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Moritsch, Monica

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Associations among Plankton Abundance, Water Quality and Sediment Quality in the San Francisco Bay: Nitrogen and Phosphorus

Monica Moritsch[1], Anna Szendrenyi[2], Charlotte Leger[3], Bryan Frossard[4]

[1]*Molecular Environmental Biology, College of Natural Resources,*
University of California, Berkeley
[2]*Enrionmental Sciences, College of Natural Resources,*
University of California, Berkeley
[3]*Conservation Resource Studies, College of Natural Resources*
University of Calirfornia, Berkeley
[4]*Integrative Biology, College of Letters and Sciences*
University of California, Berkeley

Department of Molecular & Cell Biology, University of California, Berkeley

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ABSTRACT

Nutrients from anthropogenic pollution can degrade water quality and alter the balance of marine food webs. Lying at the base of the trophic pyramid, plankton quickly respond to nutrient changes in the water, which can have repercussions throughout both pelagic and benthic food webs, and thus they serve as a good bioindicator of water quality. In early November 2009, we evaluated sediment pollution, water pollution, and plankton abundance at four shoreline sites in the San Francisco Bay. We tested the sediment for nitrogen, phosphorus, potassium, and pH levels, all factors that can affect growth of primary producers. In the water, we tested nitrate, phosphate, and pH levels. Lastly, we sampled shoreline plankton abundance both morning and evening. Sediment phosphorus and water phosphates were strongly correlated with one another, but water nitrates remained relatively constant, at low levels, across sites. Daytime plankton abundance showed a positive trend with water phosphate. These trends suggest nitrogen is quickly taken up by plankton, making nitrogen the limiting factor for them. The relationship between plankton and phosphorus is influenced by more complex factors.

INTRODUCTION

For decades the San Francisco Bay has been used as a common sewage dump (Cloern, 1982). Since the Bay Area was first settled, human impact on the region has grown with the population, creating observable changes within both marine and terrestrial ecosystems (Nichols et al., 1986).

For the first half of the twentieth century, sewage outlets for most areas led directly to creeks that fed to the Bay. Sewage treatment plants were only constructed the latter half of the twentieth century during which time the outlets were slowly rerouted (Pine, 2009 lecture). Sewage has been a major source of nitrate and phosphate pollution in the water.

Additionally, agricultural runoff flushes thousands of kilograms of nitrates and phosphates into the Bay, along with other potentially harmful chemicals and fertilizers (Carpenter, 1998). It was estimated in 1993

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[1] *Corresponding author: for questions, contact Monica Moritsch.*
E-mail: mmoritsch@berkeley.edu

that on average 174 kg/ha per year of surplus N and 26 kg/ha per year of surplus P accumulated in sediments, or eroded or leached to surface and ground waters in the United States (ibid). Ultimately, "the urbanization and agricultural practices of the San Francisco Bay area and the San Joaquin valley have substantially increased the levels of ammonia, nitrate, and phosphate in the waters of the bay (primarily from fertilizers, detergents, and sewage)" (CCSF, 2009) Additionally, the increase in the concentrations of these nutrients in the ocean has not gone without consequences. Eutrophication caused by surplus nitrogen and phosphorus has become a common and growing problem in rivers, lakes, coastal shorelines, and estuaries (Smith, 1998), changing the normal balance of biogeochemical functioning and biological community within estuarine and coastal waters (Cloern, 2001).

Anthropogenic pollutants can also supply limiting nutrients to terrestrial and aquatic ecosystems, including nitrogen, phosphorus, and potassium, which play important roles in plant growth (Yu et al., 2009). Removing nutrient limitations increases growth of photosynthetic organisms (ibid). However, in aquatic ecosystems, this growth may eventually degrade water quality as organisms begin to die and get broken down by bacteria (Campbell and Reese, 2002).

The health of marine ecosystems is integrally linked to the abundance and diversity of plankton. While increases in pollution generally lead to decreased plankton abundance the opposite may happen as well, as observed in algal blooms from seasonal or anthropogenic releases of nutrients (Turner et al., 2009). These are not the only determinants of plankton abundance; other factors of the water body, such as mixing, can affect plankton's ability to thrive (Conomos, 1979).

Whether or not plankton will grow largely depends on the nutrients available. Experiments with nitrogen-fixing cyanobacteria revealed that several elements, including iron and phosphorus, limited cell growth (Falcón et al., 2005). This implies that anthropogenic phosphorus pollution can potentially affect plankton distributions due to input of these nutrients. This, however, raises the question of over-uptake and depletion of nutrients, resulting in an eventual decline of nitrogen- and phosphorus-dependent organisms (Falcón et al., 2005).

The plankton that dominate the San Francisco Bay are particularly responsive to high nitrogen concentrations (Cloern and Dufford, 2005). The San Francisco Bay has numerous sources of anthropogenic pollution, and in some places, nitrogen and phosphorus concentrations are so high that other limiting factors may predominate (ibid). Additionally, each size class of plankton has different dominant limiting factors for growth (Sin and Wetzel, 2002). We tested levels of nitrates, phosphates, and pH in water to estimate which factors might affect plankton growth.

