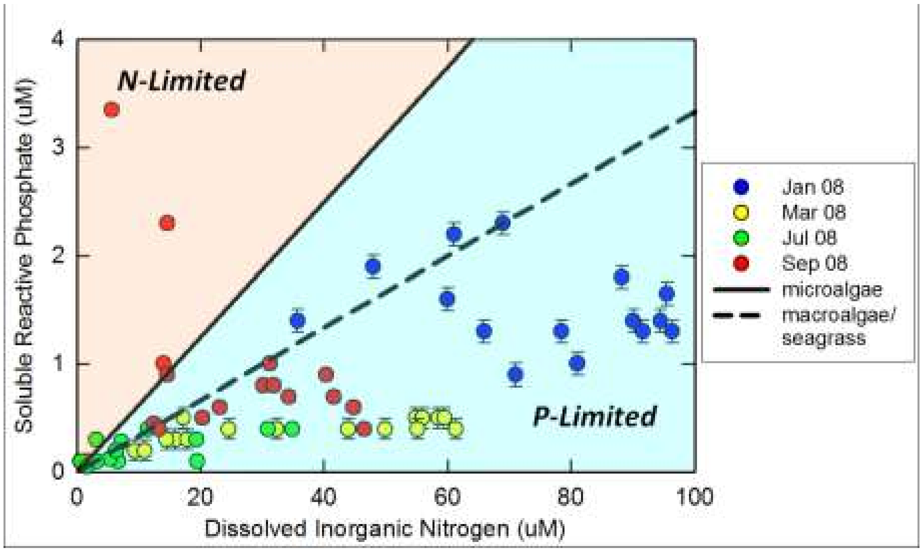


Figure 4.2. Ambient soluble reactive phosphorus versus dissolved inorganic nitrogen (nitrate, nitrite, and ammonium) from transect data. The solid black line indicates the N and P requirements for both phytoplankton and benthic microalgae (N:P = 16:1), and the dotted black line indicates the N:P ratio for macroalgae and seagrasses (N:P = 30:1). If ambient values fall above these lines the communities are N limited. If values fall below, the communities are P limited.

The Slough has the advantage, as a river mouth estuary, that sediments do not appear to have accumulated excessive organic matter with depth. Therefore, options for management of eutrophication in Loma Alta Slough are aimed at reducing the availability of nutrients for primary production during the growing season, or removing biomass from the Slough. Three types of options could be considered:

1) Reduce terrestrial loads in order to limit primary productivity. Emphasis should be placed on reducing both phosphorus as well as nitrogen from the watershed because primary productivity is P limited.
2) Increase flushing during peak periods of primary productivity, particularly when Slough is closed to surface water exchange with ocean during summer. Clearly this is a trade off with the need to close the Slough in order to limit sources of pathogens to the beach during summer. Improved circulation during closed condition could help to limit stratification and therefore ameliorate, to a minor extent, problems with hypoxia. However, limited options exist to increase circulation because of the linear configuration of the Slough.
3) Harvest algal biomass. This option could help to alleviate hypoxia and associated problems. However, the cost-effectiveness of harvesting as a management tool must be carefully considered.

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Appendix 1—Quality Assurance Documentation

This section presents the results of the QA/QC procedures conducted throughout the sampling period at Loma Alta Slough.

Sampling Equipment Maintenance:

Benthic chambers, porewater peepers and sediment cores were inspected prior to each deployment for cracks and/or deformities. Chambers were "re-plumbed" with new tubing and make-up bags during each index period and the diffuser bars were scrubbed internally and flushed with distilled water to make sure they were not clogged with sediment. Dark chambers were further inspected to make sure they were completely covered and no light was transmitted to the chamber. Peepers were cleaned and scrubbed with ethyl alcohol (to kill algae and microbial growth), rinsed in a 5% hydrochloric acid bath, then rinsed three times with distilled water prior to assembly to minimize contamination.

Data Sondes: Calibration, Drift, and Logging

Data sondes deployed in each benthic chamber and in the ambient surface water were calibrated not more than four days prior to deployment and a drift check was completed after deployment. No calibration problems or drift were apparent in any of the sonde maintenance events. During index period 1 sondes in chambers 3 and 4 failed to log data and during index period 3 the sonde in chamber 1 failed to log data. Reason for the lost data was due to a failure of the power supply.

Holding Times Violations

All water and sediment samples met the required holding times for benthic flux study in Loma Alta Slough SCCWRP special studies. Porewater samples had holding times violations for dissolved inorganic nutrients (NH4, NO3, NO2, and SRP) by UCSB for two periods: samples collected on 4/3/08 were not analyzed until 5/5/08 and exceeded the holding times by four days, and samples collected on 7/23/08 were run on 8/27/08 and exceeded the holding time by six days. These were considered minor violations and the data were used in calculations.

Laboratory Blanks

All of the laboratory blanks were reported to be below the level of detection, suggesting no bias from analytical techniques.

Field Blanks

One field blank was collected for each analyte during each benthic flux study and during each pore water peeper study. Field blank samples were collected using the same sample handling and collection equipment as field samples, except distilled- deinonized water was processed instead of sample water to assess possible contamination issues. Field blanks for total dissolved nitrogen, ammonium, total carbon dioxide and iron had a small percentage of samples fall outside the acceptable range. All other field blanks were below the minimum detection limit.

