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Synthesis for Management of Eutrophication Issues in Elkhorn Slough

Brent Hughes

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ABOUT THIS DOCUMENT

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AUTHOR AFFILIATION

At the time the report was prepared, Brent Hughes was a researcher for the Tidal Wetland Project and Water Quality Program at the Elkhorn Slough National Estuarine Research Reserve.

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The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

Abstract

Elkhorn Slough is an estuary that has been undergoing major changes in the last 100 years due to anthropogenic effects. Major changes in the slough include the opening of the Moss Landing Harbor in 1946, the construction of dikes, culverts and flood gates, and eutrophication from increased agricultural practices in the Salinas Valley.

Eutrophication has been a well-studied phenomenon in estuaries and embayments worldwide over the last 30 years, and has been attributed to intensive agricultural practices.

Elkhorn Slough has seen dramatic increases in the amount of dissolved nutrients during the last 70 years, and it has some of the highest nitrogen, phosphate and ammonia levels reported in the world. Elkhorn Slough has overwhelming indications of eutrophication and even hypertrophication, due to elevated levels of chl *a*, the presence of blooms of ephemeral algae, and periods of hypoxic and at times anoxic conditions. The ecological effects due to this alteration to the water chemistry of Elkhorn Slough have yet to be thoroughly researched. Evidence from other estuaries combined with data and observations from Elkhorn Slough over the last 40 years supports the idea that eutrophication is changing biological communities in Elkhorn Slough. The potential to reverse eutrophication through restoration projects in Elkhorn Slough remains uncertain, although limited data suggest some cause for optimism.

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Introduction

Elkhorn Slough (Figure 1) is an important estuary because it supports extensive tracts of salt marsh and wetland and has valuable educational, research, aesthetic, recreational, tourism and biodiversity resources for the local community and beyond. However, Elkhorn Slough is also heavily influenced by surrounding agricultural practices as well as tidally driven processes that lead to nutrient loading on variable temporal and spatial scales due to its complex geomorphology. It has some of the highest levels of dissolved nutrient levels compared to other estuaries in the United States (Caffrey et al. 1997 and 2002, Fry 2003) (Table1) and long-term data suggests that levels are increasing (Figure 2), and have been on the increase for the last 70 years (Caffery 2002). Elkhorn Slough has two conflicting problems: nutrient loading and tidal erosion that has depleted a large portion of marsh habitat (Malzone 1999). These processes make it difficult to manage existing habitat because decreasing the effects of one process can ameliorate the other. The goal of this report is to investigate the potential effects of eutrophication (ecosystem changes due to nutrient loading) on the Elkhorn Slough ecosystem. Data used in the report comes primarily from the Elkhorn Slough National Estuarine Research Reserve (ESNERR) through a monthly sampling program that has sampled nutrients, chlorophyll, algal cover, and physical data (dissolved oxygen, temperature, salinity, pH, and turbidity) at 26 stations throughout the slough from 1989-present. Other sources of data are cited.

Anthropogenic Influences

Certain modifications such as the construction of the Southern Pacific Railroad in 1872, agricultural land development (early 1900s), and road construction, have led to the installment of culverts, dikes, and tidally controlled flood gates which have muted tidal flow in some areas (Figure 3). The reduction in tidal flow has increased water residence time in some areas, which can amplify eutrophic effects that produce sub-optimal conditions for local biota. In 1946 the Moss Landing Harbor was constructed and a new permanent mouth was created for Elkhorn Slough. This created two new problems for the slough: main channel tidal erosion, and future tidally driven nutrient loading from the Salinas River.

The negative ecological consequences of eutrophication have been well studied in other estuaries in terms of decreased biodiversity, increases in biological invasions, changes in community dynamics due to a reduction in nutrient competition, and dramatic diel changes in biologically driven dissolved oxygen (Fong 1993, Bertness et al. 2002, Nilsson and Rosenberg 2000, Shen et al. 2008, Vaquer-Sunyer and Duarte 2008). Estuaries that are non-eutrophic are typically dominated by sea-grass and salt-marsh plants, but when nutrients are no longer a limiting factor that competitive hierarchy shifts to one dominated by ephemeral algae and bacterial mats. This overall increase in primary productivity can have profound effects on dissolved oxygen concentrations and biogeochemical pathways, especially in shallow waters, that can choke certain aerobic species with high oxygen demands. Competitive shifts to ephemeral species combined with the breakdown of biogeochemical pathways can lead to a loss in trophic functions and an overall loss in species diversity (Connell and Slatyer 1977, Bruno et al. 2003).

Indicators of Eutrophication

Nutrients: Primary Indicator

There are many parameters that suggest Elkhorn Slough is eutrophic and possibly a hypertrophic estuary. Bricker et al. (2003) presented a model to qualify estuaries as having hyper, high, medium, or low eutrophic conditions. The nitrate levels coming from the Old Salinas River Channel (Table 1), and other locations throughout the slough indicate that it is a seasonal hypertrophic estuary (>2 mg/L N) and a semipermanent high eutrophic estuary (>1 mg/L N) (Figure 4). The winter months usually bring heavy rainfall, and it is during this season that the highest nitrate concentrations are found throughout the slough (Figure 5). The highest levels of nitrate come from the Salinas River and are diluted by tidal mixing going up the slough, yet start to increase again near the head where Carneros Creek flows in (Figures 1 and 6a). Nitrate is a biologically important limiting nutrient because it can drive primary productivity (Fong 1994). Also, many salt and brackish marsh plants are known to be nitrogen limited, but not phosphorous limited (as in freshwater estuaries), and will respond to direct fertilization even in eutrophic conditions (Crain 2007). One salt marsh in Elkhorn Slough revealed evidence of nitrogen limitation; fertilization with urea led to significant plant responses (Martone and Wasson 2008; Siciliano et al. 2008).

Phosphate is also a primary indicator of eutrophication with concentrations >0.1 mg/L (Bricker et al. 2003). Every site in Elkhorn Slough except for Reserve North Marsh and Strawberry Pond have mean phosphate concentrations that would be considered eutrophic (Figure 6b). It is another nutrient that has high concentrations in

Elkhorn Slough compared to other estuaries world-wide (Table 1), and it presumably comes from agricultural sources because of its use in fertilizers. This can especially be seen at sites which are tidally restricted (Struve Pond and Azavedo Pond) or which are directly downstream from agricultural runoff (Tembledero Slough and Carneros Creek) (Figures 1, 3, and 6b). Phosphate may not be a limiting nutrient for salt marsh plants, but it is a limiting nutrient for marine algae and may be as important for driving eutrophic indicating species of algae, such as *Ulva* (Fong et al. 1994).

Ammonia levels in Elkhorn Slough are also some of the highest reported values in the world (Caffrey 2002). Ammonia, although not considered as limiting a nutrient as nitrate and phosphate nor a primary indicator of eutrophication, can be an indicator of high sewage runoff or increased microbial activity, which is another indicator of highly eutrophic system (Fong 1993). This process occurs in areas where organic deposition is high, presumably areas where residence time is greatest. This organic deposition facilitates microbial communities, which produce ammonia during aerobic decomposition. Like phosphate, the highest ammonia levels in Elkhorn Slough are found in tidally restricted areas (North Azevedo Pond and Struve Pond) or which are directly downstream from agricultural runoff (Tembledero Slough and Carneros Creek) (Figures 1, 3, and 6c).

Chlorophyll: Primary Indicator

Primary productivity can also be used as a primary indicator of eutrophication (Bricker et al. 2003). Primary productivity is of particular interest because increased nutrients can facilitate increases in primary productivity. Generally, primary productivity is considered to have a positive effect on community dynamics, however in eutrophic waters it can reach a tipping point where too much productivity can lead to hypoxia and shading (Twilley et al. 1985, Viaroli et al. 1996). Chlorophyll *a* concentrations that exceed levels greater than 20 ug/l indicate high eutrophication and >60ug/l indicate hypertrophication (Bricker et al. 2003).

Chlorophyll *a* concentrations in Elkhorn Slough indicate that the slough is a semi-permanent high eutrophic slough and episodically hypertrophic (Figure 7). These levels also indicate that Elkhorn Slough has some of the highest chlorophyll *a* concentrations in the world (Cloern and Jassby 2008). Levels of chl *a* in Elkhorn Slough can reach 120 ug/l during the summer months, and it appears that levels have been increasing from 2002-2007, as indicated by monthly grab samples at NERR sites (Figure 8). There are also differences among sites that have various degrees of tidal restriction. Brackish sites that are downstream of the Old Salinas River channel tend to have the highest chl *a* concentrations, presumably due to the high concentrations of nitrate coming down the Salinas River (Figures 6a and 9). Tidally restricted sites also have very high chl *a* concentrations probably due to increased residence times (Figure 9), and for all sites chl *a* concentrations are highest during the summer and fall.

Ephemeral algal blooms: Secondary Indicator

Secondary indicators of eutrophication include algal blooms and periods of hypoxia or anoxia (Bricker et al. 2003). Elkhorn Slough naturally has the ephemeral alga *Ulva* spp, which is an eutrophication indicator (Ho 1981) due to its rapid uptake of nutrients (Fong et al. 1994, Ho et al. 1999). Over the last 20 years it has been observed to be increasing along the main channel of Elkhorn Slough due to the increase in its optimal mudflat habitat, and potentially due to increased nutrients (Zimmerman and Caffery 2002). The effects of tidal erosions has caused an expansion of intertidal mudflats and a decrease in *Sarcocornia* marsh, which has increased *Ulva*'s available habitat.

Ulva is an ephemeral (opportunistic and short life span [0-3 months]) alga from the green algal division of Chlorophyta. It is dynamic in respect to its ecology and morphological variation (Abbott and Hollenberg 1976, Hayden et al. 2003). Two distinct forms of *Ulva* can be found in Elkhorn Slough: one (various species) has a distromatic (two cell layers) morphology, and is characterized by sheets that resemble lettuce. The other form (*Ulva intestinaloides*) has a thin tubular monostromatic (one cell layer thick) morphology, and is the most common morphology found in estuaries and Elkhorn Slough (Abbott and Hollenberg 1976, Zimmerman and Caffrey 2002).