Water quality alone is not always a sufficient indicator of pollution at a given site, however. Especially in larger bodies of water with fluctuating tidal currents, pollutants or nutrients present on shore can be washed into the water and diluted. Thus, sediment contents can provide more information on pollutants present at a given site than water data alone (NOAA, 1997). In addition to examining sediment, it is important to examine biological indicators of bay ecosystems, as their short life histories respond quickly to environmental changes (Vilela et al., 2003). Studies in freshwater habitats suggest plankton serve as a direct indicator of water quality (Case et al., 2008). Fachrul and Syach (2006) showed that as pollution in a bay system increases over time, the plankton abundance and diversity decrease. The waters become dominated by fewer, more pollution-tolerant species. This loss of diversity can affect marine food webs, resulting in repercussions for other species, as well as fishing industries (Nichols et. al., 1986).

It is difficult to predict in what ways changes in plankton abundance will affect marine ecosystems. Some plankton species support more benthic food webs, while others support pelagic food webs (Cloern and Dufford, 2005). Depending on the plankton diversity and nutritional content, marine ecosystems contain higher or lower numbers of fish and other organisms at various trophic levels, a balance that can change with the dominant species of plankton present (ibid). Thus, plankton play a key role in marine food webs, comprising the base of the trophic pyramid and therefore affecting all higher tropic levels.

We sought to understand the relationship between anthropogenic pollution and the health of the bay ecosystem, as indicated by plankton abundance. By testing sediment nutrient levels and water nutrient levels, and sampling plankton at different locations in the San Francisco Bay, we tested our null hypothesis: water and sediment pollution have no effect on plankton abundance. We expected to find a negative correlation between plankton abundance and water-sediment pollution.

METHODS

Experimental Design

We sampled plankton biomass, water quality, and sediment quality at four different San Francisco Bay Area shoreline locations. The sites included (1) Berkeley Marina 37o 51′ 45″ N, 122o 18′ 55″ W, (2) Fisherman's Wharf, San Francisco 37o 48′ 25″ N, 122o 25′ 24″ W, (3) Oakland Middle Harbor Regional Park 37o 48′ 15″ N 122o 19′ 29″ W, and (4) Albany Bulb Landfill 37o 53′ 29″ N, 122o 19′ 32″ W. We selected these sites because of the high human activity, including nearby land and water traffic, local runoff, and pollution in general, that permeates the area. Additionally, as many potential sites in the area have been paved over or have only piers with no above-water sediments, we chose sites with direct water and sediment proximity to allow sampling of sediment that comes in contact with water. In this way, we could analyze the relationship between water and sediment quality.

Between 30 October 2009 and 16 November 2009, we took multiple random samples at each site on the same day during medium to high tides, between +0.9 and +1.8 meters according to the NOAA tide calculator, to account for tidal variation in each area. We collected all the samples within a 50-meter range along the shoreline at a depth of approximately 0.5 meters. A random number generator produced twelve points along this 50-meter range where we drew three sediment, four water, and five plankton samples. We conducted all water and sediment tests on site, time permitting. If equipment constraints required us to store water samples for later, they were stored at room temperature away from direct sunlight. This was unlikely to affect the amount of nitrate and phosphate contained in each sample. We recorded general weather conditions through observation.

Sediment

We used a La Motte Soil N-P-K Kit to test sediment quality. We tested three separate 100 mL sediment samples mixed with distilled water (per the instructions of the kit) for nitrates, phosphorus, and potassium. We used a separate Leaf Luster Soil Kit to test the sediment pH. We collected the samples within 4 meters of the edge of the water line at the time of testing. If larger rocks covered the beach, we used a sand shovel to retrieve finer sediment from beneath the rock layer. All sediment samples came from within 10 cm of the surface layer of the beach.

Water

We took four random water samples from the bay in clean 125 mL plastic jars. To collect each sample, we submerged the jars within 0.5 meters below the surface of the water level. We used a La Motte Water Quality kit to test nitrate and phosphate levels by adding a series of chemicals that caused a color change in the water sample, which could be compared to a key.

Plankton

We simultaneously collected plankton samples while we drew the sediment samples. At each site, we towed an 80-μ plankton net back and forth in the water at a depth of 0.5 meters for 3 minutes. The centers of the 5-meter tows were located on one of the five random points generated in the 50-meter range (In other words, the net was towed 2.5 meters on either side of the point.) We placed the five samples of plankton into clean 125mL plastic containers. These samples were stored at room temperature out of direct sunlight. To measure the abundance of plankton, we shook each of the samples for one minute and used a pipette to measure exactly 1mL from the volumetric center of the sample of water. We transferred the sample onto a microscope glass slide and placed a cover slip with a marked 0.25 cm2 square located at the corner of it on top. We then viewed the plankton using a dissecting microscope in the UC Berkeley Department of Integrated Biology and counted the total number of plankton located within the marked region.

We returned to each location a second time between 12 November 2009 and 16 November 2009 to collect five more plankton samples from each site. This time we visited at night (after 18:00) instead of in the morning (before noon) as for the first samples. Tidal conditions remained the same. Using the same microscope and pipette techniques as before, we counted plankton in each sample. However, this time we performed two pipettes, instead of one, per plankton sample. The difference between plankton counts for the two pipettes drawn per sample was not statistically significant. This confirmed that the one pipette taken per daytime sample was representative of plankton abundance for that sample. In addition to the extra pipette, we noted phytoplankton vs. zooplankton ratio for these nighttime samples.