Laboratory Control Standards

All of the laboratory control standards were met acceptance criteria for percent recovery.

Laboratory Duplicates

Laboratory duplicates were processed by all analytical laboratories. A subset of samples (~5%) were randomly selected by the technician, split in the laboratory, and run separately to assess the comparability of the sample analysis process. All laboratory duplicates were within the analytical reporting limits for each analyte.

Field Duplicates

One field duplicate was collected for each analyte during each benthic flux study and during each pore water peeper study. Ammonium, nitrate + nitrite, and total dissolved phosphorus had a small percentage of samples fail to meet the acceptance criteria. Field duplicates for all other analytes fell within the acceptance criteria.

Laboratory Matrix Spikes

Matrix spike samples were processed in the laboratory by adding a known concentration of a specific analyte to a field sample. The sample was analyzed prior to addition of the spike and again after addition. The calculated analyte concentration was prepared and compared to the analytical concentration. Matrix spike results are acceptable when the percent recovery is between 80% and 120%. All of the matrix spike results were within the acceptable range for the Loma Alta Slough special studies.

Table A1.1 QA/QC analysis for Loma Alta Slough Data Set.

Constituent	Percentage Lab Blanks >MDL	Percentage Field Blanks >MDL	Percentage Lab Duplicates >25% RPD	Percentage Field Duplicates >25% RPD	Percentage Holding Times Violation
Water Analyses					
TN	0%	0%	0%	0%	0%
TDN	0%	12%	0%	0%	0%
NH_4	0%	12%	0%	12%	15%
NO_3 + NO_3	0%	0%	0%	12%	15%
NO_3	0%	0%	0%	0%	15%
TP	0%	0%	0%	0%	0%
TDP	0%	0%	0%	12%	0%
SRP	0%	0%	0%	0%	15%
TCO_2	0%	12%	0%	0%	0%
Fe	0%	12%	0%	0%	0%
Mn	0%	0%	0%	0%	0%

S_2	0%	0%	0%	0%	0%
Suspended CHL a	0%	0%	0%		0%
Sediment Analyses					
%OC	0%	NA	0%	0%	0%
%TN	0%	NA	0%	0%	0%
%TP	0%	NA	0%	0%	0%
Grain Size	NA	NA	NA	0%	0%
Benthic CHL a	0%	NA	0%		0%

Appendix 2 – Time line of Rail Road Trestle Construction and Inlet Berm Closure in Loma Alta Slough

May 2007 Inlet Status: Open until May 21, 2007. Then closed mouth. Rail Road Construction: N/A	
August 2007 Inlet Status: Open and Closed; Correspondence on 8/6/2007 indicates that the mouth may have been opened to reduce water level for work on Amtrak berm. 8/30/2007: Natural berm created from ocean currents and low creek flow. La Salina pumps to ocean outfall turned on. At some point between September and November, the pumps were not working and water level in the lagoon increased. This was fixed (at the latest) by November 29, 2007 Rail Road Construction: Undocumented	 

September 2007 Inlet Status: 9/14/2007: Open Rail Road Construction: N/A	
November 2007 Inlet Status: Open and Closed Open on 11/1/2007 (first two photos). Appears closed 11/26/2007. Water level lower by 11/29/2007. Rail Road Construction: Movement of earth on either side of the creek downstream of the old trestle. Fill dirt brought in from outside area. Addition of gravel and earth in stream bed. Arizona crossing with four corrugated metal pipes. Storm on 11/30/2002. Arizona crossing blown out by 14:38 on 11/30/2007.	 

	
December 2007 Inlet Status: Open Rail Road Construction: 12/3/2007 post storm photos show 3" rock wash from Arizona crossing.	 

January 2008 Inlet Status: Open (photos from 1/29/2008) Rail Road Construction: Arizona crossing downstream of trestle rebuilt. Berm construction completion on 2/8/2008.	 
February 2008 Inlet Status: Open Rail Road Construction: Arizona crossing construction rebuild completion on 2/8/2008. Storm 2/22/2008. Arizona crossing washed out with storm.	

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<td>March 2008

Inlet Status: Open

Rail Road Construction: Two pipe culverts installed beneath earth and gravel dam.

Photos: March 24,2010</td>
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May 2008 Inlet Status: Open and closed. Inlet bermed on 5/6/2008. Rail Road Construction: Earthern berm present.	
June 2008 Inlet Status: Closed Rail Road Construction: Earthen dam and pipe culverts Photos: June 17, 2008.	

	
July 2008 Inlet Status: Closed UV Treatment System testing on 7/30/2008. Backflush line shown in picture. Rail Road Construction: Earthen dam and pipe culverts	 

August 2008

Inlet Status: Closed (top photo; taken 8/4/2008)

Rail Road Construction: Earthen dam and pipe culverts east of trestles. Dam west of trestles removed before 8/26/2008.

October 2008 Inlet Status: Closed and open. Opened on 10/6/2008. Rail Road Construction: Earthen dam and pipe culverts east of trestles.	
December 2008 Inlet Status: Open Post-storm event photo 12/19/2008. Rail Road Construction: Earthen dam still partially present east of trestles.	 

Inlet status and rail road trestle construction as documented by L. Honma (Merkel Inc.) and M. Sabelis (City of Oceanside Public Works).

