

*Proposal submission for the
CALFED 2007 Supplemental PSP*

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Title of Supplemental Proposal: Foodweb Support for the Threatened Delta
Smelt and Other Estuarine Fishes in Suisun Bay and the Western
Sacramento-San Joaquin Delta

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Foodweb support for the threatened delta smelt and other estuarine fishes in Suisun Bay and the western Sacramento–San Joaquin Delta

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Summary

This proposal is for one additional, brief but intense field season to follow up on field work in 2006 - 2007. The additional work will be to estimate a carbon budget for the Low-Salinity Zone in summer, which will give us a more complete picture of the importance of carbon subsidies from the Delta to the LSZ. We will also fill in some key gaps revealed by our previous research.

Project Purpose

The original project addressed two distinct but related topics: Foodweb support for delta smelt, and potential mechanisms underlying relationships of abundance or survival of estuarine fish to freshwater flow. These topics are related through the productivity of the pelagic foodweb in the estuarine Low-Salinity Zone (LSZ, salinity ~ 0.5 – 6 psu). This is a key region of the estuary and the rearing area for numerous estuarine-dependent fishes including delta smelt.

As described below, we have completed the field work and most of the laboratory work to address our original research questions, and have begun synthesizing these results, with plans for a synthesis workshop in late spring-summer 2008. However, the research to date has revealed some unanswered questions that we hope to address with additional field and laboratory work:

1. How do riverine subsidies of phytoplankton, organic matter, and zooplankton influence dynamics in the LSZ?
2. What is the overall balance of sources and sinks of organic matter and its principal components in the LSZ?
3. What is the trophic structure leading to zooplankton consumed by fish?
4. Does *Microcystis* play a role in disrupting the LSZ foodweb?

Background and Conceptual Models

The original basis for our study was that the foodweb supporting delta smelt and other fish species of the upper estuary had been radically altered by the introduction of the clam *Corbula amurensis*, resulting in an apparent disconnect between the supply of organic matter and the demands of fish, and between the strong flow responses of some fish and the weak response of the lower trophic levels (Kimmerer 2002a). The northern San Francisco Estuary has one of the lowest levels of primary productivity in any estuary worldwide (Jassby et al. 2002). Nearly every quantitative study of reproduction or feeding in the estuary has demonstrated or inferred food limitation, e.g., in cladocerans (Müller-Solger et al. 2002), copepods (Bouley and Kimmerer 2006; Hooff and Bollens 2004; Kimmerer et al. 1994; Kimmerer et al. 2005), the clam *Corbicula fluminea* (Foe and Knight 1985), and diving ducks (Richman and Lovvorn 2004). Juvenile delta

smelt showed signs of low food consumption in at least one year (Bennett 2005), and an index of survival from summer to fall is correlated with zooplankton biomass (Kimmerer In press).

One potential cause of the Pelagic Organism Decline (POD) in ~2002 is low food supply (Sommer et al. 2007). A poor feeding environment does not necessarily imply a close correlation between abundance indices of POD fish species and abundance of food organisms. For example, moderate abundance of copepods in 2006 was not accompanied by high delta smelt abundance in fall. Nevertheless, chronic food limitation in the system may limit the scope for positive population growth in estuarine fishes, amplifying responses to other stressors.

Our conceptual model (Fig. 1) depicts principal flows of material within the LSZ foodweb and from the freshwater regions into the LSZ. As a result of previous work in the estuary and our studies in 2006-2007, we understand better how the foodweb operates and have data to determine at least semi-quantitatively most of the flows in the diagram. Principally we have learned that the foodweb is more complex than we had thought, with overlapping trophic levels.

Energy supplies to support delta smelt and other fishes can be disrupted by a variety of factors. The principal energy source for the LSZ is phytoplankton production, but there are subsidies of organisms and substances from the freshwater Delta. Sources of organic matter from seaward of the LSZ appear unimportant because concentration gradients are small, net flow is seaward, and since gravitational circulation near the LSZ is weak, at least in the dry season. Production by larger phytoplankton, especially diatoms, is more directly linked to higher trophic levels than production by smaller phytoplankton which fuel mainly the microbial foodweb. In addition, diatom growth may be constrained by high ammonium concentrations (Wilkerson et al. 2006). Bacterial growth and respiration are supported by dissolved organic carbon (DOC) which may come from local sources (e.g., sloppy feeding by animals) or from upstream. Bacteria are consumed by ciliates but also by an intermediate trophic step, probably nanoflagellates, themselves consumed by ciliates. Most of the mesozooplankton such as the copepods *Limnoithona tetraspina* and *Pseudodiaptomus forbesi* feed on microzooplankton including ciliates (Bouley and Kimmerer 2006, Gifford et al. 2007), although *P. forbesi* can also feed on phytoplankton. Preliminary results indicate that *Acartiella sinensis*, which can be important in the diet of delta smelt, may feed on early life stages of other copepods, mainly *Limnoithona*. Most of the foodweb components are also consumed by clams.

The only link to the benthos in Fig. 1 is that through consumption by clams, but there are others. In particular, release of DOC from sediments (Caffrey et al. 1996), which has not been measured in this part of the estuary, is likely to be an important term in the carbon budget. We are also uncertain of the role of DOC uptake by clams, which could get them through periods of low food abundance (Baines et al. 2007).

A potential disruption not shown in Fig. 1 is that due to the toxic cyanobacterium *Microcystis aeruginosa* (Lehman et al. 2005). This freshwater phytoplankton species is salinity-tolerant (Tonk et al. 2007) and can cause harmful effects to copepods and fish (Ojaveer et al. 2003). It was abundant in some of our samples in 2007 and may have been associated with a die-off of *P. forbesi* in July-August 2007 (see below).

Box Model We developed a simple box model to investigate the importance of upstream subsidies of available organic carbon (AOC) to the Low-Salinity Zone in summer (Cloern 2007; Sobczak et al. 2005). Following Sobczak et al. (2002, 2005), we assumed that the principal source of organic matter fueling the metazoan foodweb of the LSZ was phytoplankton. The model estimates total input of AOC to the Low-Salinity Zone as the sum of in-situ production, advection from the Delta, and dispersion. We ignored dispersive inputs from seaward of the LSZ because gradients were small, and assumed net flux was into Suisun Marsh because of net evaporation during summer. Total input of AOC is thus:

$$\Phi_{\text{AOC}} = P_{\text{LSZ}} A_{\text{LSZ}} + C_{\text{Delta}} Q_{\text{out}} + \left. \frac{dC}{dx} \right|_{\text{D-Z}} K_x A_{\text{xc}} \quad (1)$$

where Φ_{AOC} is the total input of available organic carbon, P_{LSZ} is primary production per unit surface area in the low-salinity zone, A_{LSZ} is the surface area within the LSZ, C is phytoplankton carbon, Q_{out} is net Delta outflow, x is distance along the axis of the estuary, the subscript D-Z refers to the concentration gradient from the Delta to the LSZ, K_x is the horizontal dispersion coefficient, and A_{xc} is the cross-sectional area through which the dispersion takes place.

We used data from selected stations from 115 IEP water quality surveys during June-October 1975 through 2006. Flows were daily means from the Dayflow water accounting program (<http://www.iep.ca.gov/dayflow/>). X2 values were calculated as in Jassby et al. (1995). Phytoplankton carbon was calculated using a carbon: chlorophyll ratio of 30. Primary production was calculated for each LSZ station as in Cole and Cloern (1984) using the parameters in Jassby et al. (2002), and data sources in Kimmerer (2006).