RESULTS

Overall, the results did not suggest a correlation between sediment nitrogen and plankton abundance or sediment phosphorus and plankton abundance (Figure 1, 2, and 5). The results suggested a positive trend between water phosphates and plankton abundance (Fig. 3), but this trend was not statistically significant. Nitrate levels in the water remained fairly constant with no significant differences at all sites (range 0.14-0.37 ppm).

Strong correlations appeared between sediment nitrogen and sediment phosphorus ($r^2 = 0.631$) (Fig. 6) across all sites. However, no strong correlation occurred between water phosphate and water nitrate (Fig. 1 and 2). Despite significant differences in locations, only the sediment phosphorus and water phosphate levels exhibited a significant correlation ($p = 0.0188$) as a positive exponential relationship (Fig. 4).

At the San Francisco location, we found a significantly higher (ANOVA, $p < 0.001$) number of diatoms in the water compared with all the other locations. In these samples, there were over 40 diatoms per cm2, but in all other samples, there were never more than a maximum of 25 per cm^2. The number of other types of plankton in the nighttime samples did not vary significantly, with the average staying in the range of 8-16 plankton per cm^2 (see Table 2). The nighttime set of plankton samples also revealed a significant difference between the abundance of zooplankton and phytoplankton within each site, with a larger number of phytoplankton in all locations (t-test, $p < 0.001$).

Averages (Std. Dev.) [*n*]	Soil		Water			Plankton	
	Relative Soil N	Relative Soil P	Water Nitrate (ppm)	Water Phosphate (ppm)	Water pH	Day Plankton (per cm^2)	Night Plankton (per cm^2)
SF	1.0 (0) [3]	1.3 (0.58) [3]	0.24 (0.03) [4]	0.1 (0) [4]	7.28 (0.13) [4]	11.2 (7.68) [5]	50.4 (22.24) [10]
Albany	4.3 (1.15) [3]	3.6 (1.15) [3]	0.27 (0.05) [4]	0.28 (0.13) [4]	6.95 (0.17) [4]	11.2 (5.20) [5]	21 (11.48) [8]
Marina	1.7 (1.15) [3]	2.3 (0.58) [3]	0.37 (0.23) [4]	0.1 (0.08) [4]	6.95 (0.17) [4]	25.6 (4.56) [5]	14.8 (10.56) [10]
Oakland	2.3 (1.15) [3]	4.3 (1.15) [3]	0.14 (0.08) [4]	0.6 (0.08) [4]	7.5 (0.23) [4]	32.8 (12.84) [3]	19.6 (8.24) [10]

Table 1. Physical factors at each location. These variables are important because they are most related to plankton abundance. Standard deviations shown in parenthesis. Sample size, n, shown in brackets. Sediment values based on a Low-Medium-High scale were assigned numerical values: 0 = absent, 1 = low, 3 = med. 5 = high.

Location (*n*)	**Avg. Diatom** per cm^2 (std dev.)	**Avg. Other plankton** per cm^2 (std. dev.)
Albany (8)	**8.0** (8.8)	**13.0** (6.7)
SF (10)	***42.0** (21.2)	**8.4** (3.5)
Oakland (10)	**0** (0)	**14.4** (7.4)
Berkeley (10)	**2.80** (6.3)	**16.0** (9.0)

Table 2. Comparison of average number of diatoms to numbers of other types of nighttime plankton at each location. n represents sample size. * Represents statistically significant values (ANOVA, $p < 0.001$).

Lastly, the relationship between water pH and daytime plankton (Fig. 7) appeared to be considerable but not significant ($r^2 = 0.200$). Overall trends indicate an increase in water pH may be associated with a similar increase in plankton abundance.

We used an Analysis of Variance (ANOVA) to evaluate between-site differences for all variables. These revealed significant variation between sites in: daytime plankton abundance ($p = 0.024$), nighttime plankton abundance ($p < 0.001$), water phosphates ($p < 0.001$), water pH ($p = 0.002$), sediment nitrogen ($p = 0.017$), and sediment phosphorus ($p = 0.015$) (see Table 1). Furthermore, a Mann Whitney U-test showed significant difference between abundances of nighttime plankton and daytime plankton ($p < 0.001$).

DISCUSSION

We hypothesized that the abundance of plankton decreases as nitrogen- and phosphorus- containing pollutants in both water and sediment increase. Our null hypothesis states that nitrogen- and phosphorus-containing pollutants have no effect on plankton abundance. Contrary to our alternative hypothesis, we found no relationships between plankton and nitrogen in sediment and between plankton and phosphorus in sediment. This supported our null hypothesis for sediment pollution.

However, because the relationship between phosphate levels in water and daytime plankton abundance was not significant, we could not reject the null hypothesis. As shown in Figure 4, there is a positive trend between water phosphate and daytime plankton. This trend suggests the opposite of our alternative hypothesis: that plankton abundance may increase when phosphorus-containing pollutants in water increase. More long-term investigation across all sites needs to be done in order to better understand the connection between water pollutants and plankton abundance. Monitoring water phosphates and daytime and nighttime plankton over time will help determine the pattern of regular nutrient levels at each site and will be more useful in determining the relationship.