Appendix 3 – Summary of Data to Support Modeling Studies

This appendix provides SCCWRP data in tabular format to facilitate use of the data for the development and calibration of the water quality model for Loma Alta Slough.

MASS EMISSIONS

Table A3.1. Summary of mass emission site data by analyte for all storm events.

All Storms	TSS (mg/L)	TN (mg/L)	TDN (mg/L)	NH_4 (mg/L)	NO_3 + NO_2 (mg/L)	TP (mg/L)	TDP (mg/L)	SRP (mg/L)	$CBOD_5$ (mg/L)
Mean	126.5	1.41	1.01	0.14	0.54	0.29	0.22	0.19	6.52
Minimum	35.0	0.83	0.67	0.01	0.07	0.16	0.07	0.07	1.00
Maximum	235.0	2.22	1.72	0.33	1.00	0.61	0.47	0.44	22.20

SEDIMENT DEPOSITION

Table A3.2. Be inventory data calculation input and output are shown, including bulk density, sample interval, and total, residual, new inventories.

Depth in Core *(z,cmbsf)*	**Core section Thickness** *(h,cm)*	**Wet Bulk Density**	**Be-7 Activity** *(A, dpm/g)*	**Be-7 Inventory** *(I, dpm/cm^2)*	**Total Inventory** *(I_T, dpm/cm^2)*	**Time Elapsed** *(days)*	**Residual Inventory** *(I_R, dpm/cm^2)*	**New Inventory** *(I_N, dpm/cm^2)*
15 November 2007								
0-1	1	0.911	12.144	11.06	**17.62**	initial		
1-2	1	1.106	3.216	3.56				
2-3	1	1.106	2.718	3.01				
3-4	1	1.106	-1.306	0.00				
4-6	2	1.727	-1.382	0.00				
21 January 2008								
0-1	1	0.911	3.928	3.58	**3.75**	67	1.569	**2.181**
1-2	1	1.106	0.156	0.17				
2-3	1	1.106	-3.435	0.00				
28 February 2008								
0-1	1	0.911	4.706	4.29	**4.29**	38	2.614	**1.671**

1-2	1	1.106	-1.063	0.00				
3 April 2008								
0-1	1	0.911	3.864	3.52	**3.75**	33	2.439	**1.307**
1-2	1	1.106	0.205	0.23				
2-3	1	1.116	-0.229	0.00				
15 May 2008								
0-1	1	0.911	1.054	0.96	**0.96**	42	0.556	**0.404**
1-2	1	1.106	-1.991	0.00				
23 July 2008								
0-1	1	0.911	0.355	0.32	**0.32**	69	0.132	**0.191**
1-2	1	1.106	-1.464	0.00				
20 August 2008								
0-1	1	0.911	2.509	2.28	**2.28**	28	1.588	**0.697**
1-2	1	1.106	-2.497	0.00				
30 September 2008								
0-1	1	0.911	-0.912	0.00	**1.89**	42	1.092	**0.793**
1-2	1	1.106	1.704	1.89				
2-3	1	1.116	-0.590	0.00				

Table A3.3. Inventory (*I*) and flux (ψ) summary is provided for each sampling event, where a positive mass flux represents accumulation and a negative mass flux represents a removal event. The sum of mass fluxes reveals the site experienced net removal over the course of the time series sampling event.

Index Period	Date	Total I dpm/cm^2	Residual I dpm/cm^2	New I dpm/cm^2	Mass Flux g/cm^2	Mass Flux g/cm^2/day
preliminary	1-Nov-07	17.62	0.00	0.00	0.000	0.000
1	21-Jan-08	3.75	1.57	2.18	1.177	0.018
	28-Feb-08	4.29	2.61	1.67	0.483	0.013
2	3-Apr-08	3.75	2.44	1.31	-1.270	-0.038
	15-May-08	0.96	0.56	0.40	-3.257	-0.078
3	23-Jul-08	0.32	0.13	0.19	-2.556	-0.037
	20-Aug-08	2.28	1.59	0.70	0.308	0.011
4	30-Sep-08	1.89	1.09	0.79	3.157	0.075
	Summary				**-1.959**	**-0.037**

SEDIMENT BULK CHARACTERISTICS BY INDEX PERIOD: C, N, P

Table A3.4. Sediment bulk characteristics for each index period.