A flow-weighted mean phytoplankton C concentration in Delta stations landward of the LSZ was used to calculate C_{Delta} . Negative flow in the lower San Joaquin River gave a weighting of zero. The slope of a robust regression of phytoplankton C on distance up the axis of the estuary, in and landward of the LSZ, were used to obtain the gradient in Eq. 1. This slope differed significantly from zero in about half of the cases, generally negative before 1988 and small and positive after.

Cross-sectional area at Chipps Island was obtained from a USGS bathymetric database, about 17,000 m². The spatial extent of the LSZ and dispersion coefficients were obtained from the TRIM3D model (Ed Gross, pers. comm. Dec. 2007). This model has recently been calibrated against an extensive set of data on stage, velocity, and salinity (Gross et al. in prep.). Model outputs from a series of constant-flow scenarios were combined into tables of area and volume by depth and salinity in increments of 1 (Kimmerer et al. in prep.).

The box model calculations (Fig. 2) show that nearly all of the phytoplankton carbon is from local primary production. The median proportion supplied by primary production was 92%. In only 12 surveys was more than 25% of the carbon supply from advection, during high-flow periods. In only two surveys did dispersive flux comprise >5% of the total.

The general conclusion from this box model is that most of the supply of phytoplankton carbon to the LSZ comes from in situ production. However, this does not take into account at least two important sources of labile DOC: transport from the Delta and flux from the sediments. The

time scale for advective movement between the Delta and the LSZ in summer is rather long (weeks), so phytoplankton-derived carbon in the Delta has a lot of time for transformation and oxidation during transit to the LSZ. Carbon stored in the sediments may recycle into the water column over short (e.g., clam feces and pseudofeces) or long (e.g., flow pulses) time scales.

The model results together with our field and laboratory results offer a conundrum. The supply rate of phytoplankton carbon from the Delta is small, yet microbial carbon demand within the LSZ exceeds primary production (see below), suggesting an external subsidy. Three potential sources of this mismatch are: 1) phytoplankton production is actually larger than we have estimated; 2) the total supply rate of labile organic carbon from the Delta is large, probably as DOC but possibly also in other forms; or 3) the sediments, the largest pool of C, may be contributing to a net imbalance of carbon. These sources suggest the need for a more thorough estimate of the carbon budget for the LSZ, which we propose to develop here. Estimating these fluxes will require a more fine-scale sampling scheme measuring more variables than used in the simple box model above, or in our previous (2006-2007) studies.

Summary of Progress to Date

Our previous study design focused on ~weekly sampling cruises in spring-summer 2006 and 2007 to stations at 0.5, 2, and 5 psu salinity at the surface. We completed 24 cruises in 2006 and 19 in 2007, although not always to all 3 stations. In situ measurements and samples were coupled with incubations for key metabolic rates (Table 1). Benthic samples were taken in separate, spatially-intensive surveys as well as in more limited monthly surveys (Table 1). Experiments to investigate foodweb structure included “cascade” experiments which attempted to force trophic cascades by manipulating the numbers of copepods in containers of ambient water, and two comprehensive experiments in which stable isotopes of C and N were added to water samples and incubated to observe the transfer of isotope among foodweb components.

Although many analyses are complete, other samples are still being processed (Table 1), so we do not yet have a clear picture of all aspects of our results; in particular we have not completed analysis of clam biomass and many of the zooplankton samples. Results of the first trophic transfer experiment were very encouraging (see below), but the second experiment resulted in ~300 samples for stable isotope analysis which were not budgeted for in the original proposal, and we are requesting funds for this analysis. Results have been presented in numerous talks and posters at conferences and in one symposium volume (Table 2). The current plan is to hold a workshop in late spring 2008 to develop syntheses and plan cross-disciplinary papers.

Space does not permit a full discussion of results to date. Here we present some highlights.

Phytoplankton production remains low in the LSZ, although it was slightly elevated during the high-flow period of 2006. Although generally biomass is controlled by grazing losses and growth rate by light, we have evidence that high ammonium concentration suppresses nitrate uptake and therefore limits the growth potential of diatoms (Wilkerson et al. 2006). Although our study did not focus on the effects of *Microcystis*, it was a nuisance in collections of live zooplankton for experiments, and caused some experiments to be scrapped.

Bacterial carbon demand exceeds phytoplankton production most of the time, implying a subsidy of DOC. Experiments to date suggest that freshwater phytoplankton do not lyse, but may shrink, on exposure to brackish water in the LSZ; there was little effect of exposing phytoplankton from 0.5 psu salinity to 2 psu water. However, the flux of freshwater phytoplankton to the LSZ is known only from the rather crude estimates above, and we do not yet understand the pathway by which they are incorporated into the LSZ foodweb, either through direct consumption by clams or other consumers, or through release of DOC and subsequent uptake by bacteria.

Microzooplankton play a key role in the estuarine foodweb. Most of our cascade experiments (Calbet and Landry 1999) did not induce trophic cascades, indicating that some members of the foodweb were feeding at multiple trophic levels (omnivory). This means that the foodweb has more trophic steps (see Fig. 1), and is therefore less efficient, than previously believed, which has significant implications for the potential productivity of higher trophic levels, including POD species. Tintinnid ciliates were abundant at times but not heavily consumed by copepods, although previous studies indicate they are ingested by clams (Kimmerer unpublished). Copepods continue at low abundance except for the cyclopid *Limnoithona tetraspina*. This copepod has a higher reproductive rate than previously determined, and a specific growth rate of about 10% d⁻¹. Reproductive rate was insensitive to prey abundance. The population of the calanoid copepod *Pseudodiaptomus forbesi* crashed during summer of 2007, and dead copepods were numerous around the time that *Microcystis* became abundant. *Acartiella sinensis* did not feed on ciliates or phytoplankton but may have been consuming *Limnoithona* nauplii. Since *Acartiella* can be an abundant prey of delta smelt (S. Slater, CDFG, pers. comm.), it is important to determine its trophic position and role in the foodweb.

The first trophic transfer experiment was conducted by adding ¹³C-labeled bicarbonate and ¹⁵N-labeled ammonium to water and zooplankton from the 2 psu station, then incubating for up to 3 days. Analyses of the time course of label uptake into the various fractions (Fig. 3) revealed that rapid uptake of labeled carbon by the seston occurred almost entirely in the >2 μm fraction, probably through photosynthesis by phytoplankton. In contrast, uptake of N was nearly half as fast in the <2 μm fraction, implying that bacterial growth was ~half as rapid as phytoplankton growth. *Pseudodiaptomus* initially took up both labels faster than *Limnoithona*, which caught up by the last day. This suggests that *Pseudodiaptomus* may have become food limited toward the end, or that *Limnoithona* was getting its C and N from sources whose own isotope ratios lagged behind those of both bacteria and phytoplankton, i.e., more feeding more on ciliates than was *Pseudodiaptomus*.

These results encouraged us to conduct a follow-up experiment but with more replication, two contrasting light levels, and a large array of ancillary measurements designed to tease apart the responses of different foodweb components. In addition, the ¹³C was added as bicarbonate and the ¹⁵N as leucine; the former is taken up by phytoplankton and the latter by bacteria, which should have separated the two pathways clearly. Because it is difficult or impossible to separate the smaller organisms from the water to determine their isotope ratios (York et al. 2007) we were forced to measure isotope ratios on the same fractions as in the first experiment, and rely on the ancillary measurements to help in interpreting those results.

Numerous other projects provide information useful in our study. These include a study of nutrient regeneration by *Corbula* (Kleckner et al. 2007), a laboratory study of effects of *Microcystis* on copepods (Ali Ger, UC Davis), and a study of distribution of *Microcystis* (Lehman et al. 2005).

