Quantifying Nutrient Loads and Transformations in the Delta

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High anthropogenic nutrient loads are hypothesized to be one factor that is contributing to ecosystem decline in Suisun Bay and the Sacramento/San Joaquin Delta. However, to date there has been limited systematic study of nutrient cycling and fate in Suisun Bay and the Delta. Characterizing the role of the Delta in processing nutrients and delivering loads to downstream subembayments will inform near-term management decisions regarding nutrient inputs to these regions. This presentation will describe results of a project that applies multiple approaches at a range of spatial and temporal scales to characterize and quantify the dominant imports/exports to the Delta, as well as transformation/ loss processes and internal nutrient sources or sinks within the Delta. These processes in turn play a major role in shaping ambient concentrations within the Delta and ultimately determine net nutrient loads delivered downstream to Suisun Bay. First, we used a 1-box model to assess transformations/losses on a whole Delta-scale, looking both over multiple decades and during low-flow summer months. We estimated imports, exports, and internal losses or gains (by difference) using DWR-EMP water quality data in combination with DWR-DAYFLOW data. Next, we characterized seasonal, temporal and spatial variability in nutrient concentrations and stable isotope data (NO3, NH4, and POM isotopes) within the Delta with the goal of identifying finer-scale regions and/or time periods exhibiting substantial transformations, losses or internal inputs. Finally, we used the Delta Simulation Model (DSM2-QUAL) to quantify the magnitudes of these processes required to explain observed concentrations within the Delta, and to refine estimates of nutrient loads delivered downstream to Suisun Bay.

Keywords: Nutrients, Suisun Bay, Nutrient loads
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Ocean Nutrients in the Bay-Delta System: When and Where are they Important?

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San Francisco Bay is an estuary, comprised of a mix of salty ocean waters and freshwater from the rivers that flow in through the delta and elsewhere. Wind-driven upwelling along the open coast results in high nitrate levels in ocean waters that are drawn into the Bay by the tides and estuarine circulation. The concentration of nitrate and the timing of intrusion into the Bay are primary factors in assessing the importance of ocean nutrients to Bay nutrient budgets. Preliminary estimates indicate that ocean nutrients are most important during specific events. At other times, the ocean may import organic matter, such as algal blooms, which may also be important to net loading of the Bay. In addition to the nitrate mass imported, a key question is how far into the Bay-Delta system may ocean loading have an impact on the ecosystem.

Keywords: ocean, nitrate, salinity, nutrient balance
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Biogeochemical Fluxes in Bay-Delta Sediments: Seasonal and Spatial Synthesis

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Sediments are key components of shallow water estuarine ecosystems, both responding to changing environmental conditions and at the same time, altering the chemistry of the overlying water column. Over the last 3 years, we have measured rates of sediment-water exchange of oxygen, nitrogen and phosphorus on 6 separate occasions across widely varying sites in the Bay Delta. A high degree of spatial variability of fluxes was found reflecting a broad range of organic matter loading and in the processes that promote retention or release of nutrient elements. Rates of the processes measured here fell largely within the broad range of rates for such processes reported worldwide. Small, but measureable rates of dissimilatory nitrate reduction to ammonium were found. In September 2014 in the San Joaquin River, we observed some of the highest measured rates of denitrification and soluble reactive phosphorus efflux than at any other times or at any other locations, with rates similar to those from more eutrophic estuaries. Extrapolating from both chlorophyll *a* and O_2 fluxes, the sediments may potentially have large impacts on estimates of total system productivity. Bioirrigation by animals was found to have an important effect on oxygen penetration depths; the benthic flux of oxygen and ammonium increased significantly as *Potamocorbula* biomass increased. Nutrient flux measurements in a restored wetland suggest that denitrification represent an important sink for nitrogen. In this presentation, we use this large and diverse data set to identify the key controls on sediment-water exchange in the Bay-Delta Ecosystem, and scale these rates of nutrient exchange to the rates of nutrient input.

