Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Project Information

1. **Proposal Title:**

   Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

2. **Proposal applicants:**

   Stephen Bollens, San Francisco State University
   Mary Silver, University of California, Santa Cruz
   Gretchen Rollwagen Bollens, University of California, Santa Cruz

3. **Corresponding Contact Person:**

   Stephen Bollens
   San Francisco State University
   Department of Biology 1600 Holloway San Francisco, CA 94132
   415 338-3512
   sbollens@sfsu.edu

4. **Project Keywords:**

   Habitat Evaluation
   Plankton Ecology
   Trophic Dynamics and Food Webs

5. **Type of project:**

   Research

6. **Does the project involve land acquisition, either in fee or through a conservation easement?**

   No

7. **Topic Area**:

   Decline in Productivity

8. **Type of applicant:**

   University

9. **Location - GIS coordinates:**

Latitude:	38.08
Longitude:	-122.2
Datum:	

Describe project location using information such as water bodies, river miles, road intersections, landmarks, and size in acres.

We will sample at three locations in San Pablo Bay: in the channel, over the shoal region and in the seaward edge of the Petaluma Marsh. We will also sample at three locations in Suisun Bay: in the channel, over the shoals, and in the seaward edge of Ryer Marsh.

10. **Location - Ecozone:**

    2.1 Suisun Bay & Marsh, 2.4 Petaluma River, 2.5 San Pablo Bay

11. **Location - County:**

    Contra Costa, Marin, Sonoma

12. **Location - City:**

    Does your project fall within a city jurisdiction?

    No

13. **Location - Tribal Lands:**

    Does your project fall on or adjacent to tribal lands?

    No

14. **Location - Congressional District:**

    CA 6th

15. **Location:**

    California State Senate District Number: SD 3

    California Assembly District Number: AD 06

16. **How many years of funding are you requesting?**

    3

17. **Requested Funds:**
    a) Are your overhead rates different depending on whether funds are state or federal?

       No

       If no, list single overhead rate and total requested funds:

       Single Overhead Rate: 50

       Total Requested Funds: 749,331

b) Do you have cost share partners already identified?

No

c) Do you have potential cost share partners?

No

d) Are you specifically seeking non-federal cost share funds through this solicitation?

No

If the total non-federal cost share funds requested above does not match the total state funds requested in 17a, please explain the difference:

18. **Is this proposal for next-phase funding of an ongoing project funded by CALFED?**

No

Have you previously received funding from CALFED for other projects not listed above?

Yes

If yes, identify project number(s), title(s) and CALFED program.

99-B13	**Understanding Tidal Marsh Processes and Patterns**	**Ecosystem Restoration**
99-N09	**Effects of Introduced Species of Zooplankton and clams on the San Francisco Bay Food Web**	**Ecosystem Restoration**

19. **Is this proposal for next-phase funding of an ongoing project funded by CVPIA?**

No

Have you previously received funding from CVPIA for other projects not listed above?

No

20. **Is this proposal for next-phase funding of an ongoing project funded by an entity other than CALFED or CVPIA?**

No

Please list suggested reviewers for your proposal. (optional)

Dr. James Cloern	**US Geological Survey, Menlo Park**	**650-329-4594**	**jecloern@usgs.gov**

Dr. Nicholas Welschmeyer	**Moss Landing Marine Laboratories**	**831-632-4439**	**welschmeyer@mlml.calstate.edu**
Dr. Michael Dagg	**LUMCON (Louisiana Marine Consortium)**	**504-851-2800**	**mdagg@lumcon.edu**

21. **Comments:**

Environmental Compliance Checklist

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

1. **CEQA or NEPA Compliance**
   a) Will this project require compliance with CEQA?

      No

   b) Will this project require compliance with NEPA?

      No

   c) If neither CEQA or NEPA compliance is required, please explain why compliance is not required for the actions in this proposal.

      The work proposed is research-oriented only. Small water samples will be taken of the planktonic community of San Pablo Bay and Suisun Bay. This sampling will not alter in any way the communities targeted. These communities also do not contain an endangered species, nor will there be any negative environmental impact.

2. **If the project will require CEQA and/or NEPA compliance, identify the lead agency(ies).** *If not applicable, put "None".*

   CEQA Lead Agency:
   NEPA Lead Agency (or co-lead:)
   NEPA Co-Lead Agency (if applicable):

3. **Please check which type of CEQA/NEPA documentation is anticipated.**

   CEQA
   -Categorical Exemption
   -Negative Declaration or Mitigated Negative Declaration
   -EIR
   Xnone

   NEPA
   -Categorical Exclusion
   -Environmental Assessment/FONSI
   -EIS
   Xnone

   If you anticipate relying on either the Categorical Exemption or Categorical Exclusion for this project, please specifically identify the exemption and/or exclusion that you believe covers this project.

4. **CEQA/NEPA Process**
   a) Is the CEQA/NEPA process complete?