Scope of New Work

Our studies to date have focused on three stations identified by salinity, with a sampling interval of one week for most of the cruises. Incubations and other labor-intensive measurements focused on the 2 psu station. The results to date, together with the box model described above, provide an opportunity and suggest a need to develop material budgets for the LSZ and to determine the major sources and sinks of material.

We propose to extend our previous and ongoing work to answer the questions posed in the Introduction. First, we will develop carbon and nitrogen budgets for the LSZ foodweb using box models similar to that presented above, but including principal sources and sinks and material transformations. Some of these terms will require additional field measurements as discussed below. We also propose to examine the possible role of *Microcystis* in depressing abundance of *Pseudodiaptomus*, and the trophic role of *Acartiella*.

The focus will remain on the LSZ, but most of the sampling will be conducted during an intense 2-week period of fieldwork in summer of 2008. Summer is a time of relative stasis in the foodweb and low freshwater flow, so inputs from upstream will be relatively stable. Furthermore, reverse net flow in the San Joaquin River will mean that the advective inputs will be from the Sacramento River, reducing the complexity of the problem of estimating inputs.

Inputs of key components will be estimated (Eq. 1) by determining concentration gradients along a transect from the LSZ into the Sacramento River. Measurements (Table 3) will be made at 3-km intervals from the LSZ to Rio Vista during 3 surveys. Power analysis using previous data on chlorophyll concentrations and bacterial biomass shows that this sampling scheme has 80% power (i.e. 20% chance of Type II error) for detecting a daily dispersive flux of these quantities equal to 10% of the standing biomass. On alternate days, samples will be taken within the LSZ for estimates of biomass, abundance, and (through incubation) productivity (Table 3). Additional samples will be taken as before for bivalve biomass, and core samples will be taken for benthic flux of organic matter and nutrients.

Most of the measurements listed in Table 3 will use the same approaches as described in the original proposal and carried out during 2006 and 2007. Several additional measurements will be added to those taken in 2006 and 2007:

1. Bacterial yield will be determined by 3-day incubations of filtered estuarine water in sealed bottles followed by counts of bacterial cells and estimates of biomass (McManus et al. 2004). Bacterial yield provides a measure of bioavailable DOC with a shorter incubation time than required to measure the decline in DOC (Sobczak et al. 2002, 2005). The resulting value will probably be lower but the time scale is more relevant to those of the model and the other measurements.

2. Feeding and growth of *Acartiella sinensis* will be measured using standard incubation techniques (e.g., Kimmerer and McKinnon 1987, Hooff and Bollens 2004).
3. Consumption of *Limnoithona* by clams will be measured in 24-hour incubations in beakers with suitable controls (Kimmerer et al. 1994).
4. Effects of *Microcystis* on *Pseudodiaptomus* will be determined if and when substantial *Microcystis* blooms are present, or if a die-off of *Pseudodiaptomus* is noted. Short-term bioassays will be used to determine relative effects on *Pseudodiaptomus* and *Limnoithona*, with survival and egg production as endpoints.
5. DOC uptake by *Corbula* will be examined in preliminary experiments. Zebra mussels can take up DOC directly (Roditi et al. 2000, Baines et al. 2007). We will use the methods of Baines et al. (2007) to examine DOC uptake by *Corbula*. This entails removing DOC from water using ultraviolet radiation, and comparing the change in organic weight over a 1-month period between clams exposed to DOC in natural water and those exposed to low-DOC water. In both cases small quantities of phytoplankton will be provided to ensure clams continue to filter during the experiment.
6. DOC and nutrient flux from the benthos will be estimated by determining fine-scale profiles in sediment porewater, and estimating diffusion out of sediments. This gives a conservative estimate of these rates since it does not account for bioturbation or sediment stirring by currents. However, this method is superior in many respects to the alternatives (in situ chambers and incubating cores in the laboratory), both of which have limitations (Caffrey et al. 1996, Topping and Kuwabara 2003, Kuwabara et al. 2007) Since this measurement is new to the project team, we request funds to support Dr. James Kuwabara to do this work.
7. We will complete the stable isotope analyses, which were not in the original work plan.

Relevance to the CALFED Science Program

The overall project addresses two key issues for CALFED: the potential role of lower trophic levels in the Pelagic Organism Decline, and its potential role in the “fish-X2” relationships. Although some aspects of both of these topics have changed since this project was first conceived, the fact remains that the upper San Francisco Estuary is chronically short of energy, and operates differently from foodwebs in other well-studied estuaries. Understanding how this foodweb works is critical to understanding the POD and X2 issues and how food limitation may contribute to them.

New Personnel and Qualifications

Dr. Jim Kuwabara has a Ph.D. in Environmental Engineering Science from California Institute of Technology. He joined the USGS in 1980 and has served as project chief for the National Research Program (NRP) within the Water Resources Division since 1986. His expertise is in sediment-water interactions, and he has invented a pore-water profiler for measuring benthic fluxes that will be used in this study.

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Table 1. Summary of measurements and analysis to be completed by summer 2008. N is number of samples taken in 2006 and 2007. TT1 and TT2 refer to trophic transfer experiments, for which N is the total number of incubated samples. IP, In Progress.

Topic	Measurements	N		Status
Field	Salinity, temperature, irradiance profiles (most samples)	69	43	Done
Nutrients	Nitrate, ammonium, silicate, phosphate	69	40	Done
Organic matter	DON DOC	58	32	2007 IP
	PON POC, size fractionated	240	144	2007 IP
Phytoplankton	Chlorophyll, size fractionated	69	42	Done
	Primary production – ¹³ C single samples	240	144	2007 IP
	Primary production – ¹⁴ C profiles, size fractionated	69	42	Done
	Nutrient uptake measurements	240	144	2007 IP
	Species composition	69	42	IP
Lysis	Lysis and shrinkage experiments	6	3	Done
	DOC release from above experiments	288	154	IP
	Bacterial response from above experiments	0	46	Done
Bacteria	Abundance and biomass	50	32	2007 IP
	Production	63	32	Done
Microzoo- plankton	Abundance and taxonomic composition	60	60	IP
	Consumption rate (dilution experiments)	10	6	Done
	Consumption rate (fluorescently labeled bacteria)	60	0	IP
Zooplankton	Abundance and taxonomic / life stage, 2 size fractions	139	79	2007 IP
	Growth rate	24	13	IP
	Reproductive rate (<i>Limnoithona</i>)	0	36	IP
	Molting rate (<i>Limnoithona</i>)	15	12	2007 IP
Clams	Spatial distribution of <i>Corbula</i> biomass	168	168	IP
	Temporal distribution of <i>Corbula</i> biomass	330	306	2007 IP
	Clam condition in above samples	498	474	Done
Cascade	Impact of zooplankton on microbial foodweb	9	11	IP
Trophic Transfer	Stable isotope transfer through the foodweb (5 components, 2 isotopes, plus nutrients)	0	12	Done
	Stable isotope transfer through the foodweb (8 components, 2 isotopes, plus nutrients, primary production, abundance, and C and N content)	0	40	Pending

Table 2. Presentations (talks, posters, papers) based on work done under the Foodweb project.