Although different in morphology, both types demonstrate similar ecological characteristics, that is, they both can form dense mats that can be either free-floating or attached to the substrate. However, the free-floating mats are primarily formed by *Ulva intestinaloides* and the sheet-forming species are generally found in the benthos (Mike Foster pers. comm.). *Ulva* is generally considered an early successional species, which is capable of occupying free space very rapidly by either recruitment or growth of attached

and free-floating algae (Sousa 1980, Brent Hughes unpublished data). It is also very tolerant to varying levels of salinity (15-35 ppt) (Fong et al. 1996), which makes it an excellent inhabitant of estuaries. Although it is described as having an ephemeral life history it can recruit any time of the year in Elkhorn Slough. It can also be considered a successional climax species in areas where other species of algae do not persist and *Ulva* forms conspicuous populations throughout the year (Mike Foster pers. comm.).

Population dynamics of *Ulva* in Elkhorn Slough remain a puzzle because their populations are highly variable (Schaadt 2005). *Ulva*, like many seaweeds, require attachment to the substrate for spores and gametes to settle and grow. The availability of hard substrate is rare in Elkhorn Slough and in many mudflats may be limited to shell fragments. However, *Ulva* has the ability to form weak attachments to consolidated mud or clay, therefore *Ulva* can often be detached by strong tidal currents, which leads to the formation of conspicuous floating mats. *Ulva* compensates for the lack of suitable habitat for recruitment by growing vegetatively on the substrate or on floating mats. Ebb tides can eventually remove floating *Ulva* mats and export them to Monterey Bay. This detachment and removal frees up more space for subsequent *Ulva* generations. However, in areas of Elkhorn Slough where tidal forcing is low such as in areas behind culverts or residence time is high, *Ulva* can remain for long periods, resulting in varying consequences on water quality and productivity.

Elkhorn Slough is in a phase of rapid tidal erosion (Zimmerman and Caffrey 2002). Percent cover by marsh plants, especially *Sarcocornia pacifica*, has declined dramatically over the past century (Van Dyke and Wasson 2005), which could have a profound effect on ecosystem function by stabilizing substrata, filtering of dissolved

nutrients, and providing habitat for a number of species (Callaway and Sabraw 1994, Zimmerman and Caffrey 2002). Erosion of marsh habitat into mudflats enables a competitively inferior species, such as *Ulva*, to become a dominant species in Elkhorn Slough. *Ulva* can also have negative consequences for seagrass (*Zostera marina*) communities because of its sensitivity to light and the shading capabilities of floating *Ulva* mats (Zimmerman and Caffrey 2002). However, the overall positive and negative effects of *Ulva* in Elkhorn Slough have yet to be experimentally determined. *Ulva* affects mudflat invertebrate community composition by alleviating thermal and desiccation stress for epifaunal species during low tides, and providing a nutritional resource (Pregnall and Rudy 1985, Allen 1992). In contrast, infaunal communities can be negatively affected by high *Ulva* biomass leading to anoxic conditions and alteration of biogeochemical pathways (Nelson et al. 2003). Certain locations in Elkhorn Slough that have noticeable deposits of senescent or decaying *Ulva* have decreased benthic invertebrate diversity, as well as shift in community assemblages from invertebrate to bacterial dominated (Brent Hughes pers. obs., John Oliver, pers. comm.).

Ulva has also been reported to produce an annual biomass (4,000 Mg dry weight) that is equal to or greater than that of the main salt marsh plant *Sarcocornia pacifica* (1,600 to 3,200 Mg dry weight) (Onuf et al. 1978). Most of the biomass gets washed out into Monterey Bay due to detachment of benthic populations, which form floating mats (Figure 10). Like chl *a*, peak *Ulva* abundance is found during the summer months when surface irradiance and day length is greatest (Figures 11 and 12). *Ulva* dynamics differ due to tidal restriction, where areas that are tidally restricted have a greater residence time of *Ulva* mats due a decreased tidal range (Figure 13) (Valiela et al. 1997, Fry et al. 2003,

Schaadt 2005). *Ulva* mats in Elkhorn Slough range in biomass from 75-200 g Dry Weight/m². *Ulva* reaches a “critical threshold” for this biomass where local water quality shifts from productive to lethal anoxic conditions (Viaroli et al. 1996). This may be due to *Ulva*'s ability to facilitate the abundance of invertebrates and bacteria within floating and benthic mats, whose oxygen demand surpasses the oxygen production of *Ulva* (McGlathery et al. 2007, Nezlin et al. 2006). This becomes evident at night when invertebrate and/or microbial communities deplete oxygen supplies due to decreased photosynthetic activity and increased respiration rates of *Ulva*. These communities could also be facilitated by live or decomposing *Ulva* populations whose biomass can sink to the bottom creating an organic layer, if it is not transported out to Monterey Bay by tidal currents.

The effect of persistent *Ulva* populations could be attenuated by increased residence times as well as available habitat (Valiela et al. 1997). Hudson's Landing is a good case study because it has a mixture of mudflat and fringe marsh (van Dyke and Wasson 2005) (Figure 14). However, if residence time was increased in an area, such as Parson's Slough, which has the largest mudflat habitat in Elkhorn Slough, this could facilitate increased *Ulva* productivity, and potentially have adverse effects of dissolved oxygen. Like Elkhorn Slough, Newport Bay has many of the same conditions: hypoxia events occurring near the head, at night, in the summer, and more frequently in shallower waters and it was observed that *Ulva* in Newport Bay explained 75% of the variability of dissolved oxygen values <5.0 mg/L (Nezlin et al. 2006).

Dissolved Oxygen and Stratification: Secondary Indicator

The combination of nutrient driven primary productivity, and reduced tidal flow leads to the hypoxic (>0 -30% or <2 mg/L DO) or even anoxic (0% DO) conditions, which commonly occur at areas with high residence time and extensive mudflats as well as tidally restricted areas in Elkhorn Slough (Fig. 15) (Diaz 2001). Hypoxia is a good measurement of overall water condition due to the importance of providing benthic organisms and fish with oxygen. Areas with low tidal mixing limits the amount of oxygenated water entering the system and over time can create a stratified water column that also limits benthic oxygen supply (Fig. 16). Pronounced hypoxia or anoxia events occur in the summer months when primary productivity leads to an increase in oxygen demand and high temperatures increases stratification which depletes bottom mixing and thus dissolved oxygen levels (Diaz 2001).

Hypoxia can be a primary consequence of decreased tidal flow which increases water residence time and temperature, or a secondary product of eutrophication through the process of increased primary productivity that leads to changes in benthic oxygen demand through increased organic deposition, dissolved oxygen consumption, and microbial activity. Over time, the increased production and deposition of phytoplankton and ephemeral algae changes certain biogeochemical pathways that could have long-term effects (McGlathery et al. 2007). After the organic bottom-layer is fully developed by marcoalgal deposits, the community switches from an ephemeral algal dominated to one that is anoxic and microbial dominated. This turns on the denitrification process and the sites become a nitrogen sink and also a “dead zone” (Diaz et al. 2008), which has been observed at Strawberry Pond in Elkhorn Slough (Brent Hughes pers. obs.). These “dead

zones” can be seasonal or permanent depending on location. In general, hypoxia starts negatively affecting biota when dissolved oxygen levels drop below 2 mg/L or 30% (Diaz 2001), and the United States Environmental Protection Agency (2000) has recommended a 2.3 mg O₂/liter for juvenile and adult aquatic organism survival. Upper limits of “hypoxic” conditions may be set to 5.0 mg/L as an ideal benchmark for biota (Nezlin et al. 2006).

Less extreme cases of hypoxia occur along the upper end of the main channel, from Kirby Park to Hudson’s Landing. Residence time can vary dramatically (1-50 days), with greater residence times occurring during the summer dry season (Largier 1997, Caffrey 2007). The seasonal consequences can lead to similar, yet less dramatic, ecological consequences as the more restricted sites due to hypoxia. Such is the case at Kirby Park where dissolved oxygen can fall below 2.0 mg/L during the summer (28% Dissolved Oxygen) (Figure 17).

Areas of Elkhorn Slough experience increased residence times due to man-made structures such as dikes, culverts, and flood gates, reducing the tidal range at these sites to 0-40% of the tidal range in the rest of the estuary (Ritter et al. 2008). These are usually extreme cases that lead to residence times that can last weeks. These extreme cases occur at Moro Cojo Slough, Azevedo Pond, North Marsh, and Strawberry Pond among others, and lead to increased floating macroalgal mats (Figures 10 and 12), increased periods of anoxia and hypoxia (Figures 15 and 16), increased phytoplankton production (Figures 8 and 9) and increased ammonia production caused by increased microbial activity (Beck and Bruland 2000, Caffery 2002, Los Huertos 2008). Conditions worsen in these areas during the summer when productivity and stratification is greater.

Indicators Conclusion

Indications of the level of eutrophication of Elkhorn Slough indicates that it is a highly eutrophic estuary. ESNERR data collected monthly from 1992-2007 was assessed for primary indicators: nutrients and chl *a*, and secondary indicators: macroalgal blooms and hypoxia events. All locations experienced some degree of eutrophication, and most sites have persistent indications of eutrophication. Data lumped among all tidally influenced sites indicate that Elkhorn Slough as a whole is consistently affected by eutrophication. The nutrients contributing to eutrophication: nitrate, phosphate, and ammonia, are elevated at most sites and are higher closer to the effluence of the Salinas River. Most sites have elevated concentrations of chl *a*, with the lowest concentrations occurring near the mouth of the slough where tidal flushing is greatest. Hypoxic events are also rampant at many locations in the slough, and like high chl *a* concentrations, occur less frequently near the mouth. *Ulva* blooms occur everywhere in the slough, but their persistence is dependent on tidal flushing and the size of the intertidal mudflat.

Potential Impacts to Key Estuarine Animal and Plant Species

Elkhorn Slough has a rich invertebrate (~550 spp.), fish (102 spp.) and bird (137 spp.) biodiversity (Wasson et al. 2002, Yoklavich et al. 2002, Harvey and Connors 2002). This species richness is one reason why researchers are concerned about the rapid change in Elkhorn Slough brought on by anthropogenic effects. One of the main concerns is the ecological consequences of eutrophication to key species of concern in Elkhorn Slough. Diversity of macrophytes is not as high as other groups in Elkhorn Slough (~45 species) (DeVogelaere et al. 1998) with only 4 species contributing to 90% of the overall biomass, yet their importance to slough community dynamics is unquantifiable. Decreases in tidal flushing and increases in nutrient loads can lead to hypoxic conditions, blooms of the ephemeral alga *Ulva* spp., and degradation of the main salt marsh plant *Sarcocornia pacifica* by competitive interactions with *Ulva*. The latter effect is of particular interest because salt marsh plants act as an important foundation species for community dynamics because they are exceptionally good at ameliorating environmental stress, providing and stabilizing habitat, increasing the overall diversity, and decreasing the invasibility of the marsh (Bruno et al. 2002). *Ulva* has been observed to grow as an epiphyte on *S. pacifica*, and algal mats have the capability of shading new shoots, thus preventing expansion of marsh at its lower limits.