General Findings

The positive trend between water phosphate levels and daytime plankton abundance may suggest a connection between water pollution levels and plankton abundance. The minimal correlation between sediment pollution levels and plankton abundance may be due to the short resident time of plankton over local sediment (Herrlinger, per. communication). Although the two components of sediment pollution—relative nitrogen and phosphorus—generally mirrored each other across sites (see Fig. 1), the two components of water pollution—nitrate and phosphate—were not linked. Sediment pollution is more stable and less variable to temporal and tidal changes. According to Foley, it could also mean that these nutrients are locked up in the sediment and thus are not easily removed through natural processes (pers. communication).

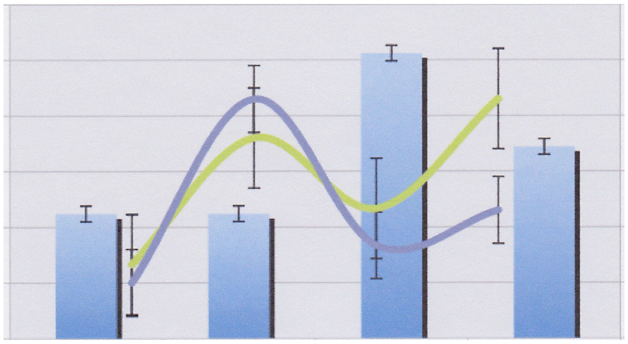

Figure 1. Comparison of sediment pollution (denoted by phosphorus and nitrogen levels) and daytime plankton abundance for each location. The phosphorus and nitrogen data points were connected with a smooth curve. Values based on average numbers from Table 1. Standard error bars shown.by phosphorus and nitrogen levels) and daytime plankton abundance for each location. The phosphorus and nitrogen data points were connected with a smooth curve. Values based on average numbers from Table 1. Standard error bars shown.

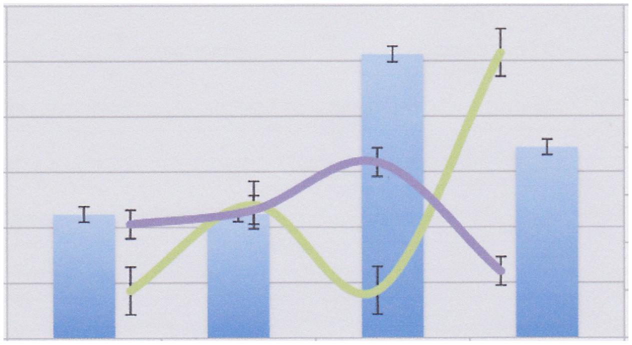

Figure 2. Comparison of water pollution (estimated by phosphate and nitrogen levels) and plankton abundance during daytime and nighttime sampling across locations. The phosphate and nitrogen data were connected with a smooth curve. Values based on average numbers from Table 1. Standard error bars shown.

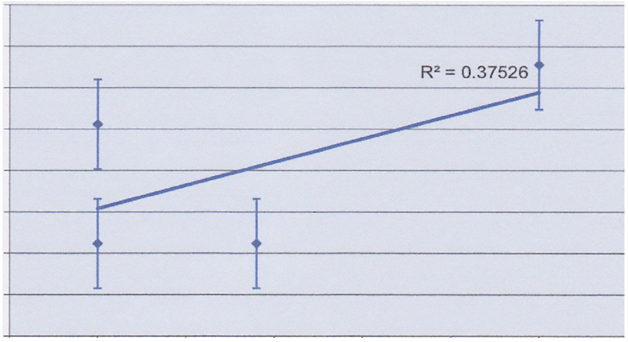

Figure 3. Positive trend between water phosphates and daytime plankton abundance Data fitted with a linear curve, nonsignificant. Values based on averages from Table 1. Standard error bars shown.

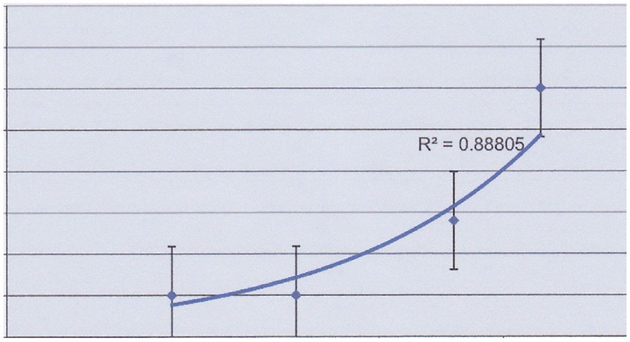

Figure 4. Comparison of phosphorus levels in sediment and phosphate levels in water. Data were fit with an exponential curve ($r^2 = .888$). (R computer software, $p = 0.0188$). Values based on average numbers from Table 1. Standard error bars shown.

