Benthic Nutrient Fluxes in the San Francisco Bay Delta: Nutrient Stoichiometry, Dentrification and Effects of Benthic Microgal Photosynthesis

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The nutrient mass balance of estuaries includes major inputs from terrestrial, atmospheric and coastal sources; in shallow water ecosystems, sediment nutrient recycling, burial and transformation can also be important. While benthic nutrient fluxes have been assessed at several sites in northern San Francisco Bay, such data across a Delta-Bay transect have not been developed. In September 2011 and March 2012, we measured benthic processes across a gradient from the Delta to Suisun Bay. Dark and illuminated core incubation techniques were used to measure rates of denitrification, nutrient fluxes (phosphate, ammonium, nitrate), and oxygen fluxes including benthic photosynthesis.

Overall rates of oxygen-based metabolism were modest, with shallow water sediments showing substantial photosynthesis by benthic microalgae. Photosynthesis generally attenuates the efflux of N and P in costal sediments, but several sites showed an enhancement of nitrification under illumination, as well as an enhancement of fluxes of soluble reactive phosphorus (SRP). The fluxes of SRP in Honker Bay, Franks Tract, Big Break and Sherman Island were directed into the sediment, likely a result of efficient scavenging by surficial sediment iron oxides. When SRP fluxes were compared to total dissolved inorganic nitrogen (DIN) fluxes for all sites, most of the data approximated Redfield proportions. However, three Bay sites had significant P retention relative to DIN, while all the Delta sites from the light experiments had excess P release relative to N. Coupled nitrification-denitrification was the dominant denitrification pathway, with ~30% of remineralized N denitrified. Our spring 2012 data shows decreased nutrient fluxes and oxygen uptake driven at least in part by cooler water temperatures compared to fall 2011.

Rates of denitrification, benthic photosynthesis, and N/P nutrient net fluxes in these shallow sediments are important to regional nutrient balance, with return fluxes of nutrients supporting phytoplankton production.

Keywords: sediment-water exchange, denitrification, benthic microalgae, sediment oxygen demand, phosphorus, nitrogen

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Order 1

New and Regenerated Productivity: an Oceanographic Concept Applied to the San Francisco Bay Delta to Understand Phytoplankton Response to Improved Irradiance and Nitrate versus Ammonium Supply

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New and regenerated primary production is a basic concept of marine biogeochemistry/marine ecology, introduced by Dugdale and Goering (1967). In the ocean, nitrate occurs in deep water and when advected to the euphotic zone is considered “new” nutrient. Ammonium is supplied to the euphotic zone and to phytoplankton by grazing or bacterial degradation of organic matter. New production sets the upper limit for yield from the ecosystem, e.g. for fish. Multiple sources of both nitrate and ammonium to the San Francisco Bay Delta makes it inappropriate to apply the new production concept directly to the estuary. However, our studies have shown that phytoplankton biomass is accumulated (forms blooms) and most carbon uptake occurs when nitrate is the nitrogen source. Evaluation of nutrient uptake and chlorophyll accumulation in enclosure experiments made at a series of irradiances (and some with nutrient additions), revealed two groups of responses, those with >10% surface irradiance and those with <10%, effectively dividing the euphotic zone into 2 layers. In the upper zone, sufficient light exists for ammonium uptake that reduce the ambient ammonium concentration to levels allowing nitrate uptake to occur. In the lower zone, with light < 10%, phytoplankton production is based only on ammonium uptake at a slow rate likely balancing in situ regeneration of nitrogen from organic N. Consequently, primary production in the upper zone may be designated “new production” and that in the lower zone,” regenerated production. Understanding these functional components of the water column helps explain the interactions of changing transparency and relative nutrient loading in estuarine production and bloom initiation in San Francisco Bay Delta.