First Author & Year	Title	Conference
Kimmerer 2006	Foodweb Support for the Threatened Delta Smelt: Subtle Interactions may be a Cause of the Pelagic Organism Decline	Calfed Science
Slaughter 2006	Foodweb Support for the Threatened Delta Smelt: Summary of Program Objectives and Preliminary Results	
Cohen 2006	The Effects of Salinity on Phytoplankton and Dissolved Organic Carbon Availability	
Hogue 2006	The Role of Excess Ammonium in Reducing Phytoplankton in San Francisco Estuary	
Ignoffo 2006	Growth and Development of <i>Limnoithona tetraspina</i> , the Most Abundant Copepod in the Estuary	
Lidstrom 2006	Phytoplankton Production within the Low Salinity Zone	
Parker 2006	Evaluating the Potential Contribution of Bacterial Carbon for Higher Trophic Levels	
Thompson 2006	Grazing Potential of <i>Corbula amuresis</i> on Lower Trophic Levels	
York 2006	Microzooplankton Dynamics in the Low Salinity Zone of the San Francisco Estuary	
Parker 2006	The Health of Urbanized Estuaries: A Reevaluation of the Consequences of Fertilizing our bays	Estuarine Ecology Teachers Workshop, RTC and SFNERR
Parker 2007	NH ₄ as a potential source of 'contaminant stress' in Suisun Bay	Contaminants working group, Davis, CA
Dugdale 2007	Do low phytoplankton growth rates signal the 'bad' habitat conditions in Suisun Bay driving the pelagic organism decline?	IEP annual workshop
Parker 2007	The importance of separate consideration of anthropogenic NH ₄ and NO ₃ inputs for effective management of estuarine cultural eutrophication.	CAERS, Bodega Bay
Kimmerer 2007	Indirect human impacts on an estuarine foodweb illustrate the false dichotomy of top-down and bottom-up.	Fourth Zoopl. Prod. Symp., Hiroshima
Kimmerer 2007	Foodweb Support for Pelagic Fishes of the San Francisco Estuary: Subtle Interactions and Decade-Scale Changes.	AFS San Francisco
Cohen 2007	Salinities in the Upper San Francisco Estuary Affect Phytoplankton Biomass and Dissolved Organic Carbon Availability	ERF Providence
Gould 2007	Population Dynamics of <i>Limnoithona tetraspina</i> : The success of an introduced copepod in San Francisco Estuary	
Dugdale 2007	DIN is an inadequate descriptor for evaluating nitrogen based effects on estuarine ecosystems.	
Parker 2007	Evaluating the Contribution of Bacterioplankton Carbon to the Foodweb of the Northern San Francisco Estuary.	
Kimmerer 2007	Foodweb Support for Pelagic Fishes of the Upper San Francisco Estuary: Subtle Interactions and Subsidies	
Thompson 2007	<i>Corbicula</i> and <i>Corbula</i> are stressing the restoration: Can we manage freshwater to limit their success?	
Wilkerson 2007	Anomalously low phytoplankton productivity in northern San Francisco Estuary.	
York 2007	Microzooplankton dynamics in the upper San Francisco Estuary.	
Conference talk and conference proceedings		
McManus, York, Kimmerer	Microzooplankton dynamics in the low salinity zone of the San Francisco Estuary (in press)	Conference Proceedings, SIL 2007

Table3. Summary of measurements to be made in summer 2008. Measurements indicated in bold are new to the project, and methods are described in the text.

Topic	Measurements	LSZ	Transect
Field	Salinity, temperature, irradiance profiles	X	X
Nutrients	Nitrate, ammonium, silicate, phosphate	X	X
Organic matter	PON POC	X	X
Phytoplankton	Chlorophyll, size fractionated	X	X
	Primary production – ¹³ C single samples	X	
	Primary production – ¹⁴ C profiles, size fractionated		
	Nutrient uptake measurements		
	Species composition	X	X
Lysis	Lysis and shrinkage experiments	X	
	DOC release from above experiments	X	
	Bacterial response from above experiments	X	
Bacteria	Abundance and biomass	X	X
	Growth rate and estimated C demand	X	
	Bacterial yield	X	X
Microzoo-plankton	Abundance and taxonomic composition	X	
	Consumption rate (dilution experiments)	X	
Zooplankton	Abundance and taxonomic / life stage, 2 size fractions	X	X
	Feeding and growth (<i>Acartiella</i>)	X	
	Consumption by clams (<i>Limnoithona</i>)	X	
	<i>Microcystis</i> effects (<i>Pseudodiaptomus</i>)	X	
Clams	Spatial distribution of <i>Corbula</i> biomass	X	
	Clam condition in above samples	X	
	DOC uptake	X	
Benthos	DOC and nutrient flux	X	
Cascade	Impact of zooplankton on microbial foodweb	X	

Figures

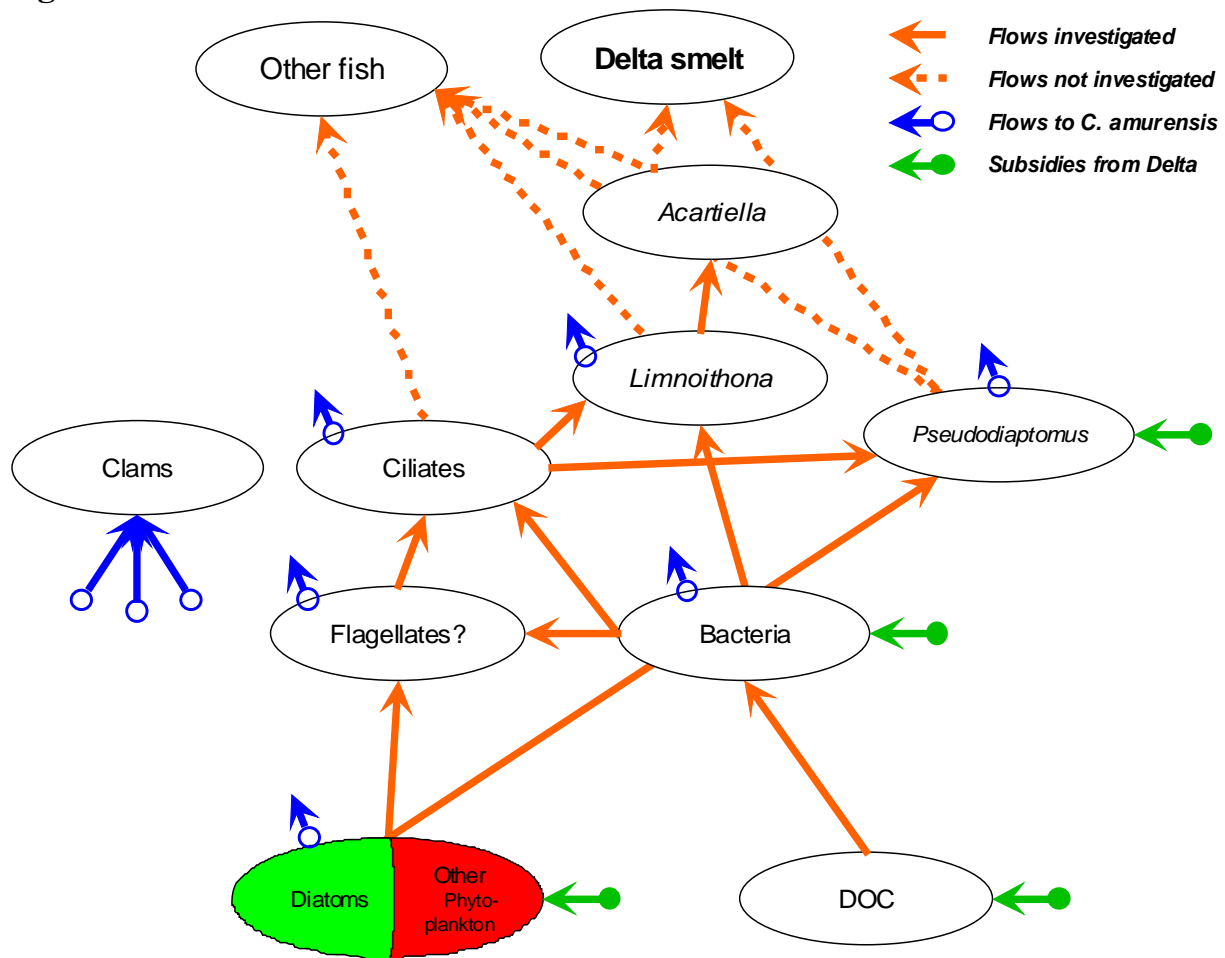


Figure 1. Simplified material flow diagram for the pelagic foodweb of the Low Salinity Zone of the San Francisco Estuary. For clarity we include mainly the components and links we propose to investigate. Links shown as solid lines will be investigated in field or laboratory work, while those shown as dotted lines will be inferred from literature data or results of other projects. We focus on events and effects in the Low-Salinity Zone (LSZ), with a salinity range of roughly 0.5 – 6. The foodweb is fueled by local phytoplankton production and by subsidies mainly due to advection from the Delta, e.g., in phytoplankton biomass and dissolved organic carbon (DOC). The foodweb may be more complex than previously thought, with additional trophic steps in the microbial web and among the copepods, both of which reduce efficiency of energy transfer to fish.