Furthermore, similarity of pollutants levels in sediment may be due to similar delivery methods such as fertilizers and leaching. The lack of such a trend between the two water pollutants may be because phosphate remains dissolved in the ocean, whereas photosynthetic organisms quickly take up nitrate. Additionally, water pollution might be more variable than sediment pollution due to rapid change in the marine environment, caused by currents, exchanges that occur within the Bay's estuary outlet, and the marine inflow from the Pacific Ocean. However, other factors may influence the relative levels of nitrogen and phosphorus at each site, such as high-phosphate fertilizers or the varying landscape and drainage features of each location (ibid).

Nitrogen

We did not observe a correlation between nitrogen in the sediment and nitrate in the water. Although the sediment nitrogen varied significantly between locations, the concentration of water nitrate remained low across all locations. This lack of variation in water nitrate levels may be attributed to the fact that nitrogen, a component of nitrate, is a limiting nutrient in the Bay's ecosystems; often low aquatic nitrate concentrations accompany high plankton levels in coastal waters because the plankton have used up all the nitrogen (Foley, pers. comm., Campbell and Reece, 2002). Studies have also shown that there is proximate nitrate limitation of surface waters—once water nitrate concentrations reach organisms' requirements, phosphorus becomes the new overall limiting nutrient (Tyrell, 1999). Furthermore, levels of nitrogen may be low because other contributing sources of nitrogen, such as nitrites and ammonium, were not measured. These other forms of 'reactive nitrogen' that are easily taken up by phytoplankton were not accounted for in our study (ibid).

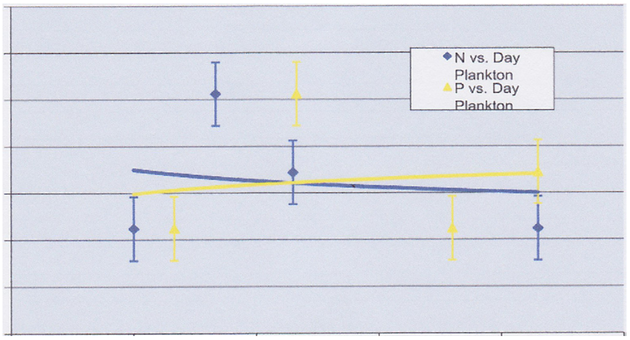

Figure 5. Further comparison of sediment pollution (denoted by phosphorus and nitrogen levels) and plankton abundance during daytime and nighttime sampling. Although there is no significant correlation, the lines suggest possible general trends through logarithmic fit curves. Values based on average numbers from Table 1. Standard error bars shown.

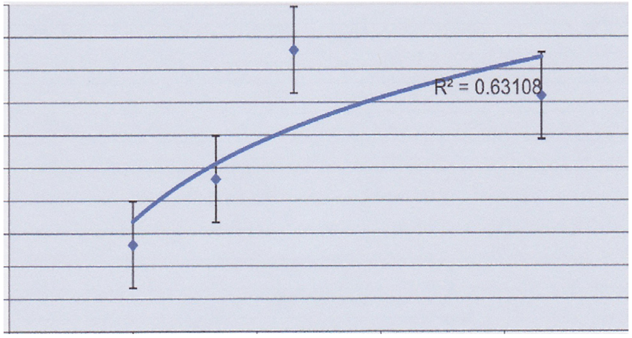

Figure 6. Positive trend between relative amounts of N and P in sediment. Data fit with logarithmic curve, but the trend is not significant. Values based on average numbers from Table 1. Key: 0=absent, 1=low, 3=medium, 5=high. Standard error bars shown.

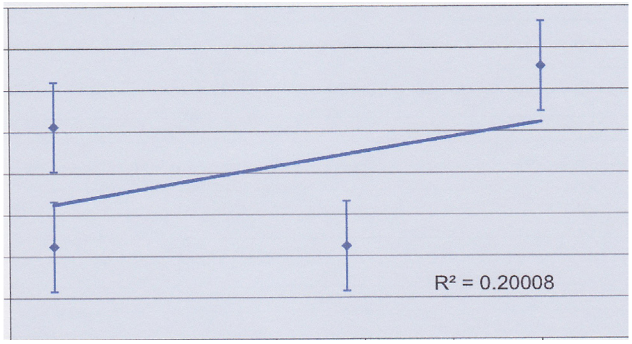

Figure 7. Positive trend observed with increasing water pH and increasing plankton abundance. Data fit with linear curves; correlation nonsignificant. Values based on average numbers from Table 1. Standard error bars shown.

PHOSPHORUS

The strong correlation observed between relative phosphorus sediment and water phosphates (see Fig. 4) could be due to the tides washing the nutrients that leach from sediment into the water (NOAA, 1997). An opposite interaction could also be true, where water high in phosphates from outflow sources leaves behind phosphorus in the sediment. In either case, the data suggest the phosphorus cycle is closely linked between land and water, and that phosphorous levels near the shoreline could be used to predict levels in the water and vice versa.

We found a nonlinear relationship: sediment phosphorus increases with water phosphate disproportionately. Further long-term studies measuring levels of sediment phosphorus, water phosphate, and other forms of phosphorus that organisms can use is required to obtain more conclusive models on the proportion of phosphate in sediment that interacts with water phosphate.