Index Period	Sample Depth	% Organic C	% Total N	% Total P	OC:N (molar)	OC:P (molar)	N:P (molar)	% Fines
Pre-liminary Sampling	0 – 1 cm	2.9	0.36	0.0658	9.40	113.9	12.11	29.5
	1 – 2 cm	2.1	0.17	0.0411	14.41	132.0	9.16	29.4
	2 – 3 cm	2.5	0.19	0.0497	15.35	129.9	8.47	29.7
	3 – 4 cm	2.5	0.24	0.0532	12.15	121.4	9.99	29.5
	4 – 6 cm	1.5	0.12	0.0402	14.58	96.39	6.61	32.4
Index Period 1 - Winter	0 – 1 cm	0.22	0.01	0.0075	25.67	75.78	2.95	7.4
	1 – 2 cm	0.16	0.01	0.0908	18.67	4.55	0.24	6.4
	2 – 3 cm	0.37	0.01	0.0132	43.17	72.41	1.68	22.9
	3 – 4 cm	0.86	0.06	0.0538	16.72	41.29	2.47	40.1
	4 – 5 cm	1.0	0.07	0.0515	16.67	50.16	3.01	53.8
	5 – 6 cm	0.93	0.06	0.0346	18.08	69.44	3.84	59.8
	6 – 8 cm	0.77	0.06	0.0600	14.97	33.15	2.21	57.9
	8 – 10 cm	0.81	0.08	0.0510	11.81	41.03	3.47	52.0
	10 – 12 cm	0.47	0.01	0.0015	54.83	809.4	14.76	28.6
Index Period 2 - Spring	0 – 1 cm	0.62	0.10	0.0205	7.23	77.97	10.78	36.7
	1 – 2 cm	0.15	0.01	0.0170	17.50	22.83	1.30	8.5
	2 – 3 cm	0.15	0.01	0.0221	17.50	17.52	1.00	3.1
	3 – 4 cm	0.21	0.01	0.0172	24.50	31.55	1.29	3.1
	4 – 5 cm	0.70	0.08	0.0291	10.21	62.24	6.10	4.0
	5 – 6 cm	0.58	0.07	0.0343	9.67	43.71	4.52	64.3
	6 – 8 cm	0.48	0.06	0.0307	9.33	40.37	4.33	64.3
	8 – 10 cm	0.39	0.01	0.0284	45.50	35.47	0.78	61.2
	10 – 12 cm	0.72	0.09	0.0281	9.33	66.20	7.09	61.4
Index Period 3 - Summer	0 – 1 cm	0.09	0.01	0.0413	10.50	5.63	0.54	1.2
	1 – 2 cm	0.02	0.01	0.0469	2.33	1.10	0.47	1.9
Index Period 4 - Fall	0 – 1 cm	0.67	0.07	0.0242	11.17	71.56	6.41	20.4
	1 – 2 cm	0.35	0.01	0.0221	40.83	40.95	1.00	6.0
	2 – 3 cm	0.41	0.01	0.0184	47.83	57.44	1.20	3.8
	3 – 4 cm	0.47	0.01	0.0259	54.83	46.95	0.86	5.6
	4 – 5 cm	0.73	0.01	0.0335	85.17	56.28	0.66	15.7
	5 – 6 cm	0.84	0.01	0.0395	98.00	54.94	0.56	33.8
	6 – 8 cm	1.2	0.07	0.0401	19.83	76.70	3.87	55.4
	8 – 10 cm	1.2	0.11	0.0571	12.73	54.30	4.27	28.5
-- Depths where no percent fines value is recorded had insufficient sample for analysis.								

SEDIMENT PORE WATER CONCENTRATIONS

Table A3.5. Pore water constituent analysis for each index period.

Sample Period	Depth	TDN (µM)	NH_4 (µM)	NO_3 + NO_2 (µM)	NO_2 (µM)	TDP (µM)	SRP (µM)	TCO_2 (µM)	S_2 (µM)	DOC (µM)	Fe (µM)	Mn (µM)
Index Period 1 – Winter 1/21/2008	Bottom water	14.6	5.8	64.0	2.1	2.5	1.9	1959	0.04	1419	0.4	1.7
	0–1 cm	120.5	52.2	14.4	18.8	8.8	10.4	621.4	0.46	720.0	60.9	1.7
	1–2 cm	284.5	344.0	4.2	2.8	20.2	24.0	1117	0.08	590.0	5.9	2.5
	2–3 cm	553.0	652.0	2.8	1.0	33.6	43.6	1631	14.88	615.0	3.6	2.0
	3–4 cm	633.8	784.0	3.0	2.6	43.1	56.6	2174	23.52	597.5	2.0	1.6
	4–5 cm	649.2	766.0	10.8	4.4	42.8	57.8	2591	31.50	767.5	3.9	1.8
	5–6 cm	568.0	720.0	4.6	5.0	42.6	59.8	2976	66.68	655.0	6.6	1.3
	7–8 cm	567.6	669.0	5.5	7.0	41.3	59.6	3159	90.38	812.5	12.1	1.4
	10–11 cm	571.5	646.0	5.2	8.4	45.9	57.7	3257	80.43	290.0	25.1	1.1
Index Period 2 – Spring 4/3/2008	Bottom water	87.3	3.9	23.3	0.9	0.8	0.0	1207	0.00	722.1	0.5	1.1
	0–1 cm	47.0	6.8	74.8	0.0	2.2	1.4	815.0	0.00	9168	53.7	5.1
	1–2 cm	40.2	2.4	44.6	0.0	0.3	1.6	811.4	0.08	3197	50.1	0.8
	2–3 cm	63.3	33.0	31.0	0.0	1.5	1.2	707.5	0.00	2298.8	30.4	0.4
	3–4 cm	222.8	155.5	191.7	0.0	14.4	14.6	934.8	0.26	2091	53.7	14.6
	4–5 cm	330.0	254.0	33.4	0.0	25.7	24.6	1054	0.58	558.2	53.7	15.1
	5–6 cm	435.3	360.0	27.0	0.0	36.1	34.6	1261	1.49	532.7	41.2	17.5
	7–8 cm	588.4	452.0	20.6	0.0	41.8	37.2	1348	0.81	529.7	53.7	20.0
	11–12 cm	648.5	576.0	28.0	0.0	50.4	48.4	1520	1.04	697.9	35.8	15.5
	14–15 cm	659.0	552.0	27.0	0.0	42.7	37.8	1434	0.81	605.4	35.8	5.5
Index Period 3 – Summer 7/22/2008	Bottom water	60.0	5.2	15.2	1.1	0.5	0.5	1005	0.00	916.3	1.3	1.2
	0–1 cm	57.1	15.2	34.0	0.0	0.5	1.0	976.6	1.12	752.5	11.8	11.7
	1–2 cm	75.2	35.8	77.4	0.0	1.2	11.0	1011	2.59	735.0	10.5	13.7
	2–3 cm	127.7	79.0	51.5	0.0	1.2	5.6	1032		1050	4.5	16.0
	3–4 cm	469.0	592.0	49.4	0.0	3.0	2.2	1659	26.77	955.0	5.7	11.5
	4–5 cm	1139.8	1048	26.2	0.0	50.2	41.8	3859	75.21	722.5	23.3	18.0
	5–6 cm	1178	1120	34.0	0.0	46.0	39.0	2851	59.04	472.5	7.5	14.0
	6–7 cm	1044	1020	21.6	0.0	45.1	36.6	2486	9.75	462.5	64.5	11.5
	9–10 cm	1092	1038	35.6	0.0	53.3	45.6	2696	9.40	529.2	21.9	10.5
	13–14 cm	1036	1008	64.2	0.0	53.9	58.0	2778	2.28			
Index Period 4 – Fall 9/29/2008	Bottom water	52.5	2.5	15.5	1.9	0.3	0.0	1005	0.00	1.3	1.1	2.4
	0–1 cm	53.6	40.0	7.2	2.2	1.4	0.0	976.6	0.00	360.0	23.3	3.6
	1–2 cm	53.0	59.2	3.6	1.2	3.6	1.2	1011	0.20	460.0	19.7	4.6
	2–3 cm	139.7	185.4	4.0	1.4	5.9	4.0	1032	21.59	610.0	11.6	4.7
	3–4 cm	376.8	456.0	2.4	0.0	13.3	19.2	1659	14.99	240.0	12.7	5.3
	4–5 cm	449.4	682.0	3.4	1.2	21.2	33.0	3859	18.87	270.0	13.3	5.6
	5–6 cm	664.9	384.0	5.2	1.0	32.7	8.6	2851	14.79	230.0	13.8	5.8
	7–8 cm	714.4	788.0	2.2	0.0	33.1	28.8	2486	17.90	227.5	4.5	6.0
	10–11 cm	630.8	692.0	0.0	0.0	28.0	35.0	2696	15.89	190.0	7.5	6.2
	13–14 cm	727.6	778.0	0.0	0.0	34.4	43.0	2778	24.49	190.0	5.7	7.1