      Not Applicable

b) If the CEQA/NEPA document has been completed, please list document name(s):

5. **Environmental Permitting and Approvals** (*If a permit is not required, leave both Required? and Obtained? check boxes blank.*)

LOCAL PERMITS AND APPROVALS

Conditional use permit

Variance

Subdivision Map Act

Grading Permit

General Plan Amendment

Specific Plan Approval

Rezone

Williamson Act Contract Cancellation

Other

STATE PERMITS AND APPROVALS

Scientific Collecting Permit Required

CESA Compliance: 2081

CESA Compliance: NCCP

1601/03

CWA 401 certification

Coastal Development Permit

Reclamation Board Approval

Notification of DPC or BCDC

Other

FEDERAL PERMITS AND APPROVALS

ESA Compliance Section 7 Consultation

ESA Compliance Section 10 Permit

Rivers and Harbors Act

CWA 404

Other

PERMISSION TO ACCESS PROPERTY

Permission to access city, county or other local agency land.
Agency Name:

Permission to access state land.
Agency Name:

Permission to access federal land.
Agency Name:

Permission to access private land.
Landowner Name:

6. **Comments.**

Land Use Checklist

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

1. **Does the project involve land acquisition, either in fee or through a conservation easement?**

   No

2. **Will the applicant require access across public or private property that the applicant does not own to accomplish the activities in the proposal?**

   No

3. **Do the actions in the proposal involve physical changes in the land use?**

   No

   If you answered no to #3, explain what type of actions are involved in the proposal (i.e., research only, planning only).

   This is a research only proposal.

4. **Comments.**

Conflict of Interest Checklist

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Please list below the full names and organizations of all individuals in the following categories:

- Applicants listed in the proposal who wrote the proposal, will be performing the tasks listed in the proposal or who will benefit financially if the proposal is funded.
- Subcontractors listed in the proposal who will perform some tasks listed in the proposal and will benefit financially if the proposal is funded.
- Individuals not listed in the proposal who helped with proposal development, for example by reviewing drafts, or by providing critical suggestions or ideas contained within the proposal.

The information provided on this form will be used to select appropriate and unbiased reviewers for your proposal.

Applicant(s):

Stephen Bollens, San Francisco State University
Mary Silver, University of California, Santa Cruz
Gretchen Rollwagen Bollens, University of California, Santa Cruz

Subcontractor(s):

Are specific subcontractors identified in this proposal? Yes

If yes, please list the name(s) and organization(s):

Mary Silver	University of California, Santa Cruz
Gretchen Rollwagen Bollens	University of California, Santa Cruz
None	None
None	None
None	None
None	None

Helped with proposal development:

Are there persons who helped with proposal development?

No

Comments:

Budget Summary

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Please provide a detailed budget for each year of requested funds, indicating on the form whether the indirect costs are based on the Federal overhead rate, State overhead rate, or are independent of fund source.

Independent of Fund Source

Year 1												
Task No.	**Task Description**	**Direct Labor Hours**	**Salary *(per year)***	**Benefits *(per year)***	**Travel**	**Supplies & Expendables**	**Services or Consultants**	**Equipment**	**Other Direct Costs**	**Total Direct Costs**	**Indirect Costs**	**Total Cost**
1	Field Sampling	1,920	39,378	14,176	0	4,000	12,842	7,000	6,000	83396.0	38,198	121594.00
2	Grazing Experiments	1,4400	17,280	259	2,000	2,500	6,421	3,000	4,000	35460.0	15,230	50690.00
3	Predation Experiments	0	0	0	0	2,500	19,263	3,000	4,000	28763.0	6,118	34881.00
4	Data Analysis and Synthesis	160	9,965	1,196	2,000	1,000	19,264	0	2,000	35425.0	8,081	43506.00
5	Project Management	80	4,983	598	500	0	6,423	0	300	12804.0	3,191	15995.00
		16560	71606.00	16229.00	4500.00	10000.00	64213.00	13000.00	16300.00	195848.00	70818.00	266666.00

Year 2												
Task No.	**Task Description**	**Direct Labor Hours**	**Salary *(per year)***	**Benefits *(per year)***	**Travel**	**Supplies & Expendables**	**Services or Consultants**	**Equipment**	**Other Direct Costs**	**Total Direct Costs**	**Indirect Costs**	**Total Cost**
1	Field Sampling	1,920	41,347	14,885	0	4,000	13,202	0	6,000	79434.0	33,116	112550.00
2	Grazing Experimemnts	1,440	18,144	272	2,000	2,500	6,601	0	4,000	33517.0	12,458	45975.00
3	Predation Experiemnts	0	0	0	0	2,500	19,803	0	4,000	26303.0	3,250	29553.00
4	Data Analysis and Synthesis	160	10,463	1,256	2,000	1,000	19,803	0	2,500	37022.0	8,609	45631.00
5	Project Management	80	5,232	628	500	0	6,600	0	300	13260.0	3,330	16590.00
		3600	75186.00	17041.00	4500.00	10000.00	66009.00	0.00	16800.00	189536.00	60763.00	250299.00