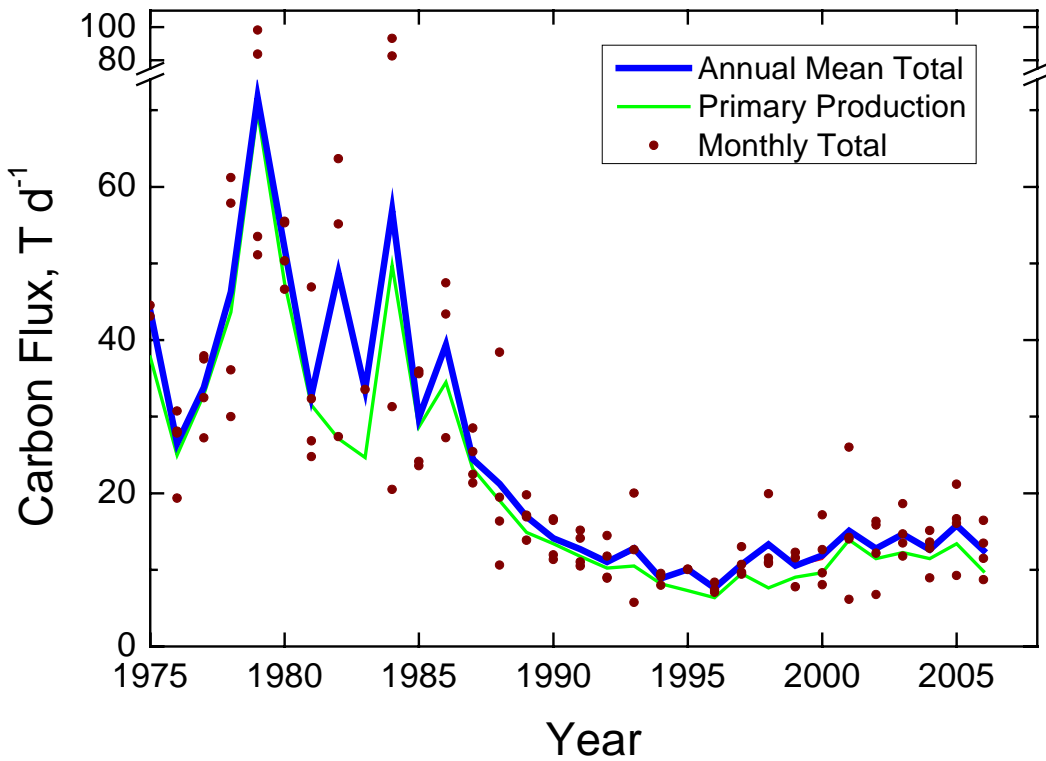


Figure 2. Estimated flux of phytoplankton carbon into the LSZ including in situ primary production, advection from the Delta, and dispersion from the Delta. Dispersion was negligible, and the difference between total and primary production is due to advection.

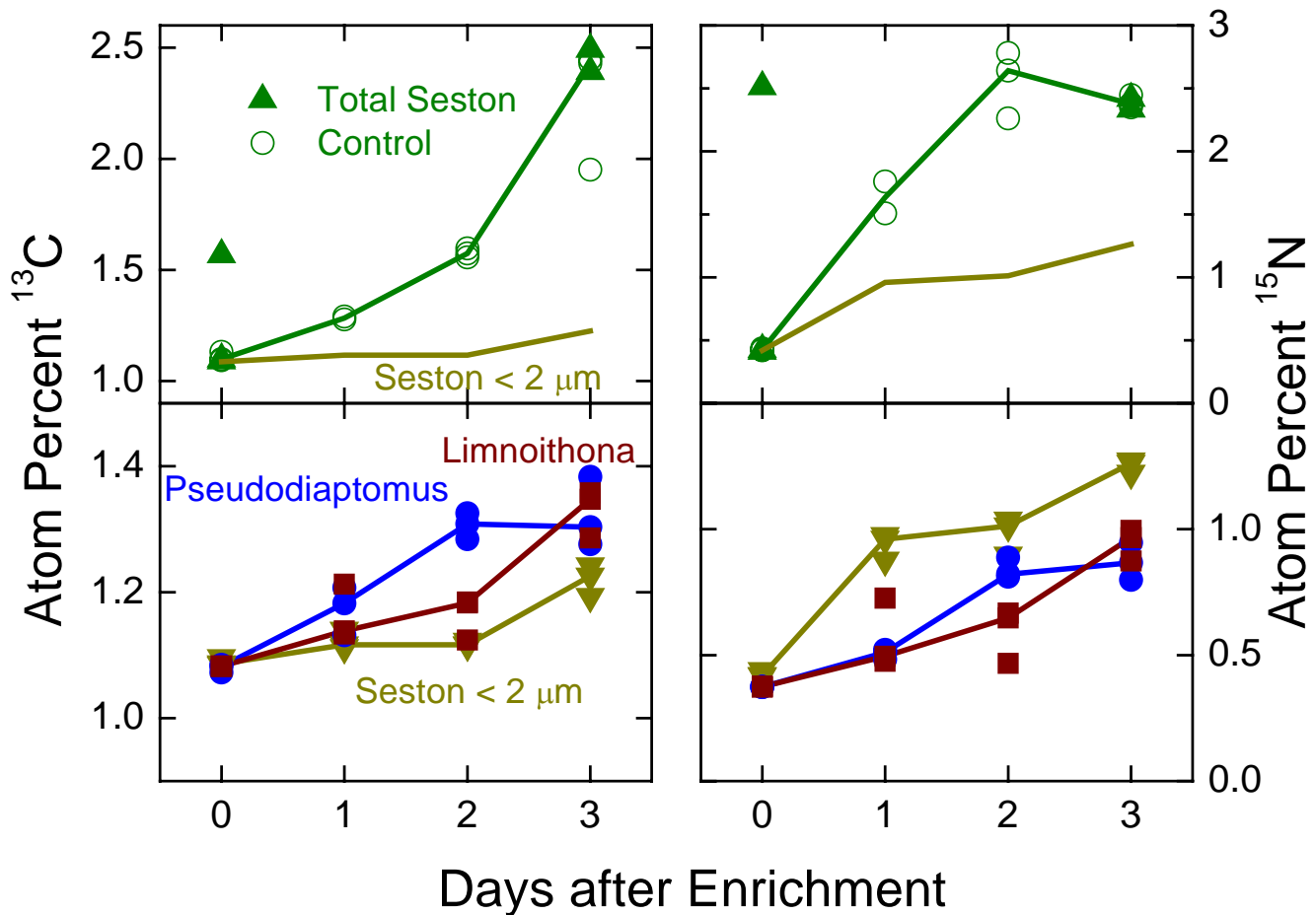


Figure 3. Results of preliminary trophic transfer experiment. Surface water from the LSZ was pre-screened to remove larger zooplankton, then copepods were added, followed by ^{13}C -labeled bicarbonate and ^{15}N -labeled ammonium. Controls and total seston (top) behaved similarly, except that some of the seston samples were lost because of jamming in the mass spectrometer (also the likely source of outliers). Patterns for C and N addition were similar except that the atom percent ^{15}N for seston < 2 μm increased much faster than the atom percent ^{13}C , presumably because bacteria were taking up N directly from the water. Seston atom percent ^{15}N leveled off after 2 days because the ammonium was exhausted. Copepods had similar patterns in general except that the atom percent ^{13}C and ^{15}N for *Pseudodiaptomus* increased faster than that for *Limnoithona*, presumably because *Pseudodiaptomus* is feeding more on phytoplankton, whereas most of the diet of *Limnoithona* was ciliates. Note differences in scales among the panels.