WATER COLUMN TRANSECT DATA

Table A3.6. Transect data for each index period during ebb tide (constituents are in mmol/L, except for chlorophyll a, which is in µg/l)).

Index Period	site #	TN	TDN	NH_4	$NO_3 + NO_2$	NO_2	TP	TDP	SRP	TSS	Chl *a*
Index Period 1 Winter	1	139.5	76.04	2.30	94.04	1.80	1.28	1.22	1.30	1.5	3.2
	2	129.5	131.3	2.40	92.04	1.80	3.59	3.44	1.40	0	4.3
	3										
	4	85.93	121.5	2.00	93.49	1.75	2.82	2.68	1.65	0.85	3.2
	5	30.98	40.17	4.10	43.82	0.60	1.29	1.36	1.90	12	13.4
	6	91.09	91.09	3.70	57.33	0.80	2.76	2.84	2.20	2	8
	7	34.39	88.02	3.50	56.43	0.80	2.04	2.69	1.60	1	3.2
	8	20.53	70.35	3.60	65.33	1.10	1.79	3.35	2.30	6	3.2
Index Period 2 Spring	1	114.0	130.9	3.30	51.52		0.91	0.00	0.50	2	6
	2	91.25	154.7	2.40	53.53		0.00	0.00	0.50	1.3	4.3
	3	124.2	96.79	2.80	55.68		0.00	0.00	0.50	7	10.1
	4	100.2	155.5	2.00	57.43		0.00	0.81	0.50	3.4	18.2
	5	75.96	47.82	1.20	8.10		0.93	0.00	0.20	19	12
	6	70.14	32.34	1.40	9.50		0.00	0.00	0.20	15.3	7.5
	7	66.11	47.77	1.80	15.41		0.36	0.00	0.50	15.3	7.3
	8	57.10	28.77	2.40	12.11		0.92	0.00	0.30	11.7	11.1
Index Period 3 Summer	1	50.70	29.25	3.50	31.42		0.32	0.00	0.40	6.7	3.2
	2	29.76	41.93	4.10	26.76		0.37	0.38	0.40	8	51.2
	3	18.86	23.20	1.23	5.95		0.09	0.21	0.28	4	13.4
	4	60.39	36.29	1.00	18.41		0.93	0.00	0.10	1.7	48.5
	5	49.47	35.09	1.10	5.20		1.49	0.00	0.20	48.15	92.6
	6	23.09	15.42	0.50	2.80		0.30	0.00	0.10	4	12.5
	7	29.41	29.49	1.20	1.90		0.49	0.00	0.30	2.3	23.6
	8	30.51	32.13	0.80	2.50		0.16	0.00	0.10	2.85	16.25
Index Period 4 Fall	1	158.5	131.2	10.01	31.62		4.56	1.59	0.70	201.3	299
	2	117.9	117.7	9.60	20.51		1.82	1.49	0.80	24.8	33.8
	3	126.7	118.0	13.51	1.10		9.02	4.59	2.30	36	155.1
	4	124.4	106.7	9.80	30.52		2.84	1.83	0.90	19.3	65.7
	5	138.7	101.1	9.20	22.01		4.05	2.04	1.00	9	40.1
	6	123.6	136.8	8.30	23.61		2.28	2.03	0.80	12	51
	7	131.4	118.7	4.75	0.90		8.11	4.93	3.35	17.15	43.1
	8	40.17	93.79	4.60	10.01		1.00	1.75	0.90	2.7	11.6

Table A3.7. Transect data for each index period during flood tide.