Daytime plankton abundances increased as water phosphates increased slightly. This could be because phosphorus, like nitrogen, is also a limiting nutrient, but only after organisms fill their nitrogen requirements (Tyrell, 1999). However, even though both nitrogen and phosphorus are both limiting nutrients, phosphate levels are usually slightly higher than nitrate levels in marine environments. This may be because phosphorus is completely absent from the atmosphere, and the only major source of phosphorus to marine environments cycles between sediment and water (as confirmed by the significant correlation between water phosphate and sediment phosphorus, Fig. 4) (ibid). Additionally, since phosphrous and nitrogen sometimes work synergistically, an increase in both nitrates and phosphates can cause more growth than proportional for each element alone because the relationship between these two inputs is interdependent and varies by location (Campbell and Reece, 2002).

SAN FRANCISCO

We counted a significantly higher abundance of the San Francisco nighttime plankton than at any other site. This nighttime sample was especially rich in diatoms (Table 2). This is consistent with Cloern and Dufford's study, which estimated diatom populations to represent over 80% of the total phytoplankton biomass in the Bay (2005). In addition, water systems, such as estuaries and current boundary fronts consisting of two body masses with different properties, like the San Francisco location, create complex water movements that support high primary production (Daly and Smith, 1993).

Since phytoplankton growth is mainly bolstered by nutrient availability, enclosed coastal environments such as bays and estuaries are expected to have more phytoplankton than open coastal environments because of higher urban nutrient inputs in enclosed coastal environments (Cebrián and Valiela, 1999). Therefore, the abundance of nighttime plankton in San Francisco, the location closest to incoming oceanic waters, may not be due to an increase in direct influx of ocean water, but due to other factors. This location may have higher populations of plankton that migrate upward at night compared to other locations; however, this is unlikely because phytoplankton tend to ascend in the early morning to optimize photosynthesis and then descend at night for better nutrient uptake (Ault, 2000).

We did not take into account the differences in the food webs at each site because we were limited by the time of visit and our inability to observe much underwater activity. Nonetheless, we observed a sea lion within 20 m of the shore and very high numbers of actively feeding carnivorous birds only at the San Francisco location. The sea lion increases the complexity of the location's food web because this animal feeds on multiple trophic levels, from zooplankton to pelagic fish to squid (Pauley et al., 1998). The other locations had birds and fish, but qualitatively, we observed much less feeding activity. While each site had at least four trophic levels due to the presence of piscivorous birds (Power, lecture 2009), the number of birds, fish, and other animals could have influenced the standing crop of both phytoplankton and zooplankton. Typically, much larger amounts of biomass are required at lower trophic levels to sustain the organisms that feed on them, but this amount varies with habitat, the presence of different top carnivores, (Campbell and Reece, 2002) and the nutritional content of each type of plankton (Cloern and Dufford, 2005).

Also adding to the complexity of the San Francisco Bay trophic food webs are invasive species of bivalves that heavily graze on phytoplankton. From 1987 to 1990, the San Francisco Bay area was colonized by the species Corbula amurensis, native to China and Japan becoming almost exclusive (Alpine and Cloern, 1992). C. amurensis actively remove phytoplankton biomass documented at often overwhelming rates to phytoplankton production. Nonetheless, the bivalves are limited by grazing from the sediment-water interface, affected by vertical flux of phytoplankton biomass in the water column (Cloern, 1996). The immense grazing capabilities of C. amurensis have been well documented in the Northern San Franscico Bay, yet little research documents their impact on phytoplankton in lower portions of the Bay, where they have also invaded (Carlton et al., 1990). The ability for high amounts of phytoplankton grazing by invasive bivalve species could have affected our results at different locations in the San Francisco Bay depending on their presence.

Daytime and Nighttime Plankton

Plankton were significantly more abundant at night than during the day. However, the time gap of approximately two weeks between daytime plankton sampling and nighttime plankton sampling may have influenced the marked change in numbers. Because water has a fairly high turnover rate due to varying tides and currents, the nighttime plankton may have simply been a new, unrelated population affected not only by day and night variance, but also because of other factors such as storms in between sampling as well as seasonal transitions (Herrlinger, per. comm.). We would need to sample within a 24-hr period, ensuring nearly identical ambient conditions, to see if the increase in nighttime plankton abundance is due to the lack of sunlight, time difference, plankton migration, or other factors.

The great variability between nighttime and daytime plankton numbers also suggests plankton populations in shoreline marine ecosystems are continually changing. Future studies might focus on one site in the bay for a time-period of at least one year in order to track annual fluctuations of plankton. The high variability of the Bay's marine environment also questions whether nutrient levels recorded at the time of plankton sampling can be used to accurately determine a relationship between the two. Ambient nutrient conditions in water may not reflect its effects on plankton populations sampled at that time. Short-term (24-hr), long-term (seasonal), weather, current, and other factors may delay or alter how plankton and nutrient levels interact (ibid). Future studies should try to determine which factors contribute to the interaction of plankton and nutrients, and how long it takes for the nutrient levels to impact plankton abundance. Such findings may help improve techniques of accurately determining nutrient level effects on plankton abundance.