Eelgrass (*Zostera marina*) forms an important habitat for many species of fish and invertebrates, yet is very sensitive to shading (<3% irradiance) which can be due to sediment and chlorophyll turbidity as well as shading by macroalgae (Smith and Horne 1988). Eelgrass can also be very sensitive to low dissolved oxygen (an indicator of

eutrophication) levels (2.96 mg/L) (Pederson 2004). Therefore, it may be limited to areas of Elkhorn Slough not affected by eutrophication. This becomes evident when looking at the distribution of eelgrass is limited to the lower slough away from the deleterious effects of eutrophication, such as increased phytoplankton and *Ulva* production that occur in the upper slough.

There have been some documented changes to invertebrate and fish communities in Elkhorn Slough (Wasson et al. 2002, Yoklavich et al. 2002). However, many of these changes have been attributed to marine invasions by non-native species and tidal erosion, and not so much to eutrophication. However, eutrophication has not been ruled out as a suspect to changes in communities (Ritter et al. 2008, John Oliver, unpublished data). Sites that have high eutrophic signatures have noticeably less biodiversity of algae, eelgrass, invertebrate, fish, and shorebird communities.

A community that was historically dominated by benthic invertebrates, fish and sea-grass can turn into one dominated by ephemeral algae, small benthic consumers and microbes depending on the tolerance of dissolved oxygen levels of local inhabitants (Fong 1993, Cloern 2001, McGathery et al. 2007). Less dramatic hypoxia levels or higher organismal thresholds may lead to sublethal stress that reduces growth and reproduction, available habitat, and increases in migration and predation (Vaquer-Sunyer and Duarte 2008). However, if a key trophic link is lost this can disrupt the entire community causing a cascading effect (Paine 1969, Estes and Palmisano 1974, Carpenter and Kitchell 1993). Hypoxia effects are species dependent, and species sublethal tolerance ranges from 0 mg/L for certain species of oysters to 8.6 mg/L for the larval stages of *Cancer* spp. crabs (Vaquer-Sunyer and Duarte 2008). Certain crustaceans also

have low-tolerances to hypoxia, and this can become important to ecosystem function because they are important consumers in the food chain. Also, species of bottom fishes such as halibut, sole, and sculpins have low tolerance to hypoxic conditions. These fish are found in Elkhorn Slough, and little is known about their persistence in hypoxic conditions.

Observations in ecological shifts have been observed due to differences in residence times along the main channel of Elkhorn Slough. Phytoplankton communities differ from the lower part of the slough near the mouth to the upper part of the slough near the head. It has been hypothesized that these differences can be attributed to residence times (Welschmeyer et al. 2007). The upper part of the slough is characterized by algal cryptophytes, and denitrifying and anoxygenic bacteria, which is typical of communities that are under stress of hypoxia and eutrophication. In contrast, the well flushed lower slough, although higher in nutrients, is composed of seagrass and phytoplankton communities, such as diatoms, which are typically found in Monterey Bay.

Increased residence time can also lead to the increase in the deposition of organic material. The upper slough (Hudson's Landing) is characterized by a surface sediment layer that is dominated by organic material (Ivano Aiello, pers. comm.). There is also a persistent and almost continuous layer of *Ulva* sp. on the intertidal mudflat (Brent Hughes pers obs.). The upper slough is also characterized by a higher cover and biomass of *Ulva* than in the lower parts of the slough (Schaadt 2005). The deposition of organic material can facilitate microbial communities coupled with increased residence times and nocturnal respiration of algae could lead to lethal and sublethal hypoxic conditions for the

local inhabitants (Figure 17). There has been an overall decline of invertebrate and fish species at Hudson's Landing over the last 30 years (Wasson et al. 2002, Yoklavich 2002). However, these studies have not directly linked to hypoxia to these declines.

To date there has not been an adequate study that has investigated the trophic dynamics in Elkhorn Slough. The altered states driven by eutrophication could have a strong influence on the trophic dynamics in Elkhorn Slough, especially for species with a persistent dissolved oxygen demand, such as sharks and skates (Cloern 2001). However, other upper-trophic members such as birds, harbor seals, and sea otters might not be as affected because their populations are mainly driven by habitat availability (Jim Harvey, pers. comm.), but these populations could be affected by decreases to their prey populations by eutrophication (Raffaelli et al. 1998).

Are the consequences of eutrophication irreversible?

The possibility of returning an ecosystem to the same conditions after a dramatic disturbance is very unlikely due to the theory of shifting baselines and “natural” changes (Jackson et al. 2001, Duarte et al. 2008). The consequences of hypoxia are often slow and not completely reversible, and is dependent on post-restoration processes (Diaz 2001, Duarte et al. 2008, Vaquer-Sunyer and Duarte 2008). The simplest way of reversing hypoxia in a wetland with high artificial tidal restriction is by restoring an area to tidally non-restricted conditions; this can bring in oxygenated water on a regular basis as well as flushing out the organic benthic layers, but the consequences is that over time any new sedimentation could be eroded due to increased current velocities. Another way of reversing the effects of hypoxia is by reducing the nutrient loading of the system. For example, in a matter of a few years areas such as the Hudson River in the United States and the Thames Estuary in England have reversed the anoxic “dead zones” to normal dissolved oxygen conditions by managing nutrients (Diaz 2008). However, areas of the Chesapeake Bay have not been able to recover after management of nutrients and still retain some of their “dead zones”.

The period that an area has had changed dissolved oxygen conditions will determine how fast or if it can recover. In Gullmarsfjord, Sweden a fjord that was exposed to eutrophic fueled hypoxia for a period of 0.5 year was able to recover after 2 years to full ecological stability (Rosenberg et al. 2002). However, the “dead zone” in the Black Sea caused by communist era agricultural practices took 10 years to recover after a 2-4 fold decrease in nutrient input (Mee et al. 2005). Recovery of an ecosystem is not only controlled by environmental factors, but also the life-histories of animals and

primary producers. For example, certain clam populations can take up to 20 years for a full recovery after a disturbance. It has been suggested that if an area has been affected by anoxia or hypoxia for more than 5 years, then recovery will be long-term (>10 years) (Diaz and Rosenberg 2008).

Present and Future Eutrophication Research

The Elkhorn Slough National Estuarine Research Reserve (ESNERR) is currently conducting a multi-spatial yet short-term (9 month) monitoring project to determine the level of eutrophication that is occurring in Elkhorn Slough. Preliminary and historical data from the ESNERR Volunteer Water Quality Monitoring Program suggests that Elkhorn Slough is a highly eutrophic estuary based on the guidelines presented by Bricker et al. (2003) and Fry et al (2003). These analyses only include nitrate not total dissolved inorganic nitrogen as suggested by Bricker et al. (2003), which would make nitrogen levels in Elkhorn Slough even higher. Chlorophyll data is a rough estimate from YSI data Sonde probes, and their level of accuracy may not be adequate. Secondary eutrophic indicators have yet to be determined for all of the sites. Algal blooms (*Ulva* spp.) are of particular importance in Elkhorn Slough and benthic blooms can be seen year round in tidally restricted and non-restricted areas (Schaadt 2005, Brent Hughes pers. obs., Mike Foster pers. comm.). Also, conspicuous floating mats are a common occurrence in tidally restricted areas during the summer and fall months, possibly due to increased sunlight and high residence time (Brent Hughes (ESNERR) unpublished data). Hypoxic conditions are also a secondary indicator and nightly hypoxic conditions are observed at almost all tidally-restricted sites.

Extending the water quality monitoring program will be essential to evaluating levels of eutrophication in Elkhorn Slough. However, experimentation will be needed to determine the ecological effects of eutrophication (Mike Foster and John Oliver pers. comm.). This would include simple removal experiments that would determine the magnitude of the effects of *Ulva* on *Salicornia*, benthic communities and trophic

dynamics. This would also involve determine what drives local dissolved oxygen levels: algae, benthic consumers, residence time, or all of the above. After that is determined, it would be important to investigate the ecological consequences of persistent hypoxic or anoxic events on the local biota.

The predictability of long-term consequences of hypoxia is difficult without data that could suggest the effects on the biota that are being affected. Elkhorn Slough is filled with pockets exposed to hypoxic conditions, such as Moro Cojo Slough, Azavedo Pond, Struve Pond, and North Marsh and to a lesser extent Kirby Park and Hudson's Landing. These areas would be ideal to investigate hypoxia because they are variable in terms of nutrient levels and primary productivity.

Conclusions

Elkhorn Slough is an estuary that has been changed by various anthropogenic influences. One of the main influences has been non-point source nutrient loading from the Salinas Valley watershed. Elkhorn Slough and the Old Salinas River Channel have some of the highest reported nitrate, phosphate, and ammonia levels in the world. This nutrient loading has presumably caused an indirect shift in certain areas of the slough due to changes in primary productivity. Data from Elkhorn Slough indicate that it is a highly eutrophic system due to nutrient loading, hypoxic conditions, and presence of algal blooms. The degree of eutrophication varies temporally and spatially, but is persistent all year long in most areas of the slough. A full ecological study on the effects of eutrophication has yet to be done in Elkhorn Slough. However, reports from Elkhorn Slough have found changes in primary production, community assemblages, biodiversity, and loss of trophic function in areas with the most indicators of eutrophication.