Keywords: sediment-water exchange, denitrification, benthic microalgae, DNRA, sediment oxygen demand
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New Insights from Continuous Monitoring of Nutrient Dynamics in the North Delta and Cache Slough Complex

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Characterizing how nutrient dynamics in the north Delta and Cache Slough complex are affected by interaction with adjacent tidal marshes and shallow water habitats is essential for developing accurate nutrient budgets, assessing the impacts of eutrophication, anticipating effects of increased future agricultural intensity and increased population in the Central valley, projecting effects of higher concentrations associated with drought conditions, and planning wetland restoration. The difficulty is that water quality and nutrient supply in estuaries change continuously as river flows, tidal- and wind-driven currents, and other physical processes move new water parcels across comparatively static geomorphic settings. We used high frequency, in situ measurements of nitrate and phosphate in concert with measurement of flow dynamics in tidal wetlands to evaluate the wetlands' effects on nutrient dynamics. We report data from studies in the north Delta and Cache Slough complex that show large variability in dynamics, from tidal to seasonal time scales, and speculate on processes driving the observed differences. We found substantial seasonal and episodic variation in the magnitude and direction of net nutrient fluxes, suggesting that long-term, high-frequency observations are necessary in order to evaluate nutrient retention in wetlands.

Keywords: nutrients, in situ, sensor, wetlands, estuaries
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Estimates of Phytoplankton Nitrogen Uptake and Pelagic Nitrification During Fall in the High Nutrient San Francisco Estuary Delta

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Large rivers carry inorganic nutrients to estuaries and the coastal ocean where they help to shape microbial community production and speciation, and the estuarine food web. Within rivers, microbial processing will influence the magnitudes, forms and the ratios of the inorganic nutrient pools that reach estuaries but at present only limited information exists about the rates of nutrient processes in the San Francisco Estuary Delta. Riverine phytoplankton in the Sacramento and San Joaquin rivers assimilate some fraction of the dissolved inorganic nitrogen (DIN) load, thereby reducing the nitrogen concentration and increasing organic matter that reaches the low salinity zone of the estuary. Additionally, chemosynthetic prokaryotes may transform nitrogen species within the DIN pool, from ammonium (NH_4) into nitrate (NO_3) through pelagic nitrification. This process results in no change in the magnitude of the DIN pool, but does alter the proportion of these two nitrogen species. The goal of this effort was to characterize phytoplankton N uptake and pelagic nitrification processes along the Sacramento and San Joaquin rivers and in Suisun Bay during the fall period, when river flows are relatively low. A series of 12 transect surveys were conducted between September and November from 2010 to 2012. Our results show that anthropogenic inputs of DIN, along with altered patterns in freshwater flow, impart strong consistent spatial patterns in DIN concentration and speciation within the Delta. These patterns in turn influence phytoplankton DIN uptake and nitrification rates in predictable ways and help to explain the resulting concentrations of DIN that reach the low salinity zone in Suisun Bay. Effective nutrient management of the San Francisco Estuary Delta should include estimates of internal nutrient processes in order to constrain the assimilative capacity of the system for anthropogenic nitrogen loads.

Keywords: Phytoplankton, Nitrogen uptake, Ammonium, Nitrification
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Continuous Monitoring of Dissolved Oxygen in San Francisco Bay, California: Using High-Frequency Data to Explore Dynamics and Mechanisms