Light Limitation

Phytoplankton growth in the San Francisco Bay is also strongly light limited, as it has higher turbidity than many other locations, limiting light penetration essential for photosynthesis (Cloern, 2001). Primary production increases logarithmically with light intensity and photic depth (Peterson et al., 1987). In the North Bay, the high sediment delivery from the Sacramento-San Joaquin delta decreases light penetration while providing excess nutrients. This area sees lower phytoplankton growth than the South Bay, which has less sediment but similar levels of nutrients from wastewater treatment plants (Cloern, 1999).

Sedimentation rates are highly variable over short periods of time and usually correspond to seasonal changes in river discharge (Jassby et al., 2002). Past studies in the San Francisco Bay have shown that rates of sedimentation could be predicted by changes in wind and runoff, where sediment particles tended to be finer in autumn and early winter due to high runoff, and coarser in summer when winds are stronger (Thomas-Becker and Luoma, 1985). Highest phytoplankton growth rates occur in the mid-spring after sediment from winter runoff has subsided, increasing the clarity of the water. At this point light is sufficient and nutrients then become limiting (Cloern, 1999). Our study, which occurred just before the autumn rains, was likely affected by light limitation, although a repeat during the spring would help to avoid this situation.

Following the Gold Rush, sediment inputs greatly increased due to hydraulic mining. The dredging of boat channels from 1975 to 1985 also contributed to the increased sediment input into the bay, but after the construction of fourteen dams barring peak river flows into the system, sedimentation began to decrease (Van Geen and Luoma, 1999) changing from a depositional to an erosional process (Jaffe et al., 1998). This decline in total suspended solids is predicted to increase the deepest light penetration in the water up to 25%, leading to higher phytoplankton growth (Jassby et al., 2002).

Estuarine Acidification

Plankton abundance also showed a positive correlation with pH. Over the 0.55 units of pH decrease, the plankton abundance slowly decreased as well. This supports Battarbee's studies in which he claims that one of the first signs of acidification in lakes is the reduction in the populations of diatomic plankton (1984). This slight trend also has implications in the biological consequences of ocean acidification. CO2-induced acidification can cause reduction of the number of photosynthetic organisms fixing carbon, which could consequently accelerate the acidification of surface waters, leading to decreased removal of dissolved CO2 from the water (Bishop, lecture 2009). As phytoplankton are primary producers in the oceanic systems, the acidification of oceans could ultimately lead to a trophic cascade, which can change the feeding patterns and abundance of top predators (Power, lecture 2009).

CONCLUSIONS

We sampled sediment, water, and plankton from four Bay Area shorelines to examine the relationship between plankton abundance and pollution. Overall, sediment nitrogen and phosphorus exhibited weak relationships with plankton, if any.

While there was not enough significant support from the results to accept our alternative hypothesis or reject the null hypothesis, the nonsignificant positive relationship observed between plankton abundance and water phosphates suggests that these two factors are connected. Water nitrate values remained low at all sites, most likely because nitrogen is a limiting factor in plankton growth and is rapidly removed from the water. We concluded that nutrient pollution does have an effect on plankton, though the mechanisms and trends of such effects are still unclear. Since our study suggests that higher levels of phosphates promote plankton growth, we cannot determine whether pollution is detrimental to marine ecosystems. Future studies should attempt to assess if phytoplankton and zooplankton respond differently to phosphates and nitrates in the water. The relative abundance of zooplankton versus phytoplankton could be used to better determine how nitrogen- and phosphorus-containing pollution affects marine ecosystems. Controlled laboratory experiments may also help determine the relationship between increased levels of phosphate and nitrates on plankton populations. Moreover, extensive sampling over the long term may clarify the local and/or temporal factors that affect plankton communities, including light limitations, suspended sediment, and increasing grazing by invasive species. Finally, a more comprehensive analysis of water and sediment quality, by including such tests as dissolved oxygen, water salinity, and temperature, may also provide a better indication of water and sediment pollution influence on plankton abundance.

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LITERATURE CITED

Alpine, A. E., and J. E. Cloern (1992), Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary, Limnology and Oceanography, 37: 946- 955.

Ault T. R, (2000) Vertical Migration by the Marine Dinoflagellate Prorocentrum triestinum Maximizes Photosynthetic Yield. Oecologia, 125(4): 466-475.

Battarbee R. W., Thrush B. A., Clymo R. S., Le Cren E. D., Goldsmith P., et al. (1984). Diatom Analysis and the Acidification of Lakes. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 305(1124): 451-477.

Bishop, J. (2009). Global Carbon Cycle. Lecture presented at UC Berkeley.

Campbell, N. A., & Reece, J. (2002). Biology (6th ed.). San Francisco, CA: Benjamin Cummings, pp. 1203; 1203-1212.

Carpenter, S. R. et al. (1998). Nonpoint pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications 8(3): 559-568.

Carlton, J.K. Thompson, L.E. Schemel, F. H. Nichols (1990). Remarkable invasion of San Francisco Bay by the Asain clam Potamocorbula amurensis. Marine Ecology. 66: 81-94.

Casé, M. et al. (2008). Plankton community as an indicator of water quality in tropical shrimp culture ponds. Marine Pollution Bulletin, 56(7): 1343-1352.

