FINAL PROJECT REPORT
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PROJECT TITLE: Foodweb support for threatened delta smelt in Suisun Bay

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This final project report comprises the following sections:

1. A brief summary of the project
2. Highlights of the findings of the project
3. A list of the published reports and those in preparation
4. Table 1 listing the samples taken during each year of the study.
5. Table 2 listing presentations given on this material.
6. In a separate zip file, PDF copies of all papers and manuscripts.

Project Summary

The project was an interdisciplinary study of dynamics of the low-salinity foodweb supporting delta smelt during summer. We examined abundance and biomass of their zooplankton prey and the processes that supported the zooplankton during spring-summer of 2006 and 2007 and summer of 2008. Spring sampling was designed to capture any early phytoplankton bloom and to examine the processes leading to summer conditions in the LSZ. The contrast between the wet 2006 and dry 2007-2008 allowed us to assess the likely effects of freshwater flow on the low-salinity foodweb.

The intent was to sample and conduct experiments on all lower trophic levels in the low-salinity zone of the estuary. We focused mainly on the low-salinity zone (LSZ) by sampling for plankton at fixed salinities rather than at fixed stations. This approach minimizes variability that would occur with sampling at a fixed station, because the salinity field moves past the fixed station taking the various plankton species with it. We sampled at salinity 2 and, for most of the observations, also at 0.5 and 5 to straddle the LSZ. In 2008 we also sampled on a transect across the LSZ and into freshwater to try to estimate fluxes into the LSZ.

Additional sampling was conducted for abundance and biomass of clams during seven spatially-intensive surveys and monthly sampling at six stations during the course of the study. In addition, benthic nutrient fluxes were measured in 2008 in Suisun Bay – western Delta to allow comparison of riverine nutrient inputs with local recycling.

Measurements based on samples taken during the fieldwork included the following (with references to papers, either in preparation, in press, or published; see also Kimmerer et al. in prep. b):

- Nutrient concentrations (Kimmerer et al. 2012)
- Nutrient and carbon uptake rates (Kimmerer et al. in prep. a)
- Benthic nutrient fluxes (2008, Kuwabara et al. 2009)
- Dissolved organic carbon and nitrogen (Parker in prep.)
- Phytoplankton biomass as chlorophyll (Kimmerer et al. 2012)
- Phytoplankton taxonomic composition (Lidström et al. in prep., Kimmerer et al. 2012)
- Phytoplankton carbon biomass (Lidström et al. in prep.)
- Bacterial biomass and production (Parker in prep.)
- Microzooplankton abundance and biomass (York et al. 2010)
- Mesozooplankton abundance (Gould and Kimmerer 2010, Kimmerer et al. in prep. b)
- Mesozooplankton biomass (Kimmerer et al. in prep. b)
- Mesozooplankton reproductive rate (Gould and Kimmerer 2010, Kimmerer et al. in prep. b)
- Clam abundance and biomass (Kimmerer and Thompson in prep.)
- Clam grazing on phytoplankton (Kimmerer and Thompson in prep.)

Measurements made by experimental incubations of 1 day or more using field-collected samples:

- Primary production (Kimmerer et al. 2012, Parker et al. submitted)
- Effects of changing salinity on phytoplankton (Cohen and Parker in prep.)
- Microzooplankton grazing and phytoplankton growth (McManus et al. 2008, York et al. 2010)
- Mesozooplankton consumption of microzooplankton and trophic cascades (York et al. in prep.)
- Mesozooplankton development and growth (Gould and Kimmerer 2010, Kimmerer and Gould 2010, Kimmerer et al. in prep. b)
- Clam grazing on microzooplankton (2008, Greene et al. 2011)

Highlights of results

- The three years of field studies provided widely different conditions with a very wet year in 2006 and dry years in 2007-2008. The salinity regime in which we sampled (0.5 to 5 at the surface) was in very different locations: Central to San Pablo Bay in spring of 2006 to the western Delta in August 2006 and much of 2007. During the first half of the 2006 study we were sampling in highly stratified water, which affected mainly the zooplankton samples (vertical tows) but not the other samples, most of which were taken in surface waters.
- Nitrate uptake in the extremely wet conditions of 2006 was the highest seen since 2000 (F. Wilkerson pers. comm.). A strong drawdown in NO_3 occurred during spring 2006 at all three

salinities. Nutrient uptake and the seasonal pattern of NO_3 for 2007 shows no spring drawdown indicating a return to more "normal" dry-year productivity conditions.