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Since passage of the 1972 Federal Clean Water Act, reported dissolved oxygen (DO) concentrations in San Francisco Bay (Bay) are routinely above the 5mg/L standard important for supporting biota, with few reported episodes below this concentration. However, long-term monitoring efforts have measured DO only in the main channel of the estuary by research vessel, and only at weekly to monthly sampling intervals. For this study we conducted the first high temporal resolution deployment of dissolved oxygen sensors in both the main channel and the perimeter of the Bay. Four optical DO sensors were deployed near bottom and sampled every 15 minutes for a year: two in the main channel (depth>12m) and two in the estuary perimeter (depth<5m). Main channel sites included one in the upper estuary near the primary freshwater inflow and one in the lower estuary near the ocean boundary; estuary perimeter sites included one at the mouth of a tidal creek in Central Bay and one in a tidal slough in South Bay. The resulting time series for main channel sites showed DO concentrations which always exceeded 5mg/L, whereas during spring, summer, and fall the tidal slough exhibited sustained hypoxic conditions (<3mg/L) and the tidal creek daily minima dropped below 5mg/L. Compared to sites in the main channel, those along the estuary perimeter demonstrated greater variability in DO concentrations at seasonal, tidal, and especially diurnal time scales. At the tidal slough site, DO concentrations varied at the spring/neap time scale, with consistently lower concentrations during neap tides indicating tidally varying transport and system metabolism. These time series are the first to concurrently document the contrasting DO patterns in the main channel versus the shallow periphery of the Bay, with results highlighting the value of high temporal resolution sampling and the importance of measurements in the shallow habitats.

Keywords: dissolved oxygen; continuous monitoring; tidal sloughs; San Francisco Bay
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High-Frequency Measurements Enable a Detailed Assessment of Surface Ammonium Concentration Dynamics in the Bay-Delta

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Problem: Anthropogenic nitrogen loading has been linked to eutrophication in estuarine ecosystems around the world. Yet in the Bay-Delta system, high anthropogenic ammonium inputs have not induced large increases in phytoplankton production, and recent research has advanced the idea that anthropogenic ammonium loading may reduce levels of primary productivity by inhibiting phytoplankton nitrate uptake. While water-column NH_4^+ concentrations have been regularly measured over the last decade throughout the Bay-Delta system, assessments of the ecological influence of anthropogenic ammonium loading on the Bay-Delta ecosystem have necessarily relied on water samples at discrete stations, often spaced kilometers apart.

Approach: In order to provide a more detailed spatial picture of ammonium concentrations throughout the Bay–Delta system, we have measured near-surface NH_4^+ concentrations using an under-way, real-time flow-through ammonium analyzer deployed on monthly cruises to the Bay-Delta beginning in early 2014. Our achieved sampling frequency -- approximately one measurement every 110 seconds while under-way – has effectively increased the spatial sampling resolution of this critical nutrient by an order of magnitude.

Results: We present a characterization of the dynamics of ammonium concentrations from anthropogenic sources in the Sacramento River, pinpointing where concentrations first rise, their variability moving downstream, and where, precisely, concentrations cease to decrease moving downstream. We also provide descriptions of the variability of ammonium concentrations, including localized “hotspots”, in Suisun Bay. Finally, we present correlations of high-frequency ammonium measurements with turbidity, salinity, temperature and chlorophyll fluorescence throughout the Bay-Delta.

Implications: The largest single source of anthropogenic NH_4^+ loading to the Bay-Delta is the effluent plume from the Sacramento Regional Wastewater Treatment Plant located in Elk Grove, CA. The detailed mapping of the dynamics of this plume and its relationship with chlorophyll fluorescence, salinity and turbidity helps inform on-going decision-making processes about the management of multiple anthropogenic stressors in the Bay-Delta system.

Keywords: ammonium, nutrients, phytoplankton, wastewater, biogeochemistry
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Egg Production and Egg Viability of the Copepods Acartia and Eurytemora Differ When Grown on Food of Varying N:P Ratios

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Ecological stoichiometric theory suggests that the chemical composition of food (phytoplankton) plays a key role in the success of grazers at all stages in their life cycles. Here, results of a controlled laboratory study are reported in which cultures of phytoplankton (the diatom *Thalassiosira*) were grown under different dissolved N:P conditions but maintained at the same growth rate and then fed to two copepod species, *Acartia tonsa* and *Eurytemora* sp., for periods of several days. Food was provided at the same carbon content level and was not limiting. When the algal food was grown at an N:P ratio of 32 vs 16, the number of eggs produced per female of *Acartia* declined 6-fold. In the case of *Eurytemora*, a similar decline in egg production was noted when food was grown in media for which N:P was 24 vs 4. Both of these copepod species have declined over time in the Bay Delta, trends that have been attributed to increased grazing from invasive clams as well as changes in the total amount of phytoplankton (food quantity). However, long-term trends in these copepod species have also been found to be related to long-term increases in N:P of the dissolved nutrients. The implications of these experimental results are that the chemical composition of dissolved nutrients can affect food quality even without a change in food quantity, and such changes may ultimately affect zooplankton reproductive success even when food is not limiting.