Index Period	site #	TN	TDN	NH_4	NO_3 + NO_2	NO_2	TP	TDP	SRP	TSS	Chl *a*
Index Period 1 Winter	1	110.4	116.3	3.30	67.73	1.00	1.11	1.39	0.90	5	13.9
	2	57.93	111.3	1.85	79.14	1.05	1.75	1.22	1.00	9.3	36.8
	3	45.94	123.1	3.00	75.44	1.10	2.18	3.99	1.30	4.3	5.3
	4	130.6	114.1	2.40	87.64	1.20	4.49	2.69	1.40	4	10.7
	5	127.7	111.0	3.60	87.94	1.50	2.41	3.37	1.30	3.7	4.3
	6	120.7	114.0	2.40	33.32	0.60	2.96	2.68	1.40	3.3	5.3
	7	118.3	114.3	2.60	63.33	1.10	1.88	2.95	1.30	4	10.5
	8	119.3	116.6	3.60	84.54	1.40	3.50	3.38	1.80	3.3	4.3
Index Period 2 Spring	1	100.1	88.34	3.00	46.82		0.00	0.00	0.40	4.3	12.5
	2	61.51	105.4	1.90	42.02		0.00	0.00	0.40	13.7	49.4
	3	139.9	121.5	1.60	53.53		0.36	0.00	0.40	12.35	48.95
	4	202.7	111.1	3.60	57.73		0.99	0.00	0.40	2.7	6.2
	5	61.51	40.50	2.80	29.51		0.66	0.00	0.40	62.4	33.8
	6	55.23	20.52	0.70	23.91		1.08	0.00	0.40	22.2	25.4
	7	62.92	43.31	1.90	14.01		0.84	0.00	0.30	19	12.1
	8	84.03	93.79	2.10	15.71		0.85	0.00	0.30	24	9.3
Index Period 3 Summer	1	31.26	33.79	2.40	16.91		0.20	0.23	0.30	2.3	4.5
	2	63.42	22.10	0.80	5.90		2.64	0.00	0.10	40.3	312.9
	3	46.91	30.24	1.20	10.20		0.64	0.25	0.40	2.7	53.4
	4	53.27	49.96	1.02	4.33		0.24	0.12	0.12	0	6.2
	5	38.81	39.67	0.80	1.00		1.13	0.00	0.10	27.7	149.8
	6	125.6	30.99	0.60	0.90		5.67	0.00	0.10	60	231.2
	7	24.27	23.24	1.10	-0.50		0.16	0.00	0.10	1.8	22.3
	8	22.89	30.55	1.05	0.70		0.12	0.00	0.05	19.7	18.25
Index Period 4 Fall	1	91.98	101.7	7.80	36.92		1.09	1.12	0.60	13.3	23.6
	2	90.74	109.9	3.70	42.72		1.10	0.60	0.40	5	32.6
	3	99.97	102.0	4.55	9.45		2.93	2.49	1.00	51	57.3
	4	104.2	98.07	6.10	28.21		1.35	1.28	0.70	6.3	16.9
	5	77.81	97.50	2.60	17.71		1.51	1.17	0.50	9.3	23
	6	85.31	96.59	3.90	19.21		2.38	1.18	0.60	5	70.3
	7	95.93	93.96	2.25	10.16		1.75	1.65	0.45	20.85	44.65
	8	99.72	86.87	2.10	11.11		2.59	1.06	0.40	6	44.25

PRIMARY PRODUCER BIOMASS AND /OR PERCENT COVER

Table A3.8. Means and standard deviations of suspended chlorophyll *a* and benthic chlorophyll *a* concentrations during each index period.

Index Period	Mean Suspended Chlorophyll a (mg/m^3)	Benthic Chlorophyll a (mg/m^2)
Index Period 1 Winter	51.71	2.22 ± 2.12
Index Period 2 Spring	73.95	2.35 ± 1.21
Index Period 3 Summer	49.59	0.92 ± 0.44
Index Period 4 Fall	41.88	1.95 ± 0.57

Table A3.9. Macroalgae total percent cover and biomass by species during each index period.

Index Period	*Cladaphora Spp.* % Cover	*Cladaphora Spp.* Biomass (g/m^2)	*Blue Green Algae* % Cover	Blue Green Algae Biomass (g/m^2)
Index Period 1 Winter	0	0	0	0
Index Period 2 Spring	4%	0.35 ± 0.16	0	0
Index Period 3 Summer	100%	356.7 ± 61.7	0	0
Index Period 4 Fall	0	0	75%	100.5 ± 81.0

RATES OF EXCHANGE BETWEEN SURFACE WATERS AND SEDIMENTS – BENTHIC FLUX

Table A3.10. Benthic Fluxes for all index periods in Loma Alta Slough.