Year 3													
Task No.	**Task Description**	**Direct Labor Hours**	**Salary *(per year)***	**Benefits *(per year)***	**Travel**	**Supplies & Expendables**	**Services or Consultants**	**Equipment**	**Other Direct Costs**	**Total Direct Costs**	**Indirect Costs**	**Total Cost**
1	Field Sampling	1,920	43,414	15,629		2,000	13,572	0	500	75115.0	30,772	105887.00
2	Grazing Experiments	1,440	19,051	286	2,000	1,250	6,786	0	2,000	31373.0	11,294	42667.00
3	Predation Experiments	0	0	0	0	1,250	20,358	0	500	22108.0	875	22983.00
4	Data Analysis and Synthesis	160	10,987	1,319	2,000	500	20,358	0	500	35664.0	7,652	43316.00
5	Project Management	80	5,494	659	500		6,785	0	500	13938.0	3,575	17513.00
		3600	78946.00	17893.00	4500.00	5000.00	67859.00	0.00	4000.00	178198.00	54168.00	232366.00

Grand Total=749331.00

Comments.

Budget Justification

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Direct Labor Hours. Provide estimated hours proposed for each individual.

Dr. Stephen M. Bollens, PI, 240 hrs/year (720 hrs total) Ms. Anne Slaughter, Research Technician, 1,920 hrs/year (5,760 hrs total) TBN Graduate Assistant, 1,440 hrs/year (4,320 hrs total) Also, see sub-contract (under Services, below) for information on the two co-PIs.

Salary. Provide estimated rate of compensation proposed for each individual.

Dr. Stephen M. Bollens, PI, $14,948, $15,695, $16,480 (1.5 months @ yrs. 1,2,3) Ms. Anne Slaughter, Research Technician, $39,378, $41,347, $43,414 (12 months @ yrs. 1,2,3) TBN Graduate Assistant, $17,280, $18,144, $19,051 (50% time academic year + 100% time summer @ yrs. 1,2,3) Also, see sub-contract (under Services, below) for information on the two co-PIs.

Benefits. Provide the overall benefit rate applicable to each category of employee proposed in the project.

Dr. Stephen M. Bollens, PI, $1,794, $1,883, $1,978 (12% @ yrs. 1,2,3) Ms. Anne Slaughter, Research Technician, $14,176, $14,885, $15,629 (36% @ yrs. 1,2,3) TBN Graduate Assistant, $259, $272, $286 (1.5% @ yrs. 1,2,3) Also, see sub-contract (under Services, below) for information on the two co-PIs.

Travel. Provide purpose and estimate costs for all non-local travel.

$4,000 per year in non-local travel is requested. This consists of one regional (e.g. CALFED @ $500) and one national (e.g. ERF or ASLO @ $1,500) scientific conference per year for both the PI and Graduate Student. Additionally, $500 per year of local travel costs are requested for meeting with individuals or groups working on similar projects (e.g., IEP, USGS, DWR, CDFG, etc.). Total travel costs = $4,500/yr.

Supplies & Expendables. Indicate separately the amounts proposed for office, laboratory, computing, and field supplies.

We request $10,000 per year in years 1 and 2, and $5,000 in year 3, for field, laboratory, and office supplies (see task-specific breakdown on attached budget sheets). Items needed include plankton nets and niskin bottles, glassware and preservative to be used in the collection and analysis of micro- and nanoplankton samples; various stains, slides, and miscellaneous supplies for analysis of samples in the laboratory; and computer supplies (e.g., MATLAB software upgrades, CDs, printer cartridges, paper, etc.) and misc. office supplies.

Services or Consultants. Identify the specific tasks for which these services would be used. Estimate amount of time required and the hourly or daily rate.

Funds are requested under a sub-contract to UC Santa Cruz to support the participation of the two co-PIs, Dr. Mary Silver and Dr. Gretchen Rollwagen Bollens. They will be substantively involved in all aspects of the research, with their effort partitioned between tasks 1-5 at 20%,10%, 30%, 30%, and 10%, respectively. Funds are requested for full-time support of G. Rollwagen Bollens as a Postdoctoral Associate ($35,463, $36,527, and $37,623 in years 1, 2, and 3). Funds are also requested to support M. Silver, Professor, at 0.25 months per year ($3,362, $3,463,and $3,567 in years 1, 2, and 3). Combined benefits for the two co-PIs are $9,293, $9,572, and $9,859 in years 1, 2, and 3. Modest travel ($2,000 per year), publications ($1,000 per year) and communications costs ($500/yr) are also included, as is the UCSC off-campus overhead rate of 24.4%. Total sub-contract costs are $198,081 over three years. Because of the expertise of the two co-PIs with microbial plankton communities generally, and SF Bay in particular, there participation is deemed essential to the success of the proposed research.

Equipment. Identify non-expendable personal property having a useful life of more than one (1) year and an acquisition cost of more than $5,000 per unit. If fabrication of equipment is proposed, list parts and materials required for each, and show costs separately from the other items.