Keywords: nitrate ammonium new production euphotic zone primary production phytoplankton bloom

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Experimental Manipulations Confirm the Role of Ammonium as a Stress to Phytoplankton in the Bay Delta

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There has been considerable debate as to the effects of elevated levels of ammonium on the food web of the Bay Delta. While the effects of nutrient quantity are reasonably well understood in terms of eutrophication, the effects of high nutrient loads on algal physiology are far less understood. It is well known that different forms of nitrogen are used at different rates by phytoplankton. Shifts in nitrogen (N) form from nitrate to ammonium generally lead to community shifts away from plankton communities dominated by diatoms to those dominated by flagellates, cyanobacteria, and eubacteria, in turn, resulting in a shift in composition of higher food webs. Here we report on a series of experimental manipulations in which both form of N and light availability were varied and the phytoplankton physiological and community response monitored on time scales ranging from hours to days. Samples were collected in the Sacramento River during fall 2011, 2012, and spring 2011. Site, seasonal, and time scale differences were observed. Overall, these experiments confirm that 1) nitrate uptake is inhibited by ammonium and the degree of inhibition increases with ammonium concentration; 2) the decrease in nitrate uptake is not compensated for by increases in ammonium uptake resulting in depression in total nitrogen uptake; and 3) biomass accumulation (growth) is depressed when total nitrogen uptake is inhibited. These data underscore the importance of elevated ammonium loads as a major stressor of the Bay Delta.

Keywords: ammonium, diatoms, inhibition, physiological response, community composition

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Inside and Outside Forces Change the San Francisco Bay Phytoplankton Community

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Our 18-year (1993-2011) record of phytoplankton species abundance and biomass in San Francisco Bay reveals striking changes in synchrony with two events: a 1999 shift in climate forcing across the Pacific Ocean, and landscape modification of the Bay.

The 1999 climate shift was associated with cooling of the coastal ocean, intensification of upwelling, and record-high abundances of marine shrimp and juvenile flatfish and crabs. Coincident changes were detected in phytoplankton biomass, including increasing baseline levels and the appearance of autumn blooms. Formerly common species, such as the diatom *Coscinodiscus marginatus* and dinoflagellate *Oxytoxum milneri*, disappeared while others, including the diatom *Thalassiosira nodulolineata* and dinoflagellate *Polykrikos schwartzii*, appeared for the first time after 1999 and have persisted in the Bay. A shift of the dominant species from *Thalassiosira rotula* to *Thalassiosira punctigera* has potential implications for higher trophic levels since *T. rotula* produces biochemicals that can block reproduction of invertebrates such as copepods.

Since 2004, the South Bay Salt Pond Restoration Program has opened numerous decommissioned salt ponds to exchange with the Bay. These connected ponds function as incubators for phytoplankton, including species harmful to invertebrates, fish, mammals, and birds. Following the ponds openings, four previously undetected toxic algal species have been detected in the South Bay (Karenia, Karlodinium, Heterosigma, and Chattonella), with three species persisting in high abundances.

Therefore, shifts in phytoplankton community composition have occurred in synchrony with local and ocean-basin scale environmental changes, but mechanisms of these shifts are not apparent. We have begun a pilot monitoring program to measure phytoplankton functional groups with diagnostic pigments and to measure algal toxins to determine if the new occurrences of toxin-producing species are a potential risk to Bay and human health. In this era when support for monitoring programs is diminishing globally, the imperative for monitoring has never been greater.

Keywords: phytoplankton, phytoplankton taxonomy, longterm data, monitoring

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Are Shallower, Slower Habitats Necessarily “greener"? How Clams Upend Conceptual Models Guiding Ecosystem Management in the Delta

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As “food for the fish-food”, phytoplankton is the dominant energy source to the pelagic food web of the Sacramento-San Joaquin Delta. However, Delta phytoplankton biomass is low and its long-term downward trend has been paralleled by declines in fish and zooplankton (fish-food). Low phytoplankton biomass and productivity are therefore implicated as factors contributing to the multi-decadal declines in fish species. For that reason, plans for managing the future Delta include actions aimed at enhancing phytoplankton productivity. Two common conceptual models shape those plans and expectations of the ultimate outcomes. The first holds that shallower aquatic habitats promote higher phytoplankton biomass and productivity than deeper habitats because they provide more sunlight energy for phytoplankton photosynthesis (the “Shallower is greener” model). The second holds that more slowly moving water is associated with higher phytoplankton biomass and productivity because longer retention time can allow for greater phytoplankton biomass accumulation (the “Slower is greener” model).

Although these conceptual models seem intuitive and reasonable, they aren’t always correct. Using mathematical models and field observations, we show that where bivalve grazing is significant (as in much of the Delta), shallower and slower habitats: 1) are not necessarily characterized by higher phytoplankton biomass or productivity; 2) may be characterized by *lower* phytoplankton biomass and productivity than deeper, faster habitats; and 3) are associated with much greater uncertainty regarding ultimate algal biomass and productivity than deeper, faster habitats. These lessons all suggest that habitat depth and transport time should not be used as indicators of phytoplankton biomass and production. Further, phytoplankton growth and loss (e.g. grazing) rates must be considered together in estimates and expectations of algal biomass or production. Consideration of only one part of the mass balance can lead to substantial error. Practical implications of these lessons for management of the Delta will be discussed.