Budget and justification

Summary Budget

SFSU	Phytopl. & Bacteria	Micro-zoop	Lysis	Zoop	Benthos	Joint	TOTAL
Salaries & Wages	32,080		1900	20017	24200	10,517	88,714
Benefits	13,887		912	9781	2130	5,220	31,930
Travel: local	500			500		0	1,000
Travel: out of state	3000			3000		0	6,000
Supplies	21,000		2,220	3,000		3,000	29,220
Other costs	4,500				2,000	6,100	12,600
Subcontracts		26,874	22,720		21,215	0	70,809
Total Direct Costs	74,966	26,874	27,752	36,298	49,545	24,837	240,272
Indirect Costs							59,600
Total							299,872

Subcontracts	U Conn	Georgia Southern	USGS	TOTAL
Salaries & Wages	13087	11000	7673	31,760
Benefits	1629	1862	1406	4,897
Travel: local			1500	1,500
Travel: out of state	2200	3588		5,788
Supplies	1000		700	1,700
Other costs			4,578	4,578
Total Direct Costs	17,916	16,450	15,857	50,223
Indirect Costs	8958	6270	5358	20,586
Total Subcontracts	26,874	22,720	21215	70,809

The proposed project is set up as a single contract with SFSU, with subcontracts to the University of Connecticut (Microzooplankton studies), Georgia Southern University (Lysis of phytoplankton), and the U.S. Geological Survey (Benthic studies). Other cost items under these categories will be incurred by SFSU. The Joint category is for boat time, field supplies, 1 month of the lead PI's time, and 0.5 month of a technician II's time for organizing fieldwork.

SFSU salaries and wages cover about 20 person-months of work including 2 months by Kimmerer, 3 months for Parker, 9 months for technical assistants, and 1 year for a student assistant at half-time. Fringe benefits vary by person but for most employees the benefit rate is 40-50%. Funds are requested for travel to 4 national meetings, 2 by members of the phytoplankton group (Dugdale, Wilkerson, Parker) and 2 by members of the zooplankton group (Kimmerer and a student). Supplies include field and laboratory supplies for each subproject, particularly for the chemical and isotope analyses proposed. The costs of these analyses have been estimated based on running 3 transects with 15 stations, plus 4 days of rate studies (Table

3), all at suitable levels of replication based on past experience. Indirect costs are calculated at 25% of all costs except for the amount of subcontracts that exceed \$25,000.

UConn: This budget is to conduct cascade and dilution experiments and bioassays for labile DOC. We have budgeted 65 days for Dr. Joanna York, who is the postdoctoral associate on the current project, and 100 hours of a graduate student assistant. Fringe benefits are 13% and 9% respectively. We request \$1000 in supplies, mainly filters and chemicals, and funds for 2 round trips to Tiburon for Dr. McManus and Dr. York, for the field work and participation in a team meeting during the field season. McManus will not take any salary from the project.

Georgia Southern University: Dr. Risa Cohen will be responsible for the lysis experiments. She requests 2 months of summer salary. Benefits are 16.93%, and overhead is 57% on salaries only. Two trips to Tiburon are planned to participate in the field work and in the synthesis meeting (this was not budgeted in the original proposal because Dr. Cohen was at SFSU at that time).

USGS: Dr. Jim Kuwabara will conduct the benthic flux measurements. He requests 40 hours' salary for himself and 120 hours for an analytical chemist, Mr. Brent Topping. Benefits are budgeted at 30% of salaries. Supplies include gases and chemicals. Travel is requested for field sampling and shipping of samples and equipment. Sample analyses (nutrients, DOC, chlorophyll) will be run at RTC in the Dugdale/Wilkerson lab. USGS also requests costs of collecting benthic blitz samples, which will be analyzed in the Kimmerer lab.

CURRICULUM VITAE

JAMES S. KUWABARA
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345 Middlefield Road MS/439
Menlo Park, CA 94025

Date of Birth: April 26, 1953
Place of Birth: Honolulu, HI
Marital Status: Married

EDUCATION

California Institute of Technology (September 1975 to June 1980)
Degrees: Ph.D. Environmental Engineering Science, June 1980
Ph.D. minor - Economics
M.S. Environmental Engineering Science, June 1976

University of Hawaii at Manoa (September 1971 to June 1975)
Degree: B.S. with academic honors in Civil Engineering

Honors and Special Appointments:

National Science Foundation Graduate Research Fellowship (1975 to 1977)
National Research Council Postdoctoral Research Associateship (1980 to 1981)
Conference Chairman, Twentieth West Coast Water Chemistry Workshop
Conference, Stanford University, December, 1986.
Final Review Panelist, Water Resources Research Grants Program, June, 1988
Session Chairman, 11th International Estuarine Research Conference, San
Francisco (November 1991).
Session Chairman, 204th National Meeting of the American Chemical Society,
Washington, D.C. (July 1992)
Guest Editor, Dedicated issue of *Estuaries* on "Trace contaminants and nutrients
in estuaries" (September 1993)
Coordinator, National Research Program, San Francisco Bay-Estuary Toxic
Substances Study, (1994-2004)
Co-investigator, Trace-solute gradients in the Santa Barbara Basin, National
Science Foundation, (1995 to 1999)
Session Chairman, "Toxics and Contaminants", Impact of USGS Research in the
Greater San Francisco Bay Area (March 1997)
Trace-element Synthesis Planning Team, USGS National Water Quality
Assessment Program, (1997 to 2000)
Proposal Review Panel, National Science and Engineering Research Council,
Ottawa, Canada, (January 1998)
Editorial Board Member, *Estuaries* Newsletter, San Francisco Estuary Institute
(1997 to present)
Coordinator, Benthic-flux study of contaminants into the water column of Lake
Coeur d'Alene, ID, USEPA-funded (1998 to 2001)
CALFED Technical Review Panel, Contaminants Proposals (August 2000)
Special Session Chairman, American Society of Limnology and Oceanography,
Albuquerque, NM (February 2001)
Associate Editor, *Water Resources Research* (2000 to 2002)
Excellence in Review Award, American Chemical Society, Environmental
Science and Technology (November 2003)
Deputy Editor, *Water Resources Research* (January, 2002 to 2004)

Associate Editor, *Water Resources Research* (2004 to 2006)
Assistant Research Advisor, Ecology Discipline, USGS (2006-present)

EMPLOYMENT

U. S. Geological Survey, Water Resources Division, National Research Program,
Hydrologist (1982 – present)
City College of San Francisco, Adjunct faculty in Earth Sciences Department (2005 –
present)
Cañada College, Adjunct faculty in Division of Science and Technology (2003- present)
National Research Council, Postdoctoral Research Associate (1980 - 1982)
California Institute of Technology, Research and Teaching Assistant (1978 – 1980)
National Science Foundation, Graduate Research Associate (1975 – 1978)

LECTURES AND INSTRUCTION

Technical Presentations since 2000.