Four different pieces of equipment, over and above those already owned by the PI and co-PIs, will be required for this project. Those are: 1 dissecting microscope with dual fiber-optic light sources ($5,000), 1 desk-top computer and printer ($2,000), and 2 custom-made plankton wheels/ship-board incubators (2 x $3,000 each). Total equipment costs are thus $13,000.

Project Management. Describe the specific costs associated with insuring accomplishment of a specific project, such as inspection of work in progress, validation of costs, report preparation, giving presentatons, reponse to project specific questions and necessary costs directly associated with specific project oversight.

Project management costs are budgeted at slightly less that 10% of overall project costs, and consist primarily of salary and benefit costs for the Principal Investiigator, Dr. Stephen Bollens, and Co-Principal Investigators, Dr. Mary Silver and Dr. Gretchen Rollwagen Bollens. Project management will entail acquisition of materials, supplies, and equipment, supervision of project staff, direction of field and experimental work, participation in and supervision of data analyses and synthesis, and overall management and administration of the project. Management will also include assuring the completion of all tasks in the time allotted, preparation of reports, manuscripts and presentations, and coordination with other Bay/Delta programs.

Other Direct Costs. Provide any other direct costs not already covered.

Other Direct Costs include ship time in years 1 and 2 (19 days of the 35-ft RV Questuary @ $500/day and 19 days of the 22-ft Proline @ $200/day = $13,300/year); tuition reimbursement for the graduate student ($2,000/year); and communications and publications costs (page charges, reprints, etc.) of $1,000, $1,500, and $2,000 in years 1, 2, anad 3, respectively.

Indirect Costs. Explain what is encompassed in the overhead rate (indirect costs). Overhead should include costs associated with general office requirements such as rent, phones, furniture, general office staff, etc., generally distributed by a predetermined percentage (or surcharge) of specific costs.

Indirect costs (overhead rate) include costs associated with general office and laboratory requirements such as rent, utilities, phones, furniture, general office staff, etc., and are prescribed by SFSU as 50% of the modified total direct costs (i.e., total direct costs - equipment - tuition reimbursement - sub-contract costs beyond the first $25,000).

Executive Summary

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

A serious problem facing the San Francisco Bay/Delta is the decline of several important native fish species. Various factors have been put forth to explain this decline, often acting simultaneously to reduce abundance. Since these factors affect both fish populations and their zooplankton prey, the success of future restoration efforts depends on a quantitative understanding of the lower food web in the Bay/Delta, and how energy is transferred upward to fish. Planktonic food web studies have traditionally focused on the classical food chain of large phytoplankton leading to large zooplankton leading to planktivorous fish. However, small (<200 µm) protistan microzooplankton have been shown to have a significant grazing impact on primary productivity, and in turn may be the preferred prey for mesozooplankton (200 2000 µm, e.g. copepods) in a wide range of aquatic environments, including estuaries. As copepods are an important component of fish diet, this can have very significant implications for the amount of material and energy that ultimately gets transferred upward to higher trophic levels such as fish, birds and mammals. We propose a research program to examine trophic relationships among planktonic primary and secondary producers in North San Francisco Bay, and to assess the conditions under which fish production may be highest. Our goals are to quantify the role of protistan microzooplankton in the planktonic food web in San Pablo Bay and Suisun Bay, and to provide insights into the structure, function and limits on productivity of the lower planktonic food web. We will measure the distribution, abundance, taxonomic composition, growth rates, grazing rates and contribution to native and introduced copepods diet of the protistan microzooplankton across a spatial gradient in each bay that reflects differences in salinity and turbidity, including deep channel, open shoals, and marsh locations. Our 3-year study will examine interannual and seasonal scales of variation, but will focus on bi-weekly sampling during periods of plankton blooms and fish recruitment in spring and early summer. We hypothesize that microzooplankton play a significant role in the North Bay food web, as both grazers of primary production and as food for higher trophic levels, and that their role is especially important during blooms and in regions of low turbidity (e.g. protected shallow marsh). Understanding microzooplankton dynamics is therefore critical to understanding the production of at-risk fish species in the Bay/Delta. This research will contribute information relevant to several ERP goals, in particular the recovery of at-risk fish species, increasing productivity and rehabilitating food web processes to support recovery of native species, enhancing harvestable fisheries, and identifying the competitive relationships between native and non-indigenous species.

Proposal

San Francisco State University

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Stephen Bollens, San Francisco State University
Mary Silver, University of California, Santa Cruz
Gretchen Rollwagen Bollens, University of California, Santa Cruz

Protistan Microzooplankton in the North San Francisco Bay Food Web: Source or Sink?