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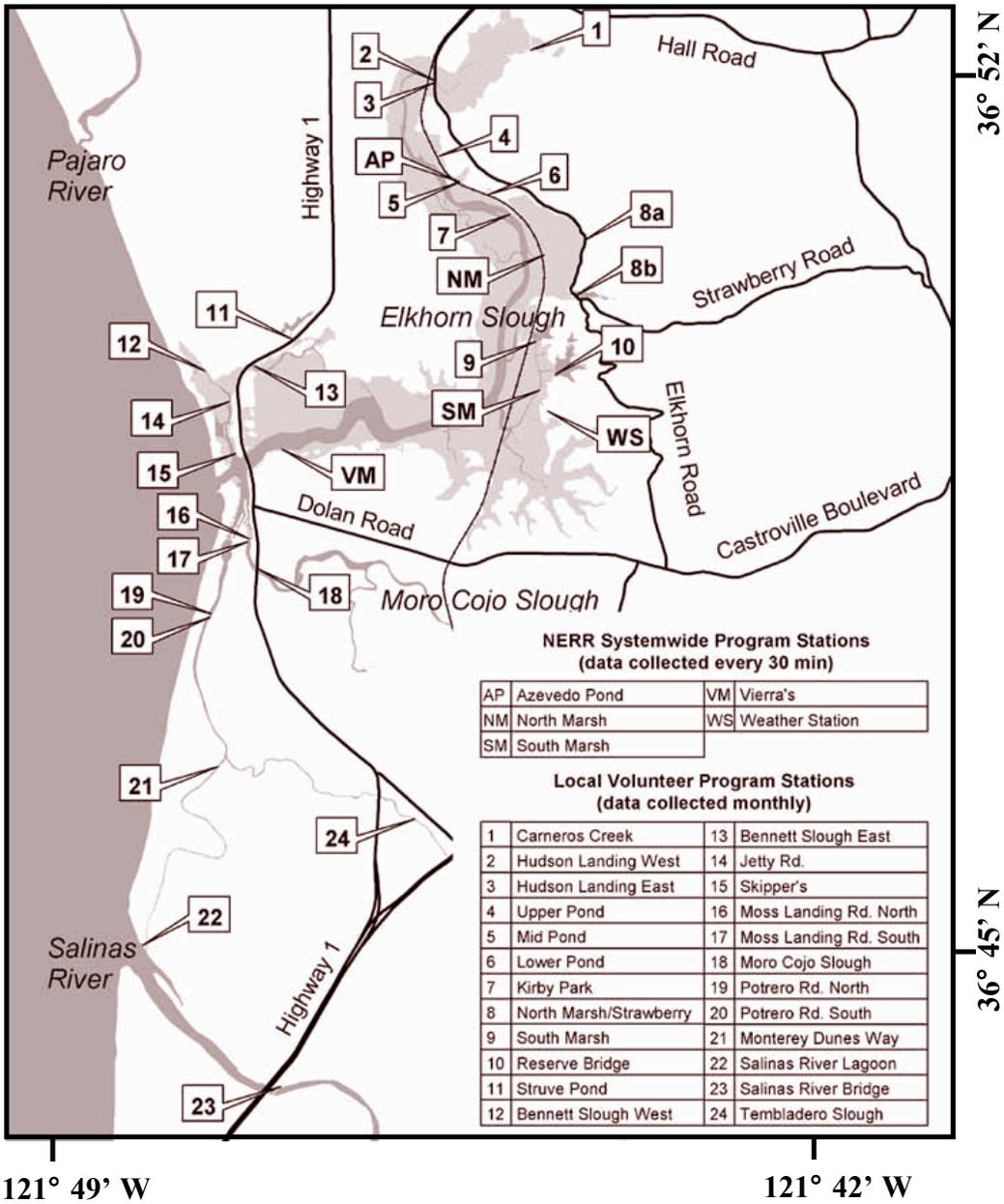


Figure 1. Elkhorn Slough, with labeled NERR and volunteer monthly water quality stations. Site codes are as follows: 1=CC, 2=HLW, 3=HLE, 4=APN, 5=APC, 6=APS, 7=KP, 8=STB, 9=RSM, 11=SP, 13=BSE, 14=JR, 15=SKL, 16=MLN, 17=MLS, 18=MCS, 19=PRN, 20=PRS, 21=MDW, 22=SRL, 23=SRB, 24=TS.

Table 1. Dissolved nutrient concentrations from various estuaries around the world. Data from Caffery et al. (1997) and Cafferey (2002).

Location	Nitrate mg/L as NO₃⁻	Phosphate mg/L	Ammonium mg/L
Elkhorn Slough	<1-130	<0.03-0.06	0-8.26
Salinas River	<1-360	<0.03-0.7	0-91
Monterey Bay	0-2	0.01-0.02	N/A
69 Danish lakes	2-40	N/A	N/A
Norsminde Fjord, DK	0.4-60	N/A	N/A
Morlaix River, FR	3-50	0.6-0.3	N/A
Morlaix, FR	1.3	0.06	N/A
Scheldt estuary	9-30	N/A	N/A
Peel Inlet, Australia	150	N/A	N/A
Harvey Estuary, Australia	2.2	0.01-0.15	N/A
Shenzhen Bay, China	0.4-4	0.05-1.2	N/A
Changjiang Estuary, China	4.4	0.02	N/A
Chesapeake Bay			
-riverine	4.4	0.01	0.01-0.24
-shelf	0.1	0.02	0-0.07
Delaware Bay			
-riverine	9	0.08	0.03-0.7
-shelf	0.9	0.04	0.01-0.17
Hudson River			
-riverine	2	0.04	0.03-0.77
-shelf	0.4	0.04	0.08
North San Francisco Bay	1.3-9	N/A	0.01-0.14
South San Francisco Bay	0.6-6	0-0.2	0-0.42
Tomales Bay	0-2	0.02-0.12	0-0.11
Septic Tank Effluent	20-70	N/A	N/A
Secondary Sewage	22-220	25	N/A

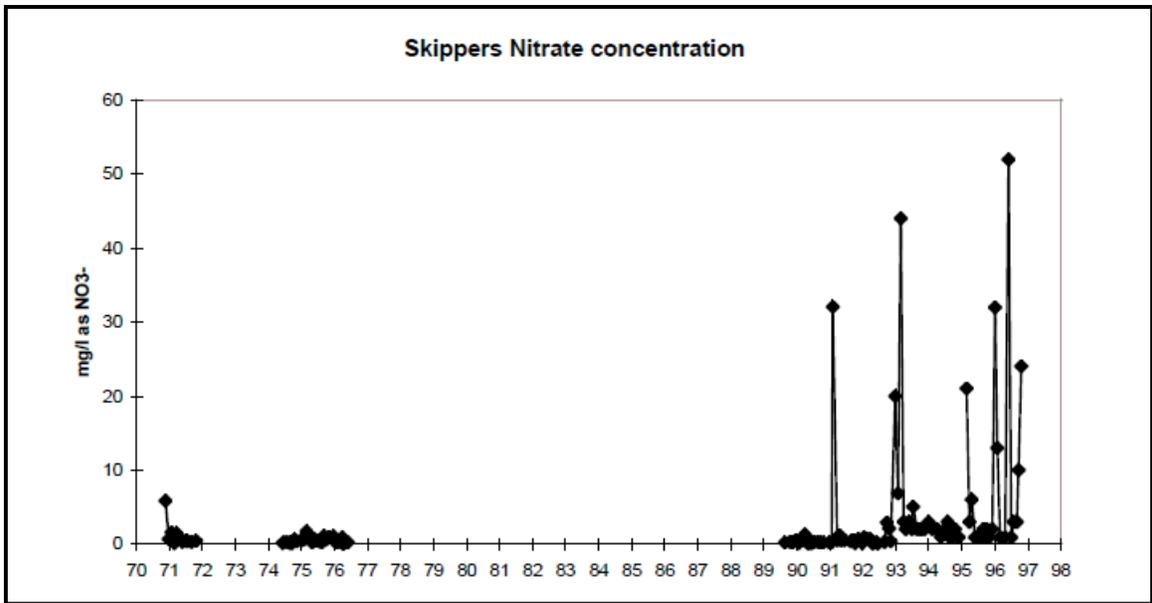


Fig. 2. Nitrate concentrations from the mouth of Elkhorn Slough between 1970 and 1996. Figure Source: Cafferey et. al. 1997.

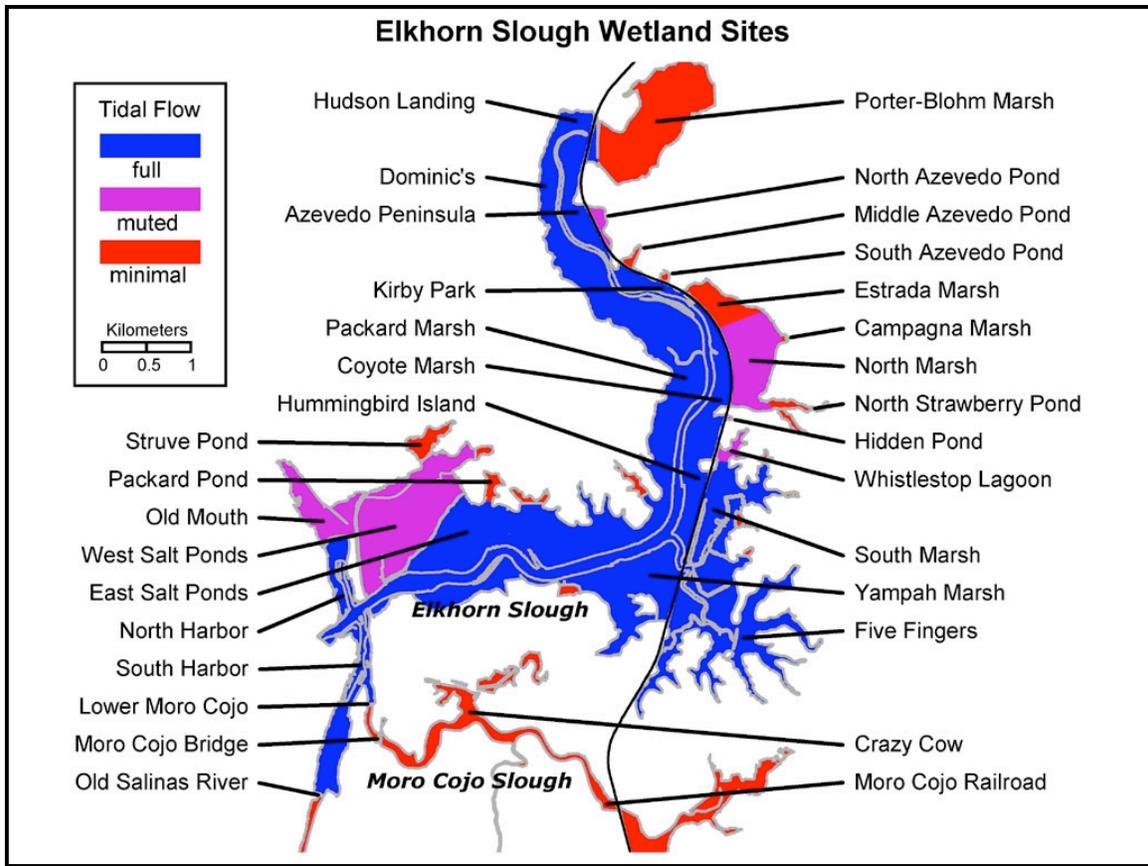


Figure 3. Variation in tidal flow at Elkhorn Slough. Labeled sites are commonly sampled by the ESNERR for water quality and other parameters (Source: Kerstin Wasson).