Keywords: Nitrogen, Phosphorus, Ecological stoichiometry, Food quality, *Eurytemora*, *Acartia*, egg production
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The Form of Nitrogen Alters Total Chlorophyll, the Composition of Phytoplankton, and Total Productivity: Experimental Results and Implications for the 2014 Spring Bloom

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It is well documented in N-limited systems that increased availability of nitrate (NO_3^-) typically leads to new production that supports a food web leading to secondary production, while increased ammonium (NH_4^+) commonly leads to greater production within a microbial loop. What has been unclear is whether changes in N form under conditions of N sufficiency alters the composition or production of the primary producers that, in turn, may affect the food web. We tested the effects of changes in N form on phytoplankton composition and rates of productivity on samples collected over a 3-year period from both the Sacramento River and Suisun Bay. Overall, proportionately more chlorophyll *a* and fucoxanthin (generally indicative of diatoms) was produced per unit N taken up in samples enriched with NO_3^- and incubated at reduced (~15% of ambient) light intensity than in treatments with NO_3^- with high (~60% of ambient) light exposure or with NH_4^+ under either light condition. Proportionately more chlorophyll *b* (generally indicative of chlorophytes) and zeaxanthin (generally indicative of cyanobacteria) was produced in samples enriched with NH_4^+ and incubated under high light intensity than in treatments with low light or with added NO_3^- at either light level. Rates of productivity enriched with NO_3^- were higher than those enriched with NH_4^+. The 2014 spring bloom in Suisun Bay was consistent with these relationships, with higher NO_3^- availability (apparently from substantial riverine nitrification) sustaining high production of diatoms. These findings confirm that N form is related to the amount and "quality" of phytoplankton, all other factors being equal. These results bear substantially on the management debate concerning the importance of reducing total N loads from sewage effluent and/or adding nitrification with or without N reductions. These results also have implications for development of numeric nutrient criteria and the importance of accounting for N form.

Keywords: nitrate, ammonium, productivity, diatoms, spring bloom
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Physiological Assessment of the "Bad Suisun" Phenomenon: Nutrient-Phytoplankton Interactions

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A dramatic decline in native and introduced pelagic fish species in the northern part of San Francisco Bay (SFB) has been linked with, among a number of factors, a decline in prey abundance precipitated by a decrease in phytoplankton production and biomass. This decline at the base of the food web has in turn been attributed to a number of ecological and environmental factors, one being the build-up of ammonium (NH_4^+) in the water column resulting from increased discharge of wastewater effluent over the last three decades. While nutrient input from effluent has traditionally been thought to promote phytoplankton growth, and in severe cases lead to eutrophication, it has also been documented that too high concentrations can lead to toxicity. Few investigations have characterized the tipping point between the concentration of NH_4^+ that supports optimal growth, and that which inhibits growth, of estuarine phytoplankton. This investigation is the first to do so with a number of phytoplankton species, including diatoms and chlorophytes, isolated from Suisun Bay in the northern part of SFB. The primary goal of this investigation is to investigate phytoplankton productivity and growth over a range of NH_4^+ concentrations, to identify optimal concentration of NH_4^+ for growth, and to characterize the tolerance threshold to NH_4^+. A secondary goal is to compare the growth of phytoplankton on NH_4^+ with that on nitrate to determine whether certain species grow better with one source versus the other. Comparisons of several species of native phytoplankton will provide a mechanistic understanding of the interactions between NH_4^+ concentration and phytoplankton growth, information that is necessary to make sound management decisions regarding the degree to which nutrients forms and concentrations exert negative control over the food web in Suisun Bay.