Stephen M. Bollens, San Francisco State University
Mary W. Silver and Gretchen Rollwagen Bollens, University of California, Santa Cruz

A. Project Description: Project Goals and Scope of Work

1. Problem Statement

A serious problem facing the San Francisco Bay/Delta, and one of the primary restoration issues to be remedied through CALFED, is the decline of several important native fish species, including steelhead trout, delta smelt and Sacramento splittail, as well as maintaining vigorous populations of harvestable fish species such as chinook salmon. Various factors have been put forth to explain declines in fish populations in the Bay/Delta: fresh water diversion, alteration of stream flows, loss of habitat, pollution, species introductions, and decreased primary and secondary productivity. Often more than one of these influences may be simultaneously acting upon fish populations and the environment to reduce abundance (Bennett and Moyle 1996). However, since many of the factors leading to the decline in fish populations are also affecting populations of their zooplankton prey, the success of future restoration efforts depends in large part on a quantitative understanding of the trophic relationships at the base of the food web in the Bay/Delta, and how energy is transferred upward to fish.

Variability in phytoplankton stocks and primary productivity has been extensively studied in the Bay/Delta, and much has been learned about the sources of organic matter to the base of the food web (Jassby et al. 1993, Canuel et al. 1995, Jassby and Cloern 2000) and variations in phytoplankton with climate, season and freshwater flow (Cloern et al. 1985, Jassby and Powell 1994, Lehman 2000). In particular, substantial evidence shows that stocks of both primary and secondary planktonic producers have been in decline in the North Bay/Delta since the mid-1970's (Orsi and Mecum 1986, Obrepski et al. 1992, Jassby et al. 1995, Kimmerer and Orsi 1996). However, there remains considerable uncertainty about the ultimate fate of primary production in this estuary.

Grazing by benthic suspension feeders is one significant pathway that removes primary production from the planktonic food web into the benthic system (Cloern 1982), indeed grazing by the introduced Asian clam *Potamocorbula amurensis* has been implicated as a major cause of the recent decreases in both phytoplankton and zooplankton abundance (Alpine and Cloern 1992, Kimmerer et al. 1994). Some of this production diverted to the benthic food web necessarily supports benthic-feeding fish species, e.g. sturgeon. Yet the continued presence of robust communities of heterotrophic plankton in the Bay/Delta (Ambler et al. 1985, Kimmerer and Orsi 1996, Bollens et al. 1999, Bollens et al., submitted, Purkerson et al., submitted) suggests a sizable fraction of pelagic primary production is being incorporated through the planktonic food web, and it is this food web which supports the at-risk pelagic fish species mentioned above.

Traditionally, planktonic food web studies have focused on the classical food chain of large phytoplankton (diatoms) leading directly to large zooplankton (copepods) and on to planktivorous fish (Fig. 1). However, a growing number of studies have demonstrated that the protistan microzooplankton (here defined as the zooplankton <200 µm, e.g. heterotrophic ciliates and flagellates) may have a significant grazing impact on primary productivity, and in turn may be the preferred prey for mesozooplankton (200 – 2000 µm, e.g. copepods) in a wide range of aquatic environments, from estuaries (Gifford and Dagg 1988, Dagg 1995, Rollwagen Bollens and Penry, submitted) to highly productive coastal upwelling zones (Neuer and Cowles 1994, Fessenden and Cowles 1994) to the oligotrophic open ocean (Gifford and Dagg 1991, Landry et al. 2000). As detailed in these and other studies outlined in the Background section below, microzooplankton grazing rates can often account for up to 80% of total grazing on phytoplankton, and microzooplankton can comprise more than 50% of copepod diets. Copepods are an important food resource for the larval and juvenile stages of several at-risk and harvestable fish species, including striped bass, delta smelt and splittail (Meng and Orsi 1991, Moyle et al. 1992, Kurth and Nobriga 2001). Thus the degree to which microzooplankton graze primary production and are further consumed by copepods can have very significant implications for the amount of material and energy that ultimately gets transferred to fish (Fig. 1). Thorough analyses of planktonic food webs must therefore include examination of the microzooplankton in addition to, and in concert with, the classical metazoan food chain.