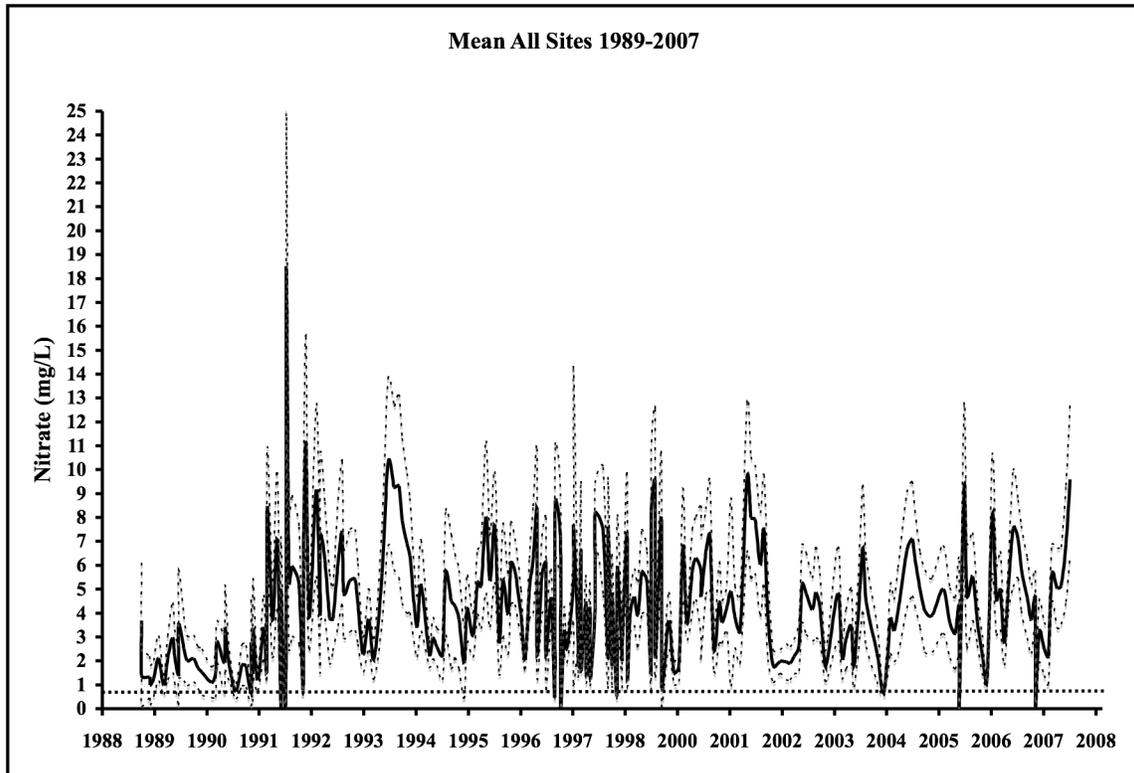


Figure 4. Mean monthly nitrate samples from 27 sites in Elkhorn Slough from 1989-2007. Straight dotted line indicates eutrophic levels as described by Bricker et al. (2003). Curved dotted lines are standard error of the mean among sites.

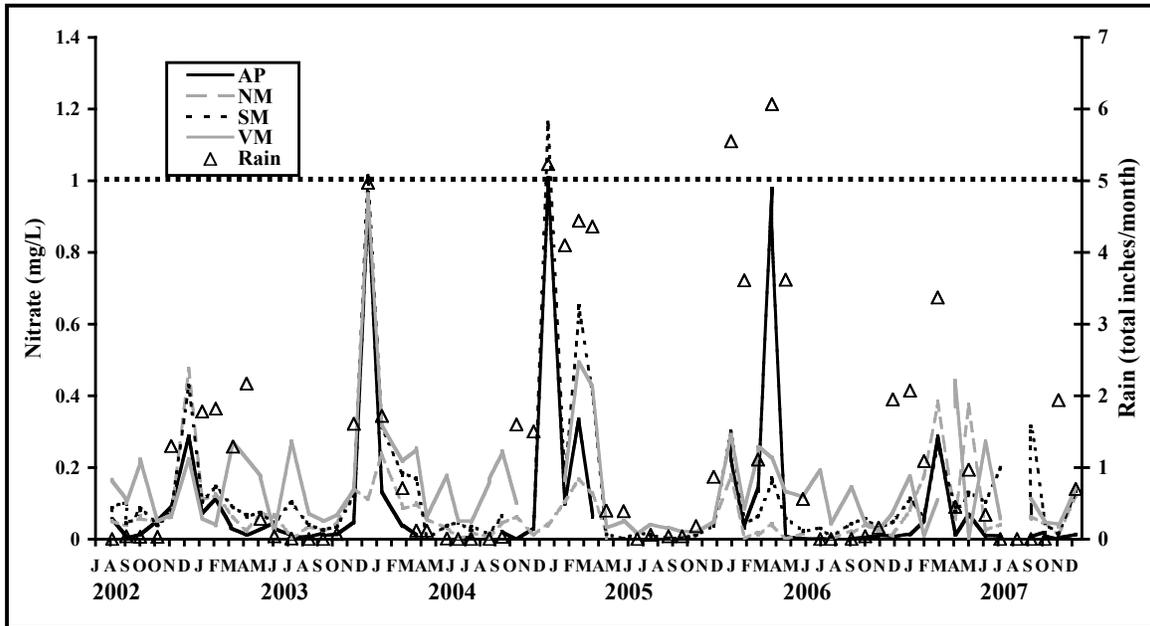


Fig 5. Monthly nitrate concentrations from grab samples at 4 sites in Elkhorn Slough from 2002-2007 along with monthly rainfall. Azavedo Pond (AP, upper slough) and North Marsh (NM, mid slough) are tidally restricted sites, and South Marsh (SM, mid slough) and Vierra Mouth (VM, lower slough) have full tidal exchange. . Straight dotted line indicates eutrophic levels as described by Bricker et al. (2003)

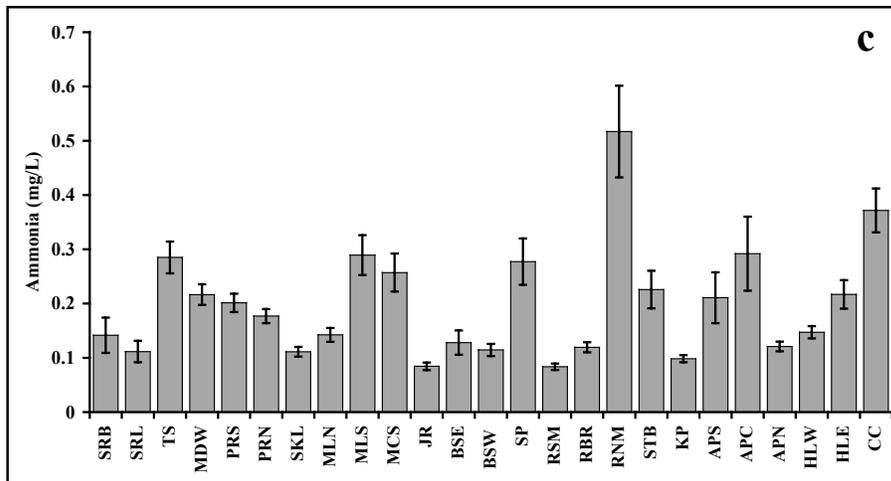
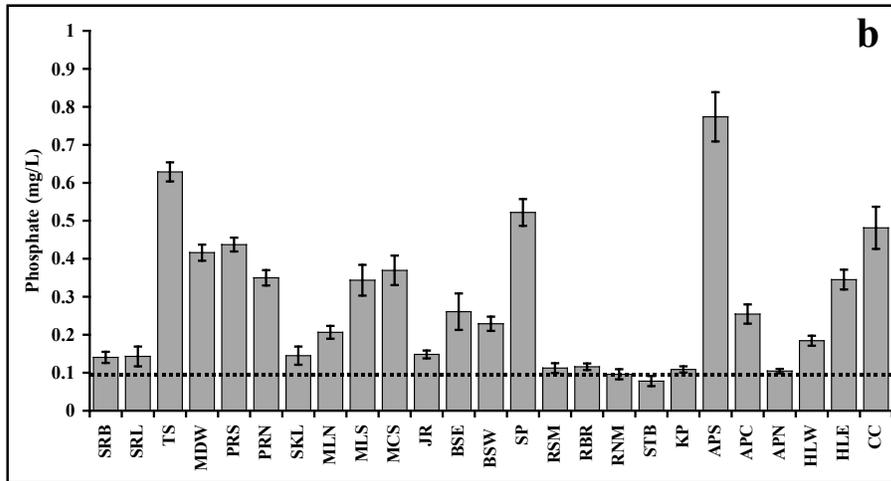
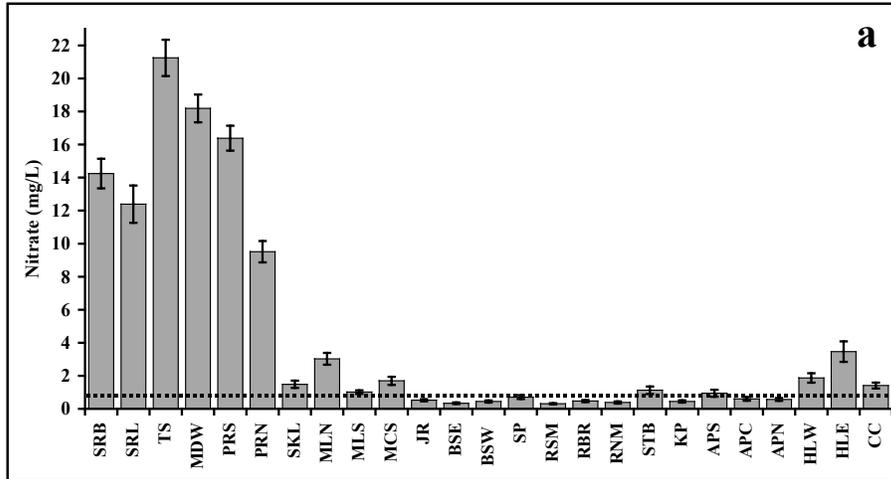


Figure 6a-c. Mean nutrient levels for 25 sites in Elkhorn Slough sampled monthly from 1992-2007. Sites are ordered based on proximity to the Salinas River with sites closest at the left. Refer to Figure 1 for station codes. Error bars are standard error of the mean.