Keywords: Phytoplankton Suisun Bay Diatoms Chlorophytes Ammonium Nitrate Tolerance Growth
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Heavy Hitters in the San Francisco Bay Phytoplankton Community - Diatoms, Dinoflagellates, and Cryptophytes

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Phytoplankton are the largest living component of San Francisco Bay (in mass/tons of carbon). These microscopic, single-celled plants are the primary food source on which the Bay's consumers, such as zooplankton, bivalves, crabs, fish, birds, and seals, ultimately depend. Over 600 phytoplankton species have been detected in the Bay, they come in a variety of shapes, sizes, nutritional value, functionality, and potential toxicity, and the combination of those variables determines their value as a food resource to consumers.

Since 1992, our long-term USGS research program has been measuring phytoplankton taxonomic composition, abundance, and biomass throughout San Francisco Bay. Cloern and Dufford (2005) analyzed the first decade of this record and discovered that three functional groups dominate phytoplankton biomass (as cell biovolume): diatoms, dinoflagellates, and cryptophytes. In recent years, it has been hypothesized that elevated concentrations of certain nutrient forms and changes in nutrient ratios have created shifts in the relative percentages of these groups. Here we analyze data from the salty, ocean-influenced parts of the Bay to answer the following questions: (1) What are the relative contributions of the three dominant groups to total phytoplankton biomass? (2) Do these contributions differ between San Pablo, Central Bay, and South Bay? (3) Are there seasonal fluctuations of these contributions, and have they changed over time?

Keywords: phytoplankton, microalgae, primary production, taxonomy, diatoms, dinoflagellates, cryptophytes
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Does San Francisco Bay have a Harmful Algal Bloom problem?

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San Francisco Bay is well-known for multiple impairments directly and indirectly linked to human activity, including excessive mercury, PCBs, invasive species, and increasing concentrations of ammonium. These impairments are associated with increased urbanization, diverted water flow, point and non-point introduction of pollutants and contaminants. Despite these many impacts and alterations, San Francisco Bay is generally considered to be resilient to eutrophication, and harmful algal blooms (HABs) caused by nuisance and toxic phytoplankton are considered to be episodic and unusual events. However HABs and related toxins have received insufficient study and monitoring to date, and, in fact, both HAB-forming cells and toxins are routinely found in the Bay/Delta. Here we present 3+ years of toxin monitoring, 20+ years of phytoplankton composition, and toxin levels in a newly acquired set of bivalve tissue samples to explore the potential HAB issue in San Francisco Bay and to establish a baseline for identifying trends in HAB dynamics, together with recommendations for monitoring potential events and impacts. Both microcystins (freshwater toxin) and domoic acid (marine toxin; Amnesic Shellfish Poisoning) are nearly ubiquitous in the Bay, and it is likely that other toxins including saxitoxin (Paralytic Shellfish Poisoning), okadaic acid (Diarrhetic Shellfish Poisoning) and yessotoxin (responsible for the mass abalone mortality in Sonoma during 2012) are at least occasionally present. Using data on both toxin and cell abundance, we will explore several questions, including: Do toxin concentrations in the Bay reach levels that could cause adverse impacts? What is the source of marine toxins – transport of coastally-produced toxins into the Bay or production by marine HAB-species within the Bay? Has "intrusion" of estuarine HAB organisms occurred following the opening of the South Bay salt ponds?

Keywords: harmful algal blooms, phytoplankton, nutrients
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Examining Long-Term Phytoplankton Monitoring Data in the San Francisco Estuary: What Changes Have Occurred?