- Chlorophyll concentrations in whole water were about twice as high in 2006 as in 2007, but concentrations in cells larger than 5 µm were not higher, despite the increased uptake of nitrate. Biomass estimated from counts did not differ between the two years, and carbon:chlorophyll ratios were much lower than previously reported.
- In general, the phytoplankton biomass from counts was about 60% >5 µm in spring and about half >5 µm in summer. About 1/3 of the spring biomass was in diatoms; in 2006 these were mainly marine centric diatoms presumably mixed up into the surface from deeper more saline water, whereas in 2007 they were mainly the pennate diatom *Entomoneis* sp., presumably benthic, which had not been reported as abundant before. Diatoms made up only about 15% of the summer biomass. Picoplankton made up about 1/3 of the biomass in both years and seasons, and flagellates and cryptophytes the remainder.
- Primary production was low at all times, particularly in spring 2006 when light levels were low. Half of the production was >5 µm. Growth rates were consistently low. Primary production was related to the composite parameter of chlorophyll divided by available light as has been found previously, but with a lower slope. Taken together the results for phytoplankton do not suggest a spring bloom in either year, and suggest that phytoplankton growth is not as robust as it once was.
- The effects of salinity on phytoplankton lysis depended on cell origin. In contrast to our expectations, freshwater phytoplankton did not visibly lyse upon reaching brackish water, but saline phytoplankton did. Cell assemblages from 5 psu were adversely affected when exposed to lower salinity water as demonstrated by lower carbon fixation, lower chlorophyll concentration and poorer cell condition at lower salinity. Analyses showed increases in DOC concentrations when saline phytoplankton were exposed to lower salinities, and decreases in DOC concentrations when freshwater phytoplankton were exposed to higher salinities.
- Bacterial production and abundance estimates were comparable to previous measurements made in Suisun Bay. Estimates of bacterial growth efficiency ranged between 0.1 and 0.2, lower than estimates in other large estuarine systems, suggesting high bacterial carbon demand. Biomass of bacteria averaged 30-40% of phytoplankton biomass, while net bacterial carbon production averaged 70-80% of primary production; during the early spring (Mar – Apr), bacterial production was often higher than primary production.
- Tracer experiments with fluorescently-labeled bacteria showed generally low grazing rates by microzooplankton on bacteria. Dilution experiments showed that microzooplankton grazing tracked phytoplankton growth rate, as has been reported in many other aquatic systems. The grazing rate by microzooplankton on phytoplankton was 0.9 * growth rate – 0.3 d^{-1}.
- Abundance of common zooplankton species in samples taken during 2006 and 2007 agreed well with data from IEP sampling during the same period. Our samples were focused on a narrow salinity range but have greater temporal and taxonomic resolution. Biomass was

about twice as high in 2006 as in 2007, but reproductive and growth rates were not higher in 2006.