Kuwabara, J.S., 2000, Flux of trace metals and nutrients across the sediment water interface in Lake Coeur d'Alene, Idaho: Pilot-study results and implications, U.S. Environmental Protection Agency, Region 10, Seattle, WA, April 2000.

Kuwabara, J.S., Topping, B.R., Woods, P.F., Berelson, W.M., Balistrieri, L.S. and Steding, D.J., 2000, Nutrient flux from sediments into the water column of Lake Coeur d'Alene, Idaho: Implications for Zn-P interactive effects on primary productivity, American Geophysical Union Fall Meeting, San Francisco, CA, December 2000.

Kuwabara, J.S., 2001, Studies on San Francisco Bay: A long-term ecological perspective, American Society of Limnology and Oceanography Spring Meeting, February 2001.

Topping, B.R., Kuwabara, J.S., Parchaso, F., Hager, S.W., Arnsber, A.J., and Murphy, F., 2001, What regulates dissolved-nickel distributions in the South Bay? State of the Estuary Meeting, October 2001.

Kuwabara, J.S., 2001, Opportunities for Collaboration Between District Programs and the NRP: An Example at Lake Coeur d'Alene, ID, Pleanry presentation at Workshop on Reservoir and Lake Limnology, Coeur d'Alene, ID, October 2001.

Marvin-Dipasquale, M. and Kuwabara, J.S., 2001, Water-column and sediment mercury cycling in Lahontan Reservoir (Carson River EPA Superfund Site), Society of Environmental Toxicology and Chemistry Meeting, November 2001.

Kuwabara, J.S., Marvin-Dipasquale, M., Praskins, W., Byron, E., Topping, B.R., Agee, J.L., Kieu, L.H., and Parchaso, F., 2001, Processes Affecting Mercury Dynamics in Lahontan Reservoir, Nevada, AGU Fall Meeting, San Francisco, CA, December 2001.

Gandhi, N., Bhavsar, S., Diamond, M., Praskins, W., Byron, E., Marvin-Dipasquale, M., and Kuwabara, J., 2002, Development of mercury speciation, fate and bioaccumulation model: Application to the Lahontan Reservoir, Nevada, Society of Environmental Toxicology and Chemistry Meeting, December 2002.

Alpers, C.N., Hunerlach, M.P., Taylor, H.E., Marvin-Dipasquale, M. C., Kuwabara, J.S., Krabbenhoft, D.P., 2003, Preliminary results of mercury and methylmercury

- transport studies in the Bear River and Yuba River watersheds, 1999-2002, CALFED Science Conference, January 2003.
- Alpers, C.N., Marvin-Dipasquale, M. C., Kuwabara, J.S., Stewart, R., Saiki, M., Krabbenhoft, D.P., Taylor, H.E., Kester, C.L., and Rye, R.O., 2003, Studies of mercury transport, transformation, and bioaccumulation in the Bear River, California: A watershed affected by historical gold mining, American Society of Limnology and Oceanography Spring 2003 Meeting, February 2003.
- Kuwabara, J.S., Topping, B.R., Woods, P.F., Berelson, W.M., and Laurie S. Balistrieri, 2003, Zinc-phosphorus interactive effects on primary production: Environmental management implications, Zinc Signals 2003 Meeting, May 2003.
- Gandhi, N., Bhavsar, S.P., Diamond, M.L., Byron, E., Kuwabara, J. S., Marvin-Dipasquale M. and Praskins, W., 2003, Application of BIOTRANSPEC model to estimate mercury speciation, fate and bioaccumulation in Lahontan Reservoir, Nevada, Society of Environmental Toxicology and Chemistry Meeting, December 2003.
- Kuwabara, J.S., Alpers, C.N., Marvin-Dipasquale, M., Topping, B.R., Carter, J.L., Stewart, A.R., Fend, S.V., Parchaso, F., Moon, G.E., Krabbenhoft, D.P., Agee, J.L., Kieu, L.H., 2003, Effects of benthic flux on dissolved-mercury distributions in Camp Far West Reservoir, California, AGU Fall Meeting, San Francisco, CA, December 2003.
- Alpers, C.N., Hunerlach, M.P., Marvin-DiPasquale, M., May, J.T., Hothem, R.L., Saiki, M.K. Stewart, A.R., Kuwabara, J.S., Taylor, H.E., and Krabbenhoft, D.P., 2004, Mercury cycling and bioaccumulation in fish in northern Sierra Nevada watersheds contaminated by historical gold mining, California-Nevada and Humboldt Chapters of the American Fisheries Society, April 2004.
- Topping, B.R., Kuwabara, J.S., and Marvin-Dispasquale, 2004, A comparison between three mining-impacted water bodies in the western United States, AGU Fall Meeting, San Francisco, CA, December 2003.
- Alpers, C.N., Hunerlack, M.P., Marvin-DiPasquale, M., May, J.T., Hothem, R.L., Saiki, M.K., Stewart, A.R., Kuwabara, J.S., Taylor, H.E., USGS, and Krabbenhoft, D.P., Mercury contamination, methylation, and bioaccumulation associated with historical gold mining, Sierra Nevada, California: GAC/MAC Special Mercury Session, Halifax, May, 2005.
- Kuwabara, J.S., Topping, B.R., Lynch, D.D., Murphy, Fred, Carter, J.L., Lindenberg, Mary, 2007, Internal cycling of nutrients in Upper Klamath Lake, Oregon: Klamath River Water Quality Coordination Meeting, Klamath, CA, April 2007.
- Kuwabara, J.S., 2007, Benthic sources of biologically reactive solutes to the water column of Upper Klamath Lake and associated wetlands, Oregon: Upper Klamath Lake Workshop, Bureau of Reclamation, Klamath Falls, OR, December 2007.
- Kuwabara, J.S., 2007, Internal recycling of biologically reactive solutes in Upper Klamath Lake and associated wetlands, Oregon: Upper Klamath Lake Workshop, Bureau of Reclamation, Klamath Falls, OR, December 2007.
- Kuwabara, J.S., Topping, B.R., Lynch, D.D., Murphy, F., Carter, J.L., Lindenberg, Mary, 2007, Benthic Fluxes of Dissolved Macro- and Micronutrients to the Water Column of Upper Klamath Lake, Oregon: AGU Fall Meeting, San Francisco CA, December 2007.

Invited Lectures (since 2000).

- Oregon Graduate Institute - Benthic flux of trace contaminants in the water column of San Francisco Bay, Department of Environmental Science and Engineering, May 1999.
- Kansas District Seminar Series – Flux of trace metals and nutrients across the sediment water interface in a mining-impacted lake, Lawrence, KS, September 2000.
- Workshop on Reservoir and Lake Limnology – NRP research opportunities in District programs – an example at Coeur d'Alene Lake, Plenary Session, Coeur d'Alene, ID, October 2001.
- Water Resources Division Seminar Series – What's mud got to do, got to do with it: Benthic flux of contaminants in mine-drainage systems, Reston, VA, May 2002, also presented in Menlo Park, CA, June 2002.
- National Research Program Lectureship Series - Benthic flux of contaminants: A legacy affecting water-quality, (Lectures given in 7 states during the Summer 2004).
- Limnological Modeling Workshop - Incorporating Biogeochemistry into Limnological Models, Boise, ID, November 2005.
- San Francisco State University - Benthic flux of nutrients and toxicants in lentic systems, Distinguished Speaker Series, San Francisco, CA, October 2006
- Upper Klamath Lake Workshop - Benthic Sources of Dissolved Nutrients to the Water Column of Upper Klamath Lake, Oregon. Klamath Falls, OR, January, 2007.
- American Institute of Hydrology - Benthic Flux of Orthophosphate in Upper Klamath Lake, Oregon. Reno, NV, April, 2007.