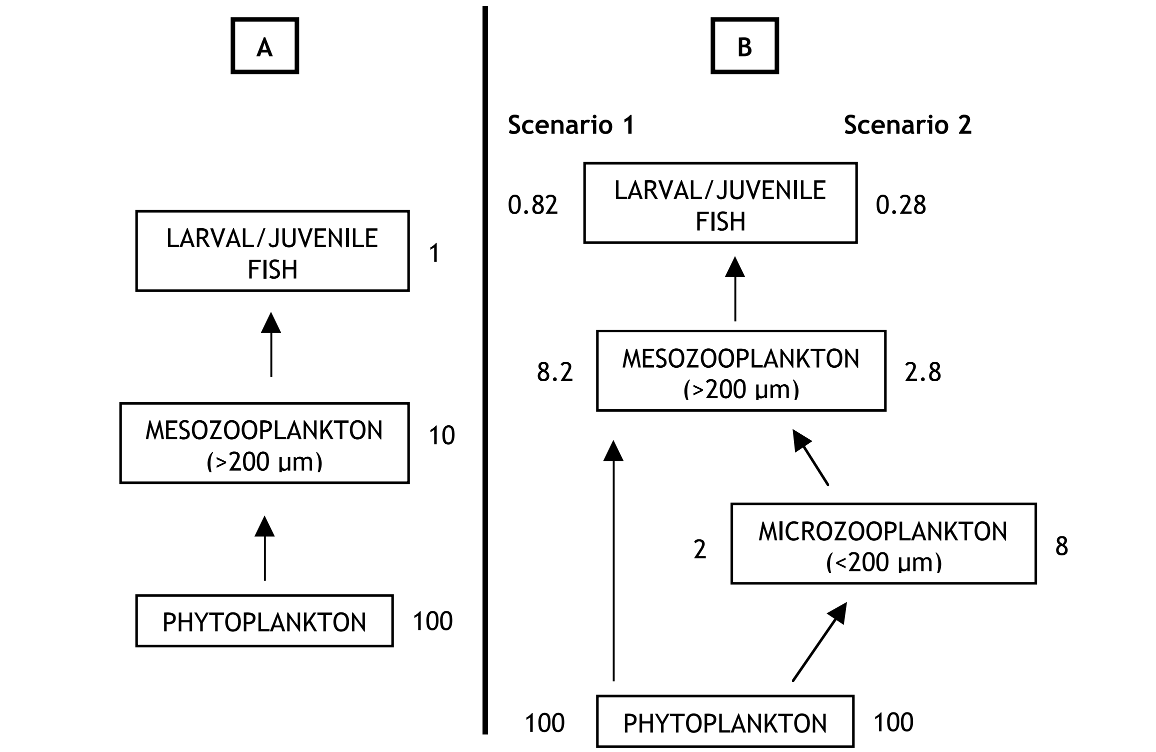

Figure 1. Variations in the structure of the planktonic food web, with potential implications for fish production (using arbitrary units) under several scenarios. Trophic transfer efficiency is assumed to be 10%. A: the traditional linear food chain from phytoplankton to fish. B: the more complex food web arising from the addition of microzooplankton. Scenario 1 has microzooplankton grazing only 20% of phytoplankton biomass, resulting in 0.82 units of fish production, slightly less than A. Scenario 2 shows microzooplankton grazing 80% of phytoplankton biomass, resulting in only 0.28 units of fish production, substantially less than the other scenarios.

Goals and Objectives

Our primary goals in this proposal are to quantify the role of protistan microzooplankton in the planktonic food web of North San Francisco Bay (San Pablo Bay and Suisun Bay) and to provide insights into the structure, function and limits on productivity of the lower planktonic food web. While recognition of the importance of microzooplankton in pelagic food webs is rapidly increasing within the scientific community, this component of the planktonic system is still largely uninvestigated in many marine and estuarine environments, including San Francisco Bay.

Our objectives for achieving these goals are to examine the distribution, abundance, taxonomic composition, growth rates, grazing rates and contribution to copepod diet of the protistan microzooplankton in San Pablo Bay and Suisun Bay. These parameters will be compared between the two bays, as well as across a spatial gradient within each bay, including deep open water (channel), open shoals, and protected shoals (marsh). These sites have been chosen for two reasons: 1) differences in salinity which lead to differences in the planktonic assemblage (i.e. between San Pablo and Suisun Bays), and 2) differences in turbidity which may affect grazing efficiency of micro- and mesozooplankton (i.e. between bays, as well as between sites within each bay). Examination of temporal variation will include interannual, seasonal (wet vs. dry), and bi-weekly (during plankton bloom/fish recruitment periods) sampling.

This is a research proposal – we do not propose any restoration action per se. However the information this project will provide is crucial for understanding the planktonic food web dynamics that directly affect the fate of at-risk and harvestable fish species in the Bay/Delta.

Hypotheses

Our proposed field and experimental program is designed to address several hypotheses concerning the role of protistan microzooplankton in the North San Francisco Bay food web.

1. Protistan microzooplankton (<200 μm) comprise a significant proportion, both in terms of abundance and biomass, of the total planktonic community in San Pablo Bay and Suisun Bay.

2. Protistan microzooplankton (<200 μm) are the dominant planktonic grazers of phytoplankton in San Pablo Bay and Suisun Bay where turbidity is low; microzooplankton grazing impact is lower under conditions of high turbidity.

3. Protistan microzooplankton (<200 μm) are the dominant food resource for copepods in all habitats, but are selected for to a greater degree in low turbidity habitats.

4. Native copepod species have different food preferences than introduced copepod species, with different implications for energy transfer to fish.

5. There are distinct seasonal (bloom vs. non-bloom, wet vs. dry) differences in both microzooplankton grazing impact on phytoplankton and the importance of microzooplankton in copepod diet. Microzooplankton grazing impact is higher and their contribution to copepod diet is stronger during periods of phytoplankton blooms.