- Most of the zooplankton biomass in summer of all three years was in *Limnoithona tetraspina*, a tiny cyclopoid copepod. The biomass of *Acartiella sinensis*, which preys on *L. tetraspina*, was second highest in late summer.
- The calanoid copepod *Pseudodiaptomus forbesi* declined in abundance in late July or early August of both 2006 and 2007, with many of the copepods in poor physical condition. While this was happening other copepods (*A. sinensis* and *L. tetraspina*) remained abundant and in apparently good condition. We do not know the cause of this event, which has occurred in previous years.
- Reproductive and growth rates of copepods were generally low. On a weight-specific basis reproductive rates of *Eurytemora affinis* (in spring) and *P. forbesi* (summer) were about 10% d^{-1} and growth rates of juveniles about the same, except that growth rate of *E. affinis* was over 20% d^{-1} during spring 2006. Reproductive and growth rates of *L. tetraspina* were about 5% d^{-1}. When compared to literature values for growth rates of these and related species, these values are quite low and support the idea that the LSZ is a poor food environment for copepods. Reproductive rates of *A. sinensis* were measured on 3 occasions and found to be rather high, corresponding to about 25% d^{-1}.
- Cascade experiments showed evidence of consumption of ciliates by *P. forbesi* and *L. tetraspina*. Chlorophyll and bacteria seldom responded, probably indicating omnivory at various trophic steps, and possibly the existence of an additional trophic step. The results of similar experiments with *A. sinensis* indicated increases in ciliate growth rates with copepod biomass, probably as a trophic cascade due to predation by *A. sinensis* on *L. tetraspina* nauplii in the water used for incubation
- *Corbula* recruitment was limited to areas of salinity higher than ~2, but adult *Corbula* were present and usually abundant throughout the sampling period, either because of prior recruitment when salinity intrusion was greater, or an indication of post-larval transport of juveniles and adults. *Corbula* and *Corbicula* overlapped in their distributions, and no area was free of clam grazing at any time.
- An analysis of grazing by the two clams on phytoplankton showed that grazing rate was sufficient to prevent net growth of phytoplankton at all times, provided grazing within the water column was taken into account. A similar analysis with long-term monitoring data showed that this situation has persisted since the introduction of *C. amurensis*. This situation requires a subsidy of phytoplankton biomass from elsewhere, predominantly the freshwater Delta. Mixing diagrams using chlorophyll and salinity data from transects in 2008 support this interpretation that the LSZ is a net sink for phytoplankton.
- Clams grazed at high rates on microzooplankton, and this grazing has probably caused a reduction in microzooplankton biomass beyond what would have occurred solely due to the reduction in phytoplankton biomass.

Conclusions

Many conclusions have been drawn from this study (see references). We highlight a few of them here:

1. The LSZ does not provide a consistent source of high-quality, abundant food for higher trophic levels.
2. Effects of freshwater flow on the dynamics of the LSZ are not very large; in particular there was no stimulation of phytoplankton growth rate zooplankton reproductive rates, both of which are sensitive indicators of conditions.
3. It is likely that the higher biomass of centric diatoms and copepods seen in 2006 compared with 2007 and 2008 was more a result of hydrodynamic trapping and mixing than an excess of growth.
4. Clam grazing remains the dominant feature of conditions in the LSZ.
5. We cannot draw any conclusions about the role of ammonium in limiting phytoplankton blooms because ammonium was never below the ~2 µM threshold for inhibiting nitrate uptake.

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York, J., G. McManus, W. Kimmerer, A. Slaughter, and T. Ignoffo. Trophic links in the plankton of a large temperate estuary: top-down effects of a non-native copepod assemblage

Parker AE. The role of heterotrophic bacteria in the foodweb of the Low Salinity Zone of the San Francisco Estuary, CA. Estuaries and Coasts

Table 1. Summary measurements and analyses with the number of samples taken in 2006 – 2008.

Topic	Measurements	2006	2007	2008
Field	Salinity, temperature, irradiance profiles (most samples)	69	43	30
Nutrients	Nitrate, ammonium, silicate, phosphate	69	40	30
Organic matter	DON DOC	58	32	0
	PON POC, size fractionated	240	144	0
Phytoplankton	Chlorophyll, size fractionated	69	42	30
	Primary production – ^{13}C single samples	240	144	30
	Primary production – ^{14}C profiles, size fractionated	69	42	3
	Nutrient uptake measurements	240	144	0
	Species composition	69	42	0
	Lysis and shrinkage experiments	6	3	3
Bacteria	Abundance and biomass	50	32	0
	Production	63	32	0
. Microzooplankton .	Abundance and taxonomic composition	60	60	0
	Consumption rate (dilution experiments)	10	6	0
	Consumption rate (fluorescently labeled bacteria)	60	0	0
Mesozooplankton	Abundance and taxonomic / life stage, 2 size fractions	139	79	30
	Growth rate	24	13	0
	Reproductive rate (*Limnoithona, Acartiella*)	0	36	3
	Molting rate (*Limnoithona*)	15	12	0
Clams	Spatial distribution of *Corbula* biomass	169	164	55
	Temporal distribution of *Corbula* biomass	330	306	201
	Clam condition in above samples	498	474	256
Cascade	Impact of zooplankton on microbial foodweb	9	11	0