Index Period	Light/ Dark	Benthic Flux (mmol m^{-2} d^{-1})												
		DO	TCO_2	TDN	TDP	DOC	NH_4	NO_3	DIN	SRP	DON	DOP	Fe	Mn
Index Period 1 Winter	light	40.84	60.79	3.26	131.9	40.84	0.44	2.21	2.65	0.00	58.13	3.26	-3.33	-0.30
	light	62.45	43.63	1.10	302.0	62.45	11.13	8.07	19.21	1.11	24.43	-0.01	-0.38	-0.95
	light avg	51.65	52.21	2.18	217.0	51.65	5.79	5.14	10.93	0.55	41.28	1.63	-1.85	-0.62
	light stdev	15.28	12.13	1.53	120.2	15.28	7.56	4.14	11.70	0.78	23.83	2.31	2.08	0.46
	dark	65.49	113.6	3.77	355.4	65.49	4.72	-2.14	2.58	-0.37	111.0	4.14	0.00	0.83
	dark	101.4	1.63	-0.09	-680.2	101.4	22.93	4.42	27.35	0.22	-25.73	-0.31	-0.09	-0.01
	dark avg	83.42	57.62	1.84	-162.4	83.42	13.82	1.14	14.97	-0.07	42.65	1.91	-0.05	0.41
	dark stdev	25.36	79.18	2.73	732.3	25.36	12.88	4.64	17.52	0.42	96.70	3.15	0.07	0.60
Index Period 2 Spring	light	61.03	-11.92	0.50	-131.5	61.03	0.00	0.00	0.00	0.00	-11.92	0.50	-0.71	0.29
	light	60.00	23.35	-1.03	721.6	60.00	-0.36	-1.16	-1.52	0.00	24.87	-1.03	-0.60	-0.07
	light avg	60.51	5.72	-0.26	295.0	60.51	-0.18	-0.58	-0.76	0.00	6.47	-0.26	-0.65	0.11
	light stdev	0.73	24.94	1.08	603.3	0.73	0.25	0.82	1.07	0.00	26.02	1.08	0.07	0.25
	dark	2.77	21.48	-0.13	-100.1	2.77	-0.29	-0.30	-0.59	0.00	22.07	-0.13	0.19	0.10
	dark	-4.03	-1.77	-1.91	544.8	-4.03	1.11	-1.16	-0.04	0.00	-1.73	-1.91	0.64	0.34
	dark avg	-0.63	9.85	-1.02	222.4	-0.63	0.41	-0.73	-0.32	0.00	10.17	-1.02	0.41	0.22

	dark stdev	4.81	16.44	1.26	456.0	4.81	0.99	0.60	1.59	0.00	16.83	1.26	0.32	0.18
Index Period 3 Summer	light	-135.2	1.53	-0.37	-318.3	-135.2	0.14	0.14	0.29	0.07	1.24	-0.44	1.37	-0.11
	light	-4.13	-2.91	-0.49	404.0	-4.13	-0.07	-0.12	-0.19	0.00	-2.72	-0.49	-0.57	0.00
	light avg	-69.65	-0.69	-0.43	42.9	-69.65	0.04	0.01	0.05	0.04	-0.74	-0.47	0.40	-0.06
	light stdev	92.66	3.14	0.09	510.7	92.66	0.15	0.19	0.34	0.05	2.80	0.04	1.37	0.08
	dark	-88.54	3.73	0.51	-3199	-88.54	-0.63	-0.32	-0.95	0.00	4.68	0.51	4.43	0.64
	dark	40.18	2.98	0.01	-241.5	40.18	1.16	-0.61	0.56	0.00	2.42	0.01	0.95	0.34
	dark avg	-24.18	3.36	0.26	-1721	-24.18	0.27	-0.46	-0.19	0.00	3.55	0.26	2.69	0.49
	dark stdev	91.02	0.54	0.36	2092	91.02	1.27	0.20	1.48	0.00	1.60	0.36	2.46	0.21
Index Period 4 Fall	light	-293.1	-37.06	-0.29	2891	-293.1	-2.79	-8.02	-10.80	0.00	-26.26	-0.29	-0.56	-0.14
	light	-26.30	32.50	-0.14	202.0	-26.30	-3.57	-4.81	-8.38	0.00	40.88	-0.14	-0.21	0.01
	light avg	-159.7	-2.28	-0.22	1547	-159.7	-3.18	-6.41	-9.59	0.00	7.31	-0.22	-0.38	-0.07
	light stdev	188.6	49.19	0.11	1902	188.6	0.55	2.27	2.82	0.00	47.47	0.11	0.25	0.10
	dark	-2.17	-18.74	0.21	-479.1	-2.17	-3.55	-2.38	-5.93	0.00	-12.81	0.21	-0.17	0.73
	dark	12.31	17.48	0.46	-1635	12.31	-1.21	-3.21	-4.42	0.00	21.89	0.46	0.18	1.67
	dark avg	5.07	-0.63	0.33	-1057	5.07	-2.38	-2.79	-5.17	0.00	4.54	0.33	0.01	1.20
	dark stdev	10.24	25.61	0.18	817.7	10.24	1.66	0.59	2.25	0.00	24.54	0.18	0.24	0.66

Table A3.11. Predicted Diffusive Fluxes by index period for each constituent of interest.