Training.

- City College of San Francisco, Earth Sciences Department, Adjunct Faculty (January 2005 – present)
- Cañada College, Department of Science and Technology, Adjunct Faculty (August 2003 to present)
- National Water Quality Assessment Program, U.S. Geological Survey, Importance of sediment-water interactions on contaminant transport in mine-drainage systems, September, 2002.
- California Institute of Technology, Environmental Biology (September 1978 – June 1979)

Instructional Outreach (since 2000)

- Project Web site: http://wwwrcamnl.wr.usgs.gov/solute_transport/index.html
- Presentations at all USGS Western Region Open Houses including May 2003:
 - “The Toxic Substances Hydrology Program in San Francisco Bay”,
 - “How Clean is Clean?” (A hands-on demonstration about ionic strength and water-quality sampling technique).

MENTORING EXPERIENCE

Thesis committees for graduate students, post-doctoral adviser

- (a) Yvonne R. Hunter, Ionic strength effects on dissolved organic carbon sources to San Francisco Bay, Masters Candidate, San Jose State University, 1992-1995.

- (b) Sergio S. Wilhelmy, Geochemistry of trace metal contamination in the Southern California Bight, Doctoral Candidate, University of California, Santa Cruz, 1992-1993.
- (c) Tamara M. Wood, Diagnostic modeling of trace metal partitioning in South San Francisco Bay, Doctoral Candidate, Oregon Graduate Institute, 1991-1993.
- (d) Yan Zheng, The marine geochemistry of germanium, molybdenum and uranium: the sinks, Doctoral Candidate, Columbia University (Advisor and co-investigator only, did not serve on her thesis committee), 1997-2000.
- (e) George Toevs, Peeper measurements of metal flux from sediments in Lake Coeur d'Alene, ID, Masters Candidate, University of Idaho, 2002-2003.
- (f) Noah Knowles, Modeling the influence of hydroclimatic variability on water quality in the San Francisco Estuary, NRC Post-doctoral Research Associateship, USGS, Menlo Park, 2002 to present.

PUBLICATIONS:

- Kuwabara, J.S., 1975, An optimization scheme for the controlled culture of *Macrobrachium rosenbergii* (giant prawn) larvae: University of Hawaii, Honolulu, HI, undergraduate thesis, 57 p.
- Wang, J.K. and Kuwabara, J.S., 1976, Engineering analysis of prawn larvae culture: Transactions of the American Society of Agricultural Engineering, v. 19, p. 1197-1200 .
- Kuwabara, J.S., 1980, Micronutrient requirements for *Macrocystis pyrifera* (L.) (giant kelp) gametophytes determined by means of a chemically defined medium, Aquil: California Institute of Technology, Pasadena, CA, doctoral thesis, 170 p.
- Kuwabara, J.S. and North, W.J., 1980, Culturing microscopic stages of *Macrocystis pyrifera* (Phaeophyta) in Aquil: a chemically defined medium: Journal of Phycology, v. 16, p. 546-549.
- North, W.J., V. Gerard and Kuwabara, J.S., 1980, Recent research on biomass production by freshwater and marine macrophytes: In Klass, D.L., ed., Biomass as a Non-Fossil a Fuel Source, Chap. 4: ACS Symp. Ser., No. 144, American Chemical Society, Washington, D.C. p. 77-98.
- Kuwabara, J.S., 1981, Gametophytic growth by *Macrocystis pyrifera* in response to various iron and zinc concentrations: Journal of Phycology, v. 17, p. 417-419.
- North, W.J., Gerard, V. and Kuwabara, J.S., 1981, Farming *Macrocystis* at coastal and oceanic sites, In Srivastava, L.M., ed., Synthetic and degradative processes in marine macrophytes: Water de Gruyter, N.Y. p. 247-264.
- Kuwabara, J.S., 1982, Micronutrients and kelp cultures, evidence for cobalt and manganese deficiency in Southern California deep seawater: Science, v. 216, p. 1219-1221.
- North, W.J., Gerard, V., Manley, S.L. and Kuwabara, J.S., 1982, Environmental considerations involved in farming *Macrocystis*: In Proceedings Second International Gas Research Conference, Newport Beach, CA.
- Anderson, L.M., Kuwabara, J.S. and North, W.J., 1983, Effects of Cu, Zn, Fe and Mn on growth of *Macrocystis* gametophytes and sporophytes, In Soule, D.F. and Walsh, D., eds., Waste Disposal in the Oceans: Minimizing Impact Maximizing Benefits: Westview, CO, p. 140-151.

- Kuwabara, J.S., 1983, Effects of trace metals and natural organic materials on coastal communities, In Bascom, W., ed., Effects of Waste Disposal on Coastal Communities: Southern California Coastal Water Research Project, CA, p. 136-146.
- Kuwabara, J.S., Leland, H.V. and Bencala, K.E., 1984, Copper transport along a Sierra Nevada stream: *Journal of Environmental Engineering*, v. 110, p. 646-655.
- Kuwabara, J.S., Davis, J.A. and Chang, C.C.Y., 1985, Culturing *Selenastrum capricornutum* (Chlorophyta) in a synthetic algal nutrient medium with defined mineral particulates: *Hydrobiologia*, v. 124, p. 23-27.
- Kuwabara, J.S., 1985, Phosphorus-zinc interactive effects on growth by *Selenastrum capricornutum* (Chlorophyceae): *Environmental Science and Technology*, v. 19, p. 417-421.
- Leland, H.V. and Kuwabara, J.S., 1985, Heavy metal toxicity to aquatic organisms, In Rand, G.M. and Petrocelli, S.R., eds., *Fundamentals of Aquatic Toxicology Methods and Applications*: Hemisphere Publications, N.Y., p. 374-415.
- Kuwabara, J.S., 1986, Physico-chemical processes affecting copper, tin and zinc toxicity to algae, In Evans, L.V. and Hoagland, K.D., eds., *Algal Biofouling*, Chapter 9: Elsevier Science Publishers, Amsterdam, Netherlands, p. 129-144.
- Kuwabara, J.S. and Leland, H.V., 1986, Adaptation by *Selenastrum capricornutum* (Chlorophyceae) to copper: *Environmental Toxicology and Chemistry*, v. 5, p. 197-203.
- Kuwabara, J.S., Davis, J.A. and Chang, C.C.Y., 1986, Algal growth response to particle-bound orthophosphate and zinc: *Limnology and Oceanography*, v. 31, p. 503-511.
- Chang, C.C.Y., Davis, J.A., and Kuwabara, J.S., 1987, A study of metal ion adsorption at low suspended-solid concentrations: *Estuarine, Coastal and Shelf Science*, v. 24, p. 419-424.
- Kuwabara, J.S. and Helliker, P. 1988, Trace contaminants in streams, In Cheremisinoff, P.N., Cheremisinoff, N.P. and Cheng, S.L., eds., *Encyclopedia of Civil Engineering Practice*, Chapter 26: Technomic Press, v. 5, p. 739-766.
- Kuwabara, J.S., Chang, C.C.Y. and Pasilis, S.P., 1988, Effects of algal growth on arsenic transport in Whitewood Creek, South Dakota: Preliminary Results, In Mallard, G.E., ed., *U.S. Geological Survey Toxic Substance Hydrology Program - Surface-Water Contamination: Proceedings of the Technical Meeting*, Denver, Colorado, February 2-4, 1987: U.S. Geological Survey Open File Report 87-764, p. 33-37.
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