Table 2. Presentations (talks and posters) 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 2006
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 Limnoithona tetraspina, 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 Corbula amuresis 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	NH4 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 NH4 and NO3 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.	4th Zooplankton 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 Limnoithona tetraspina: 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	*Corbicula* and *Corbula* 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.	
Lidstrom 2007	Phytoplankton Production within the Low Salinity Zone	State of the Estuary, Oakland
Lidstrom 2008	Phytoplankton Production within the Low Salinity Zone	SFSU Graduate showcase
Parker 2008	Food limitation and the pelagic organism decline: quantifying carbon supply from heterotrophic bacteria to the food web of Suisun Marsh and the northern San Francisco estuary	IEP annual workshop
Dugdale 2008	Potential role of contaminants in declines of pelagic organisms in the upper SFE, CA	NCEAS Workshop

		on POD
Dugdale 2008	Origins of high nutrients and low productivity conditions in Suisun Bay, and the Sacramento and San Joaquin Rivers	IEP annual workshop
Parker 2008	CALFED Foodweb Project: Quantifying organic matter supply to the foodweb of the low salinity zone the San Francisco Estuary	CALFED Science Conference, 2008
Cohen 2008	CALFED Foodweb Project: Phytoplankton-derived DOC enhances bacterial biomass and production in the low salinity zone of the Upper San Francisco Estuary	
Wilkerson 2008	CALFED Foodweb Project: The interannual variability of nutrients and phytoplankton nutrient uptake in the low salinity zone	
Kimmerer 2008	CALFED Foodweb Project: Structure and function of the foodweb of the Low-Salinity Zone in the San Francisco Estuary	
Lidstrom 2008	CALFED Foodweb Project: Phytoplankton ecology within the Low Salinity Zone of the northern San Francisco Bay Estuary	
Slaughter 2008	CALFED Foodweb Project: Zooplankton abundance, composition, and mortality during 2006-2008	
Gould 2008	Growth and fecundity of *Limnoithona tetraspina*: The most abundant copepod in the upper San Francisco Estuary	
Kimmerer 2009	Structure and Function of the Low-Salinity Zone Foodweb in The San Francisco Estuary.	CAERS, Bodega Bay
Slaughter 2009	Feeding and reproduction of *Acartiella sinensis*, an introduced predatory copepod in the Low Salinity Zone of San Francisco Estuary	State of the Estuary, Oakland
Ignoffo 2009	The Growth and Development of Calanoid Copepods in the Food Limited San Francisco Estuary	CERF, Portland, OR
Kimmerer 2009	Introduction to Zooplankton Dynamics in Estuaries.	Invited, CERF, Portland, OR
Gould 2009	Development, Growth and Fecundity of the Introduced Copepod *Limnoithona tetraspina* in upper San Francisco Estuary.	CERF, Portland, OR
Slaughter 2009	Copepod Abundance, Composition and Reproductive Rates in a Food-limited Estuary	CERF, Portland, OR
Greene 2009	Grazing impact of the overbite clam on the microzooplankton assemblage of the northern San Francisco Estuary.	CERF, Portland, OR Delta Science Conference 2010
Ignoffo 2010	The Growth and Development of Calanoid Copepods in the Food Limited San Francisco Estuary	Delta Science Conference 2010
Slaughter 2010	Abundance, Composition, Feeding, and Reproductive Rates of Key Copepod Species in the Food-Limited Low Salinity Zone of the San Francisco Estuary	
Kimmerer 2010	The Pelagic Foodweb of the upper San Francisco Estuary: Changing Conditions and Changing Understanding	
Kimmerer 2011	Biotic *vs.* physical control of zooplankton in estuaries	Zooplankton Production Symposium, Pucon, Chile
Slaughter 2011	Predatory impact and reproductive rate of *Acartiella sinensis*, an introduced predatory copepod in San Francisco Estuary	
Ignoffo 2011	How they survive: The growth and development of copepods in the food limited San Francisco Estuary	
Kimmerer 2011	Complex interactions and inter-decadal changes in the pelagic foodweb of the upper San Francisco Estuary	CERF, Daytona Beach FL