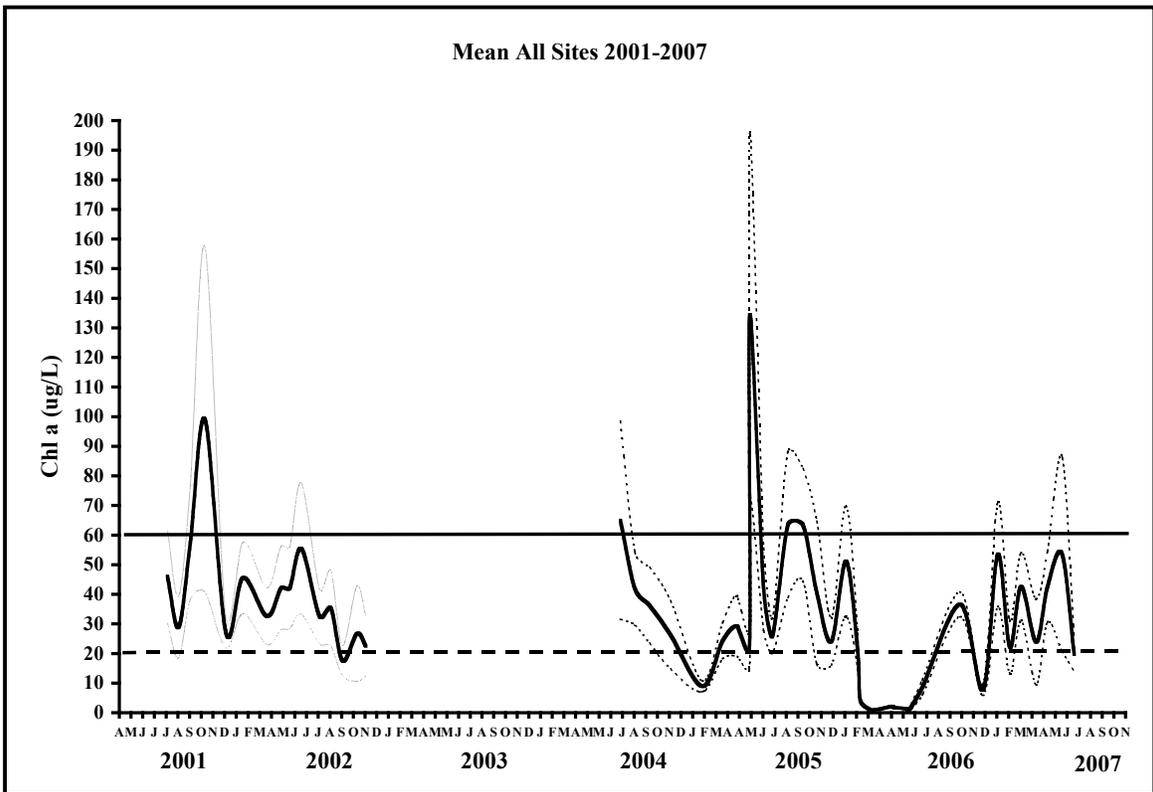


Figure 7. Mean monthly chl *a* readings from YSI chlorophyll probes at 27 stations along Elkhorn Slough. Straight dotted line indicates high eutrophic conditions, straight bold line indicates hypertrophic conditions. Curved dotted lines indicate SE.

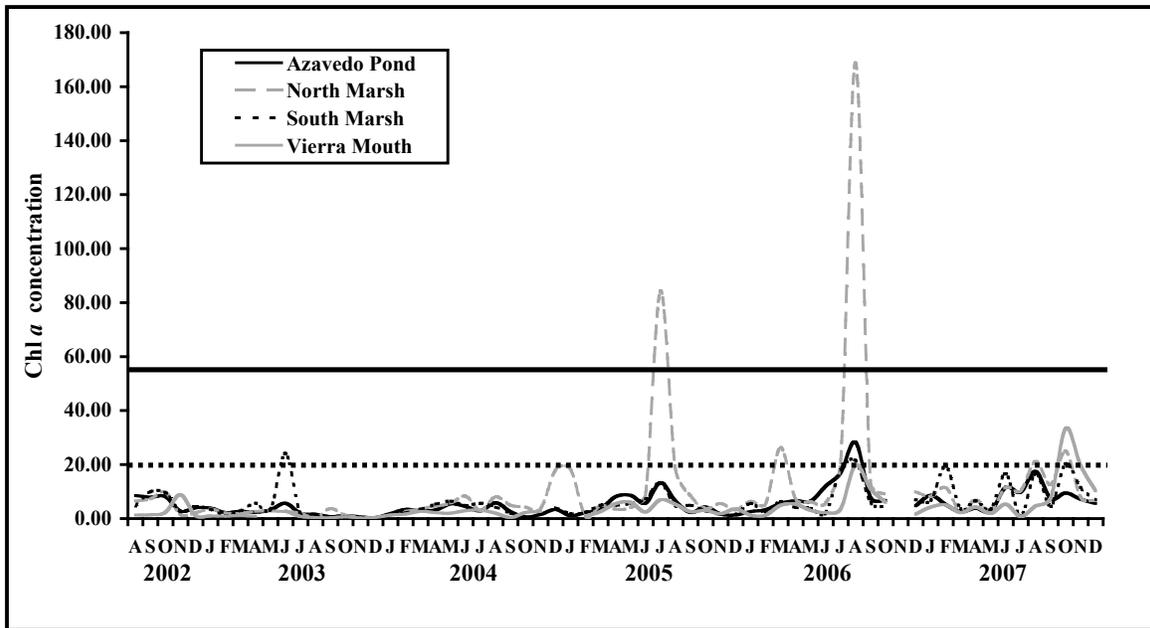


Figure 8. Chl *a* concentration (ug/l) from monthly grab samples at four sites in Elkhorn Slough. Azevedo Pond (upper slough) and North Marsh (mid slough) are tidally restricted sites, and South Marsh (mid slough) and Vierra Mouth (lower slough) have full tidal exchange. Straight dotted line indicates high eutrophic conditions, straight bold line indicates hypertrophic conditions.

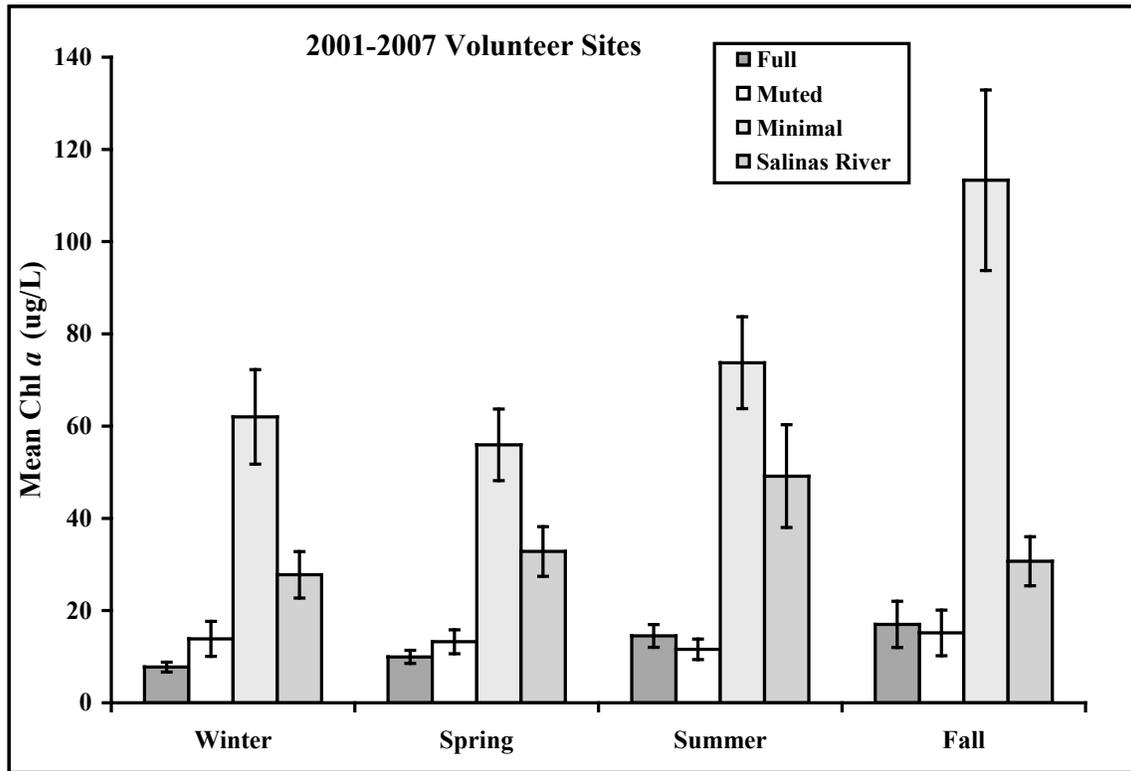


Figure 9. Mean chlorophyll a concentrations collected monthly from 25 stations in Elkhorn Slough. Sites were grouped based on tidal restriction (full, muted, and minimal) or if directly downstream from the Salinas River. Data was collected using YSI data Sondes.



Fig. 10. Floating *Ulva* mat, blooming at a tidally restricted site (Moss Landing Road South) from summer 2007.