Keywords: Delta phytoplankton clam bivalve grazing transport model restoration habitat

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Spatial, Temporal, and Tidal Effects on the Distribution of Zooplankton in the Deep Water Ship Channel of the San Joaquin River, CA

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As part of a larger study investigating dissolved oxygen dynamics in the tidally-influenced San Joaquin River (SJR) of the Sacramento –San Joaquin Delta Estuary, algal and zooplankton distributions were analyzed for the enhancement of a water quality model necessary to adaptively manage watershed use. The study reach consisted of a 10-mile segment of the Deep Water Ship Channel (DWSC) within the SJR below the Port of Stockton, including the Turning Basin. Monitoring was performed during summer and fall of 2011 and summer of 2012. Three studies were performed: spatial distribution, evaluation of the effect of the Turning Basin on zooplankton abundance in the DWSC, and zooplankton grazing rate quantification. Lateral and vertical distributions at fixed stations, under differing tidal conditions, were highly variable. In the SJR longitudinal monitoring, zooplankton concentrations increase with distance downstream from the Port of Stockton. However, the highest zooplankton concentrations were found in the tributary Turning Basin of the DWSC. These data suggest that the Turning Basin serves as an incubating reservoir of zooplankton that exchange with tidal circulation. Additional studies were conducted in 2012 to verify these observations under lower net flow conditions and directly measure grazing rates with microcosms to incorporate zooplankton in the water quality model.

Keywords: zooplankton, Deep Water Ship Channel, San Joaquin River, grazing

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Invasive Zooplankton Alter Nutritional Prey Quality for Fish in San Francisco Estuary

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Degradation of carrying capacity and consequent food limitation has been proposed as one of the key factors driving the recent decline of pelagic fishes in the upper San Francisco Estuary. Recent dramatic drop in fish biomass, however, was not accompanied by equivalent decrease in zooplankton carbon, the key food source for threatened and endangered fish species. We tested whether essential nutrient concentrations of zooplankton community changed with the establishment of invasive species. Fatty acid (FA) associated food quality is a critical factor that regulates the energy transfer between primary producers and consumers, and plays an important role in growth, development and reproduction success in heterotrophs. We compared the fatty acid profiles of dominant native and invasive zooplankton species collected in the Estuary. Lower concentrations of essential FAs in invasive species would suggest negative changes in the food quality for fish. Our analyses show substantial differences in long-chain polyunsaturated FAs (PUFAs) across zooplankton taxa. The invasive cyclopoid *Limnoithona* that currently dominates plankton communities had the lowest concentration of eicosapentaenoic acid (EPA). We also detected substantially lower accumulation of monounsaturated fatty acids (MUFAs) by *Limnoithona*, potentially associated with their carnivorous diet. Higher accumulation of EPA but no accumulation of docosahexaenoic acid (DHA) in cladocerans was confirmed in our analysis of *Daphnia*. These taxonomical differences in the FA composition altered nutritional quality of the whole community, because native cladocerans significantly declined while invasive *Limnoithona* increased after their introduction in the early 1990s. Observed shifts in the essential FAs of the whole zooplankton community likely modified growth and survival of secondary consumers. On the basis of these results, plankton biomass and the available zooplankton composition data from long-term monitoring program, a food quality index for pelagic fishes can be developed and used to optimize the management decisions.

Keywords: Fatty acids, food quality, food quantity, invasive species, fish, zooplankton

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The Other Fish Food: A Preliminary Look at Spatial and Temporal Trends in Amphipod Abundances in the Upper Sacramento-San Joaquin Estuary