We will address these hypotheses through an extensive, two-year program of field and experimental investigations. We will assess the distribution and abundance of the <200 μm protistan plankton on a bi-weekly (February – July) and bi-monthly (August – January) basis at three locations within both San Pablo Bay and Suisun Bay: in the channel, over the shoals, and in the fringing marsh. In addition, over the same two years at two of the locations (channel and marsh) in each bay, we will experimentally determine microzooplankton grazing impact on phytoplankton, and determine microzooplankton contribution to the diets of both native and introduced copepod species. These experiments will be conducted in March, April, May and October of each year to describe variability over the spring bloom and the critical period of fish recruitment. These two years of extensive observations and experiments will be followed by one year of sample and data analysis, interpretation and synthesis.

2. Justification

Conceptual model

Based on the growing body of literature describing microzooplankton dynamics in both estuarine and marine habitats, as well as recent observations of microzooplankton grazing and copepod omnivory in San Francisco Bay (described in Background section below), we have developed a conceptual model illustrating the potential role of microzooplankton in the food web of the North Bay (Fig. 2). In particular, we are concerned with how the physical environment mediates the structure of the planktonic food web and the magnitudes of linkages within the web, and thus the availability of materials and energy to planktivorous fish.

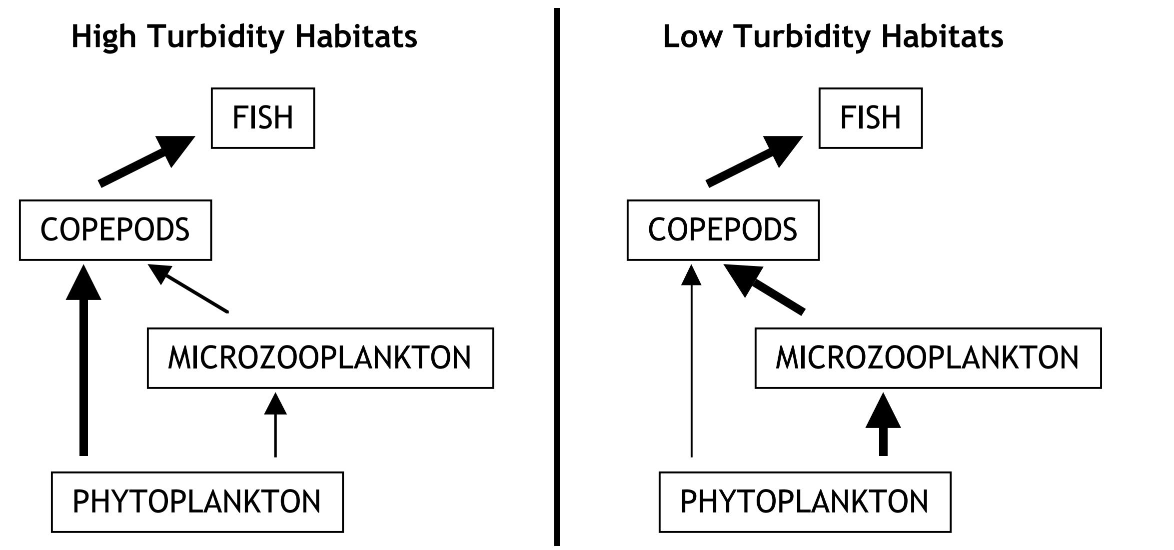

Figure 2. Conceptual model to illustrate the relative magnitudes of trophic connections in higher turbidity habitats, e.g. unprotected shoals and deep channels, versus lower turbidity habitats, e.g. protected shallow marsh. Other gains/losses to phytoplankton, such as benthic grazing, larval fish consumption of microzooplankton and advection are beyond the scope of this proposal and are not shown.

As suspension feeders, the ingestion rates of both microzooplankton and mesozooplankton (i.e. copepods) are affected by turbulence, either positively or negatively. Turbulent mixing may enhance feeding rates through higher encounter rates with prey (Saiz et al. 1992, Peters and Gross 1994, Shimeta et al. 1995). However, in some environments such as shallow estuaries, turbulent mixing may increase turbidity, which tends to reduce feeding rates and alter competition among species through interference with increased levels of non-nutritious suspended particulate matter (Kirk and Gilbert 1990, Kirk 1991, Lougheed and Chow-Fraser 1998, Miquelis et al. 1998). Therefore, our conceptual model predicts that in regions of high turbulence microzooplankton grazing may be limited by turbidity, and the transfer of carbon and energy takes a more direct pathway from phytoplankton to fish (Fig. 2A). In shallow protected areas where turbulent mixing is reduced and turbidity is low, microzooplankton grazing could be relatively high, thereby shifting to a predominately 4-trophic level system and reducing the efficiency of the food web (Fig. 2B).