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The northern San Francisco Estuary (SFE) has experienced major ecological disturbances due to anthropogenic activities over the past century, and the pronounced declines post-2000 of several important pelagic fish species serve as recent evidence that these disturbances affect all levels of the SFE food web. Conceptual models, developed with broad input from regional and national experts, recognize that multiple factors have acted in concert to degrade the northern SFE habitat, including: water withdrawals, land use changes, invasive species, and contaminants including nutrients. A few recent studies have argued, based on analysis of multi-decade monitoring data (Department of Water Resources Environmental Monitoring Program (DWR-EMP)), that food web restructuring in the northern SFE is due in large part to shifts in phytoplankton community composition that have resulted from high anthropogenic nutrient loads. With the goal of developing an improved understanding of how and when changes in phytoplankton community composition occurred and of the hypothesized bottom-up nutrient-phytoplankton driver of food web restructuring, we examined the DWR-EMP phytoplankton monitoring data from 1975-2007. This presentation will present our observations related to the following fundamental questions: 1. Is there evidence to indicate that phytoplankton community composition has changed in the northern SFE? In particular, have diatoms decreased and been replaced by other (undesirable) classes of phytoplankton? 2. When did changes occur, and were they abrupt or gradual changes? 3. Using simulations designed to assess the robustness of the DWR-EMP data, what types of changes in community composition could have been confidently identified?

Keywords: phytoplankton ecology, long-term monitoring, microscopy, data analysis
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What Caused the Diatom Decline in Suisun Bay after 1986?

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Measurements from the IEP Environmental Monitoring Program have shown that phytoplankton biomass (as chlorophyll *a* concentration) decreased five-fold in Suisun Bay after introduction of the clam *Potamocorbula amurensis* in 1986. The diatom component (as cell abundances) decreased ten-fold after 1986, and one proposed explanation for the selective loss of diatoms is suppression of diatom growth by sewage-derived ammonium. We explore a more direct explanation: diatoms are removed by clam grazing faster than other algae because they sink. Diatoms, especially in the presence of high sediment concentrations, sink rapidly. Fast vertical transport to the sediment-water interface makes phytoplankton cells accessible to clams that can permanently remove them, thus preventing their resuspension back into the water column. Relative to diatoms, motile and non-sinking algae may be transported more slowly down into the bottom zone of clam filtration. We used a numerical model of a coupled shoal-channel system representative of Suisun Bay to: (1) explore the linkages between algal sinking, clam grazing, turbulent mixing, light availability, and horizontal transport; (2) assess whether those linkages can result in differential removal of diatoms and non-diatoms by benthic filter feeders; and (3) evaluate the plausibility of a sinking-grazing based mechanism to explain why the diatoms declined faster than flagellates, green algae and cyanobacteria in Suisun Bay after 1986.

Keywords: phytoplankton, diatom, clam, Suisun Bay, sinking, model, Potamocorbula, sedimentation, algae
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The Suisun Bay Problem: Food Quality or Food Quantity?

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Suisun Bay provides habitat for endemic fish species occupying low salinity habitats of the San Francisco Bay-Delta estuary. It is a highly disturbed biological system, manifested as decreased primary production, proliferation of non-native species, restructured communities across multiple trophic levels, and population collapses of pelagic fishes. The consensus of the broad scientific community is that these symptoms of environmental degradation are the result of multiple human disturbances including landscape transformations, altered freshwater inflows, nutrient and contaminant inputs, and disruption by introduced species. In recent years an alternative explanation has emerged that these changes were driven by a single factor – growing wastewater inputs of ammonium and associated increases in the N:P ratio. The proposed underlying mechanism is an altered chemical environment that slows growth of diatoms and/or promotes growth of other algal forms, leading to degraded quality of the phytoplankton food resource for consumers. If this explanation is correct we would expect patterns of change in the Suisun Bay phytoplankton community that are synchronous with patterns of change in ammonium loading. We analyzed phytoplankton data collected by IEP and USGS to look for four patterns that would be expected if the alternative explanation is correct: (1) significant decline of diatom abundance; (2) synchrony of the diatom decline with increasing ammonium loading; (3) increased abundance of non-diatom algal groups; and (4) indicators showing that that the phytoplankton food quality is low.

Keywords: Suisun Bay, ammonium, phytoplankton
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