Index Period	Predicted Diffusive Fluxes (mmol m^{-2} d^{-1})					
	NH4	NO3	DON	SRP	DOP	DOC
Winter	0.43	-0.05	-3.62E-02	1.15E-02	-5.93E-04	-0.68
Spring	0.10	0.01	-8.60E-02	-1.90E-04	-2.68E-04	8.26
Summer	0.48	0.08	-4.60E-02	4.48E-03	1.76E-04	-0.33
Fall	0.29	-0.01	-2.05E-01	7.20E-04	1.49E-03	0.80

Table A3.12. Summary of linear regression relationship between predicted diffusive fluxes and in situ chamber flux data.

Constituent	In Situ Flux Data Used For Regression	Regression Equation	R^2 and Pr>F
NH4	Dark Chambers	$NH4_{IS}$ = 2.6+17.5*$NH4_{DF}$	R^2 = 0.17, Pr>F : 0.60
	Light Chambers	$NH4_{IS}$ =-2.3 + 9.0*$NH4_{DF}$	R^2 = 0.17 Pr>F : 0.58
	All	$NH4_{IS}$ =-2.4 + 13.3*$NH4_{DF}$	R^2 = 0.17, Pr>F : 0.59
NO3	Dark Chambers	$NO3_{IS}$ =-1.8 +21.5*$NO3_{DF}$	R^2 = 0.26, Pr>F : 0.41
	Light Chambers	$NO3_{IS}$ =-3.7 +58.9*$NO3_{DF}$	R^2 = 0.22, Pr>F : 0.43
	All	$NO3_{IS}$ =-2.8 + 40.23*$NO3_{DF}$	R^2 = 0.23, Pr>F : 0.42
DON	Dark Chambers	DON_{IS} = 26.4 + 119.9*DON_{DF}	R^2 = 0.25, Pr>F : 0.49
	Light Chambers	DON_{IS} = 21.5 + 85.8*DON_{DF}	R^2 = 0.12, Pr>F : 0.64
	All	DON_{IS} = 24.0 + 102*DON_{DF}	R^2 = 0.18, Pr>F : 0.57

SRP	Dark Chambers	SRP_{IS} = - 3E-36 + 3E-31*SRP_{DF}	R^2 = 0.02, Pr>F : 0.89
	Light Chambers	SRP_{IS} =-0.05 +48.1 * SRP_{DF}	**R^2 = 0.84, Pr>F : 0.05**
	All	SRP_{IS} =-0.02 + 20.9* SRP_{DF}	**R^2 = 0.855, Pr>F : 0.04**
DOP	Dark Chambers	DOP_{IS} = -0.43 +610*DOP_{DF}	R^2 = 0.53, Pr>F : 0.48
	Light Chambers	DOP_{IS} = 0.34 +64.5*DOP_{DF}	R^2 = 0.19, Pr>F : 070
	All	DOP_{IS} = -0.38 +337*DOP_{DF}	R^2 = 0.70, Pr>F : 0.37

DATA ON ADDITIONAL FACTORS CONTROLLING BENTHIC FLUX

Table A3.13. Number of benthic infauna in each chamber and slough average.

Index Period	Chamber	Polychaetes (individuals/ m^2)	Capitellids (individuals/ m^2)	Oligochaetes (individuals/ m^2)	Mollusks (individuals/ m^2)	Crustaceans (individuals/ m^2)	Other (individuals/ m^2)	Total Polychaetes (individuals/ m^2)	Total Infauna (individuals/ m^2)
Index Period 1 Winter	Chamber 1 (light)	0	0	0	0	0	0	0	0
	Chamber 2 (dark)	0	0	0	0	0	0	0	0
	Chamber 3 (light)	0	0	0	0	0	0	0	0
	Chamber 4 (dark)	0	0	0	0	0	0	0	0
	Average	0	0	0	0	0	0	0	0
	Standard Deviation	0	0	0	0	0	0	0	0
Index Period 2 Spring	Chamber 1 (light)	0	0	0	0	0	0	0	0
	Chamber 2 (dark)	1020	0	0	0	0	0	1020	2040
	Chamber 3 (light)	1020	509	1020	0	0	509	1530	4580
	Chamber 4 (dark)	4070	509	509	0	0	2550	4580	12200
	Average	1530	255	382	0	0	764	1780	4710
	Standard Deviation	1760	294	488	0	0	1210	1970	5350
Index Period 3 Summer	Chamber 1 (light)	0	0	0	0	0	0	0	0
	Chamber 2 (dark)	0	0	0	0	0	0	0	0
	Chamber 3 (light)	0	0	0	0	0	0	0	0
	Chamber 4 (dark)	0	0	0	0	0	509	0	509
	Average	0	0	0	0	0	127	0	127
	Standard Deviation	0	0	0	0	0	255	0	255
Index Period 4 Fall	Chamber 1 (light)	0	0	0	0	0	0	0	0
	Chamber 2 (dark)	0	0	509	0	0	0	0	509
	Chamber 3 (light)	0	0	0	0	0	0	0	0
	Chamber 4 (dark)	509	0	0	0	0	509	509	1530
	Average	127	0	127	0	0	127	127	509
	Standard Deviation	255	0	255	0	0	255	255	720