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Dietary studies have shown that amphipods are important components of the diets of many native and non-native fishes in the San Francisco Estuary (estuary); however, spatial and temporal trends in amphipod abundances in the estuary are not well studied. The Department of Water Resources' multi-year spatially extensive benthic special study provides an opportunity to examine the trends in abundance of several species of amphipods in the Delta and the low salinity zone (LSZ) of the estuary. We selected sampling locations distributed throughout the Delta and LSZ using a Generalized Random Tessellation Stratified (GRTS) design, a spatially balanced method of randomly selecting sites. Site selection was weighted towards non-bay water bodies (e.g., sloughs, flooded islands, and rivers), as previous studies have shown little site to site variation in benthic communities in the bays compared to other areas of the estuary. We analyzed samples from 48 sites in May and October of 2007-2011. Although 13 species of amphipods were collected, four represented 97% of total amphipods collected: *Gammarus daiberi* (31%), *Americorophium spinicorne* (27%), *Americorophium stimpsoni* (21%), and *Hyalella* sp. (18%; requires submerged aquatic vegetation). Total amphipod abundance was highest in May 2008 and lowest in May 2011. The highest abundances of amphipods were consistently found at the two sites in Sherman Lake, while the lowest abundances were found at sites in the main channel in Suisun Bay. The amphipod community at the majority of sites was made up of at least two or three species; few sites had only one species present. Our results suggest that the quantity and species composition of amphipods in the food web will vary both regionally and by microhabitat. Future analyses of the over 600 other sites sampled during GRTS will help us further understand this variation, as well as seasonal and yearly variation in amphipod abundances.

Keywords: Amphipods Benthic community Food web

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Influence of Biotic Interactions on the Distribution of the Copepod *Pseudodiaptomus forbesi* in the Upper San Francisco Estuary

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Distributions of estuarine organisms are dictated in part by physiological tolerances to salinity, but salinity is not the only factor that determines where species are found. This study examines how biological interactions may influence the distribution of the copepod *Pseudodiaptomus forbesi* in the upper San Francisco Estuary (SFE). Two lines of evidence suggest that biotic interactions, not physiology, limit the range of *P. forbesi in* the SFE. First, historical records show that *P. forbesi* was abundant across a broader range of salinity before than after 1993, when two copepods were introduced to the estuary that may compete with or prey upon *P. forbes*i. Second, laboratory experiments on the salinity tolerance of this species show that it is physiologically capable of tolerating a wider range of salinity than it currently inhabits in the SFE. Feeding experiments show that while *P. forbesi* exploits some food sources that are not used by the other species there is also some overlap, indicating potential for competition. Predation on *P. forbesi* by one of the introduced copepods was also examined in laboratory experiments and may have some effect on its population.

Copepods are an important food source for many fish species and *P. forbesi* in particular can constitute a large fraction of the diet of the endangered delta smelt. Understanding the ecology and distribution of this species provides insight into the productivity of the system and the resources available to higher trophic levels.

Keywords: copepod, feeding, FlowCAM, diatom, flagellate, ciliate, prey, diet, delta smelt

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Evidence of Food Web and Biogeochemical Changes in the San Francisco Estuary as Indicated by Stable Isotope Analysis of Historical Zooplankton Samples

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In recent years, numerous species introduction and alterations of freshwater flow have resulted in a strong decline of phytoplankton biomass and subsequent impacts in both zooplankton and pelagic fish communities of the San Francisco Estuary (SFE). Here we use carbon and nitrogen stable isotopes of zooplankton, a key component in estuarine systems and a major food source for many important and endangered fish species, as a bioindicator to document foodweb and biogeochemical changes in the SFE over the past decades. This retrospective analysis based on long-term series of zooplankton samples collected from 1976 through 2010 should provide insights into the relative contribution of local phytoplankton and terrestrially-derived organic matter sources to the plankton-based foodweb, trophic levels of the dominant species, trophic interactions, and how they have changed related to primary environmental modifications. We present preliminary results from an experiment aimed at validating the use of archived samples. We measured the impact of common preservation methods (freezing *versus* formalin), and duration of preservation on the stable isotope composition of six copepods and one mysid species. Initial results indicate a limited impact of formalin preservation on stable carbon isotopic composition (<1‰), which occurred rapidly after preservation and remained rather constant over time (thus predictable). Preservation effects were more variable and species-dependant for stable nitrogen isotopes (from <1‰ for *Acartiella sinensis* and *Hyperacanthomysis longirostris* to unexpectedly high for *Pseudodiaptomus forbesi*) but remained for most species smaller than the expected trophic enrichment and should still allow the calculation of correction factors, as they were stable over time. Preliminary results based on historical samples collected in the San Joaquin river at Buckley Cover will also be presented. These results will be valuable in improving our understanding of the upper SFE and of the possible mechanisms contributing to the Pelagic Organism Decline.

Keywords: Zooplankton, Stable Isotope, Foodweb, Organic Matter, Low Salinity Zone

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