Cebrián J., and Valiela I. (1999). Seasonal patterns in phytoplankton biomass in coastal ecosystems. Journal of Plankton Research 21(3): 429-444.

Cloern, J. E. (1982). Does the Benthos Control Phytoplankton Biomass in South San Francisco Bay? Marine Ecology Progress Series, 9: 191-202.

Cloern, J. E. (1996). Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California. Review of Geophysics. 34, 127-168.

Cloern, J. E. (1999). The relative importance of light and nutrient limitation of phytoplankton growth: a simple index of coastal ecosystem sensitivity to nutrient enrichment. Aquatic Ecology. 33: 3-16.

Cloern, J. E. (2001). Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series. 210: 223-253.

Cloern, J. E. and R. Dufford (2005). Phytoplankton community ecology: principles applied in San Francisco Bay. Marine Ecology Progress Series. 285:11-28.

Community College of San Francisco (CCSF) (2009), Department of History of Time and Life. (2009). San Francisco Estuary - 1880's and Today. Exhibit at CCSF. Retrieved from http://www.ccsf.edu/Departments/History_of_Time_and_Life/PDFs/SanFranciscoEstuary36x24.pdf.

Connor, M. (2005). Water Quality Improvements Are Critical to Waterfront Development: Lesson from Boston, San Francisco and Kitakyushu. San Francisco Estuary Institute. Retrieved from http://www.sfei.org/cmr/cmrreports.htm.

Conomos, T. J. (1979). Properties and Circulation of San Francisco Bay Waters. SAN FRANCISCO BAY: THE URBANIZED ESTUARY Investigations into the Natural History of San Francisco Bay and Delta With Reference to the Influence of Man. 47-84.

Daly K and Smith O. W. (1993). Physical-Biological Interactions Influencing Marine Plankton Production. Annual Review of Ecology and Systematics, 24: 555-585.

Fachrul, M.F. and Syach, J.N. (2006). The Effect of Water Quality Disturbances on Phytoplankton Communities in Jakarta Bay, Indonesia. Retrieved from http://balwois.com/balwois/administration/full_paper/ffp-1199.pdf.

Falcón et al. (2005). Growth kinetics of N2 fixing cyanobacteria with phosphorus and temperature. Marine Ecology Progress Series. 285: 3-9.

Foley, Melissa. (2009, November 22). Personal communication.

Herrlinger, Tim. (2009, November 14 and December 5). Personal communication.

Jaffe, B.E., Smith R.E., Torrezan, L.Z. (1998). Sedimentation and bathymetric change in San Pablo Bay: 1856-1983.

US Geological Survey Open File Report 98-759. Retrieved from http:geopubs.wr.gov/open-file/of98-759.

Jassby, A. et al. (2002). Annual Primary Production: Patterns and Mechanisms of Change in a Nutrient-Rich Tidal Ecosystem. Limnology and Oceanography. 47(3): 698-712.

National Oceanic and Atmospheric Administration (NOAA). (1997). NOAA's Review of Sediment Quality Investigations in San Francisco Bay. NOAA Technical Memorandum NOS ORCA 116. Retrieved from http://response.restoration.noaa.gov/book_shelf/140_SFtext.pdf.

Nichols, F. H. et al. (1986). The modification of an estuary. Science, 231: 537-573.

Peterson, D. et al.(1987). Phytoplankton productivity in relation to light intensity: a simple equation. Estuarine, Coastal, and Shelf Science. 24: 813-832.

Pine, T. (September, 2009). Strawberry Creek. Lecture presented at Bio 1B Field Section lab meeting, UC Berkeley.

Power, M. (2009, October 26). Ecosystem Ecology. Lecture presented at UC Berkeley.

Sin, Y. and R. L. Wetzel (2002). Ecosystem modeling analysis of size-structured phytoplankton dynamics in the York River estuary, Virginia (USA). II. Use of a plankton ecosystem model for investigating control factors on phytoplankton and nutrient dynamics. Marine Ecology Progress Series. 228: 91-101.

Smith, V. H. (1998) Cultural eutrophication of inland, estuarine, and coastal waters. In M.L. Pace and P.M. Groffman, editors. Successes, limitations, and frontiers in ecosystem science. Springer-Verlag, New York, New York, USA.

Thomson-Becker, E.A. and Luoma, S.N. (1985). Temporal fluctuations in grain size, organic materials and iron concentrations in intertidal surface sediment of San Francisco Bay. Hydrobiologia. 129(1): 91-107.

Turner, J. T. et al. (2009). Plankton studies in Buzzards Bay, Massachusetts, USA. VI. Phytoplankton and water quality, 1987 to 1998. Marine Ecology Progress Series, 376: 103-122.

Tyrell, T. (1999). The relative influences of nitrogen and phosphorus on oceanic primary production. Nature, 400: 526-531.

Van Geen A., Luoma, S. N. (1999). The impact of human activities on sediments of San Francisco Bay, California: an overview. Marine Chemistry. 64(1-2): 1-6.

Yu, W. et al. (2009). Effects of nutrient cycling on grain yields and potassium balance. Nutrient Cycling in Agroecosystems. 84(3): 203-213.