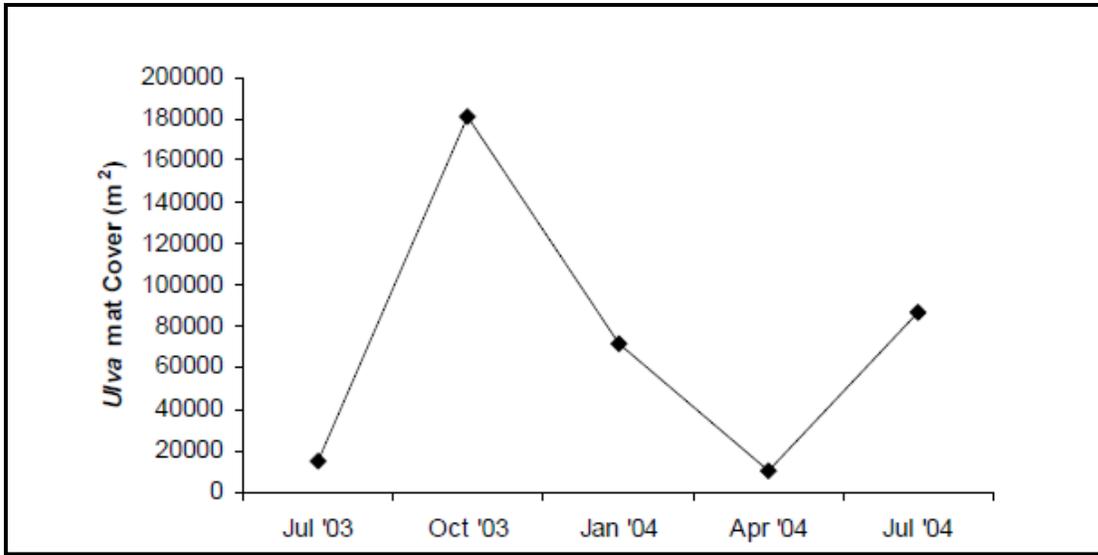


Fig. 11. *Ulva* benthic mat cover from the main channel (not tidally restricted) (Schaadt 2005).

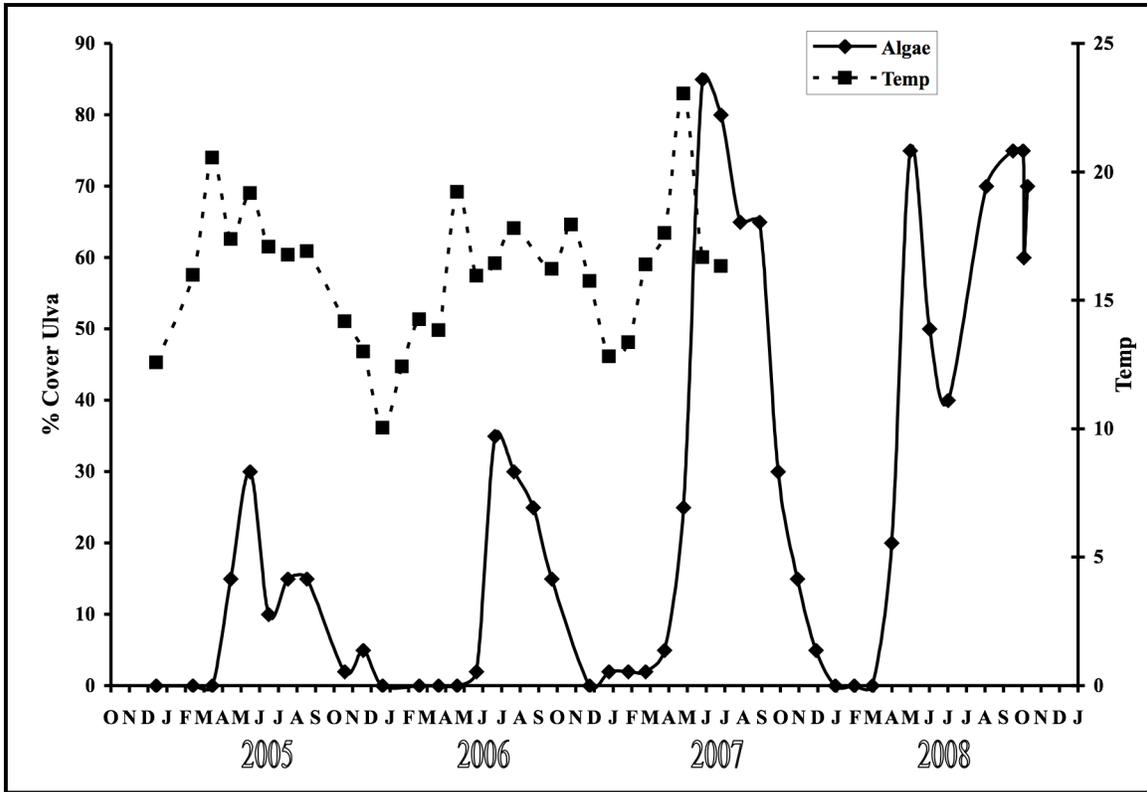


Fig. 12. *Ulva* floating mat % cover (2001-2008) from a tidally restricted site and corresponding temperature readings (2001-2007) (Moss Landing Road South).

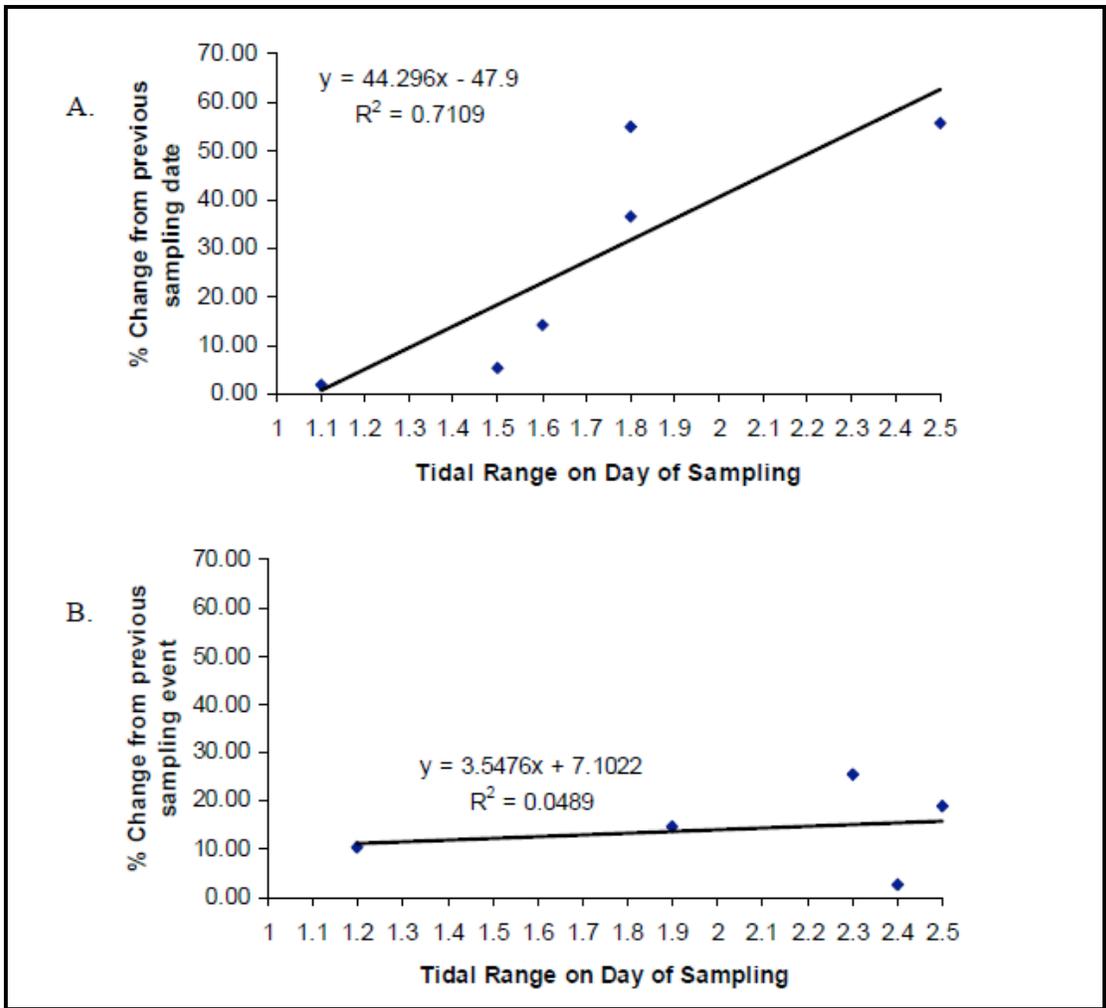


Figure 13. Differences in changes in benthic *Ulva* cover between a non-restricted flow site (A) and a restricted flow site (B) (Schaadt 2005).

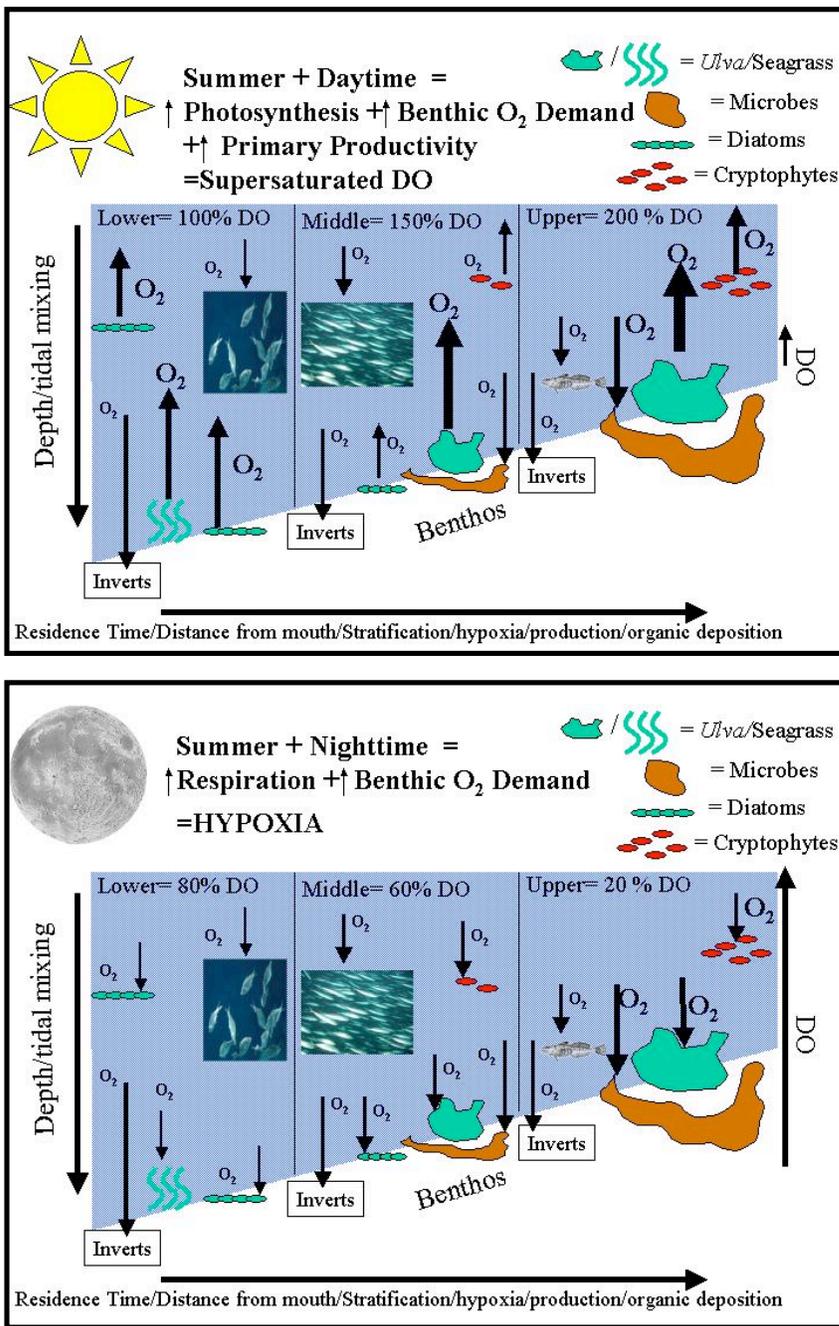


Figure 14. Conceptual model of the summer dissolved oxygen budget in Elkhorn Slough. Data and information used to generate this model comes from: Hughes (unpublished data), Fong (1993) Valiella et al. (1997), Cloern (2001).Yoklavich (2002), Schaadt (2005), Nezlin et al. (2007), Welschmeyer et al. (2007).

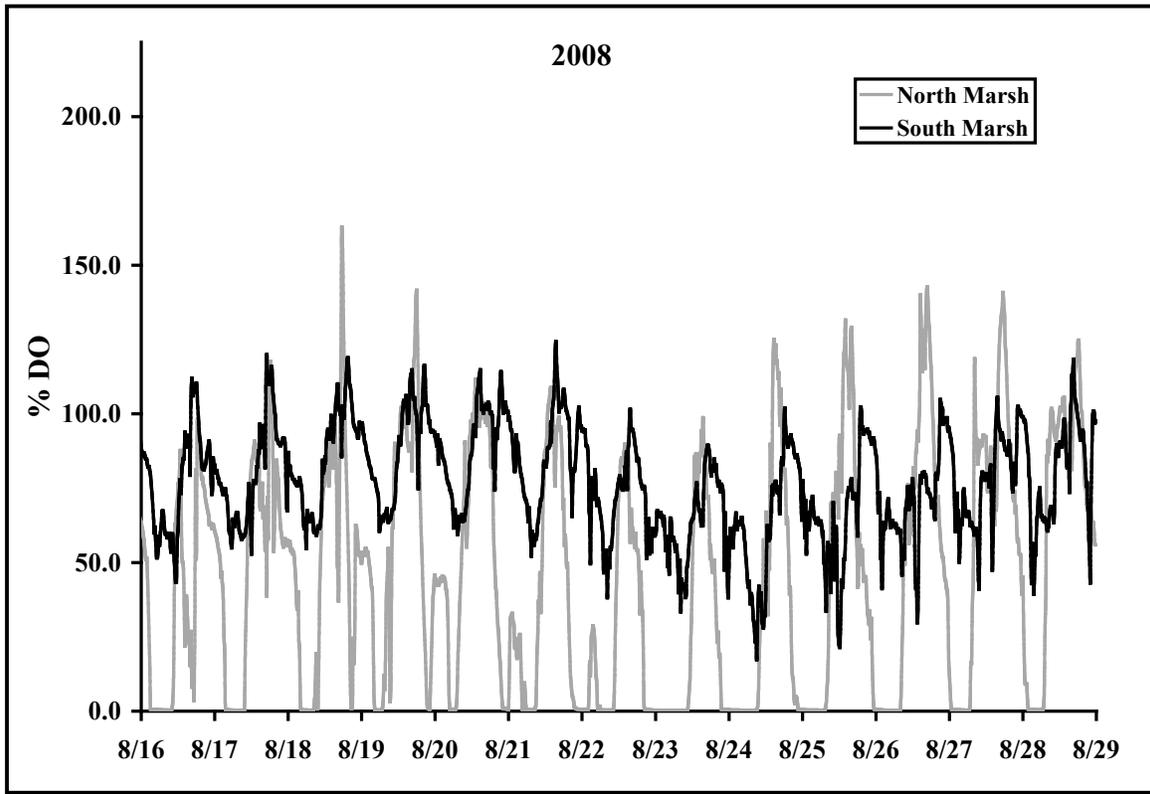


Figure 15. Dissolved Oxygen at a tidally restricted (North Marsh) and tidally non-restricted site (South Marsh).

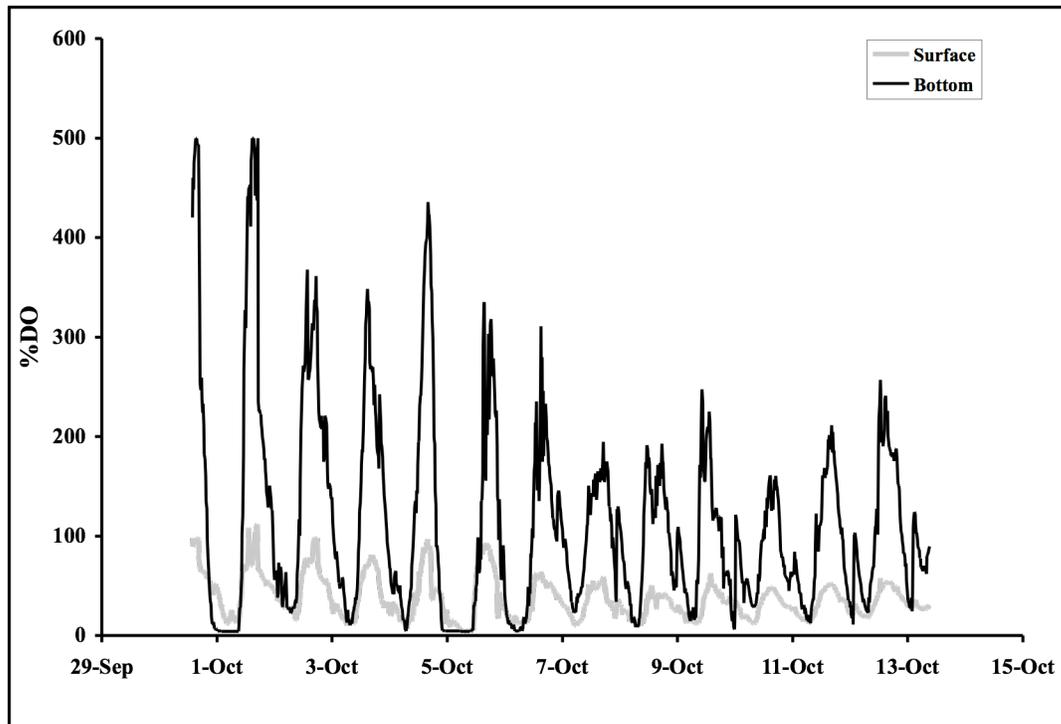


Figure 16. Stratification of dissolved oxygen at a tidally restricted site (Moro Cojo Slough) during a lunar tidal cycle in 2008.

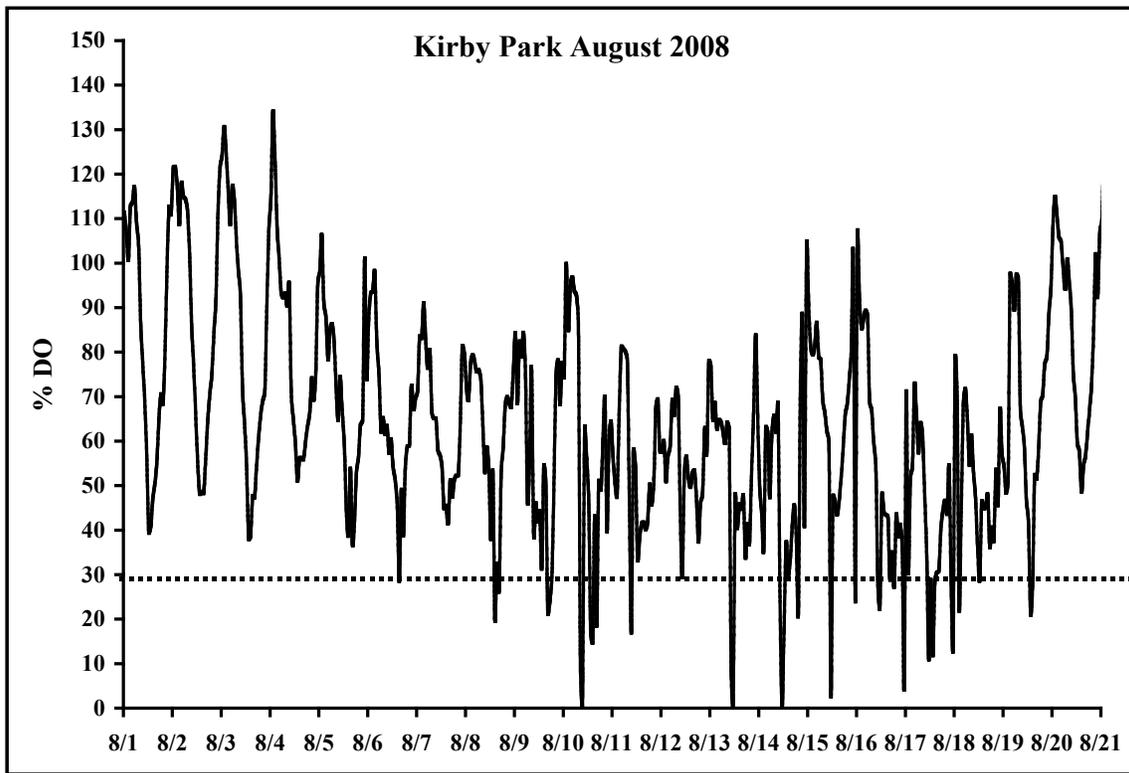


Figure 17. Summer dissolved oxygen at a non-restricted tidal site in upper Elkhorn Slough that has an increase in residence time and primary productivity compared to the lower slough. Dotted line indicates hypoxic conditions. Data from the Monterey Bay Aquarium Research Institute LOBOviz (v. 3.0) (<http://www.mbari.org/lobo/loboviz.htm>).