Our selection of study sites to examine the role of microzooplankton in the pelagic food web is driven by the predictions of our conceptual model. San Pablo Bay and Suisun Bay show distinct differences in both the magnitude of suspended particulate matter (SPM) present in the water column, as well as the timing of peak turbidity over a seasonal cycle. For instance, in 1999 and 2000, the Suisun Bay channel was characterized by significantly higher annual mean SPM concentration than San Pablo Bay (USGS Water Quality of San Francisco Bay website http://sfbay.wr.usgs.gov/access/wqdata), indeed a turbidity maximum is consistently found in Suisun Bay, often associated with the position of the 2 ppt bottom salinity isohaline known as the X_2 (Jassby et al. 1995). Further, peaks in turbidity typically first appear in Suisun Bay and then migrate downstream into San Pablo Bay. In addition, salinity levels in both bays are often quite different, leading to differences in the planktonic assemblages which could have significant impacts on the structure of the food web. For these reasons we intend to compare and contrast the lower food web dynamics between Suisun and San Pablo Bays.

We will further explore the differences in planktonic food web dynamics among sites showing a gradient in turbidity by sampling and conducting experiments in deep channel, open shoal and protected marsh locations within each bay. We expect turbidity to range from lowest in the shallow protected marsh sites, moderate to high in the deep channel sites, to highest turbidity in the unprotected open shoal locations. This sampling scheme will thus provide the opportunity to explore how the different planktonic assemblages present in San Pablo vs. Suisun Bay respond to variations in the physical environment.

Background

Microzooplankton abundance

Microzooplankton are here defined as the heterotrophic and/or mixotrophic protistan organisms <200 µm, and are numerically dominated by ciliates, dinoflagellates and other flagellates (Sherr and Sherr 1994). In coastal and open ocean marine systems microzooplankton have been shown to be highly abundant, often reaching densities comparable to autotrophic phytoplankton, and have growth rates that may equal or exceed phytoplankton (Banse 1982, reviewed in Sherr and Sherr 1994). In addition, several studies have found that microzooplankton are present in high abundances relative to phytoplankton in some subtropical and temperate estuaries (Buskey 1993, Lovejoy et al. 1993), as well as San Francisco Bay (Rollwagen Bollens and Penry, submitted). Samples taken from the San Pablo Bay channel showed that heterotrophic ciliates (loricate and aloricate) were both more abundant and had higher carbon biomass than diatoms during February 2000, and were nearly twice the biomass of diatoms during the spring diatom bloom observed the following April (Rollwagen Bollens and Penry, submitted).

Microzooplankton as grazers

Microzooplankton have been demonstrated to exert significant grazing impact upon primary producers in virtually all of the open ocean and coastal marine environments where they have been studied. In these environments, microzooplankton consume from 13 – 100% of primary productivity per day (e.g. Burkill et al. 1987, Strom and Welchmeyer 1991, Verity et al. 1993, Landry et al. 1995, Tamigneaux et al. 1997, Lessard and Murrell 1998, Edwards et al. 1999). In contrast, copepods in these environments (traditionally considered to be the major grazers of phytoplankton) rarely consume > 30-40% of daily phytoplankton production, even under bloom conditions (e.g., Bautista & Harris 1992, Dagg 1993, Dam et al. 1993, 1995; Landry et al. 1994, Rollwagen Bollens and Landry 2000).

The majority of studies in estuaries also show a significant microzooplankton impact on phytoplankton, with microzooplankton consuming on average a greater proportion of primary production than in the more widely studied open ocean regions (Gifford 1998, Gallegos 1989, McManus and Ederington-Cantrell 1992, Froneman and McQuaid 1997, Ruiz et al. 1998, Sautour et al. 2000). For example, in an investigation of microzooplankton ingestion of phytoplankton undertaken in a shallow estuary in the northern Gulf of Mexico, Dagg (1995) found that grazer-induced mortality on phytoplankton was always high (grazing rate:growth rate on average equaled 1.01), and that >95% of the grazing upon phytoplankton was by microzooplankton.

Of particular interest for planktonic food web studies in San Francisco Bay are the results of Murrell and Hollibaugh (1998), who conducted microzooplankton grazing (dilution) experiments at several stations in the North Bay. Of 14 experiments measuring grazing upon the phytoplankton community completed in channel stations in Suisun and San Pablo Bays, only 3 returned statistically significant results, of which two experiments demonstrated microzooplankton grazing to balance 39-67% of phytoplankton growth. Despite this relatively high grazing impact, albeit in only 2 of 14 experiments, the authors concluded that the assumptions of the dilution method were violated (e.g. different light regimes within bottles of different dilution, predator-prey interactions), and that in general microzooplankton have only a weak grazing impact in San Francisco Bay.

The Murrell and Hollibaugh (1998) study was thorough and well designed, yet their results stand in striking contrast to the observations of substantial, even dominant, microzooplankton herbivory in many other estuaries. We suggest that their results likely reflect the balance of planktonic grazing to phytoplankton growth in deep channel stations where turbidity is relatively high, leaving open the issue of how microzooplankton grazing may impact phytoplankton in areas of low turbidity. In light of this, it is important to re-visit the question of microzooplankton grazing in the North Bay, and particularly to compare grazing impact between the deep channel and the shallow marsh locations of San Pablo and Suisun Bays. Microzooplankton may play a more significant role in the food webs of the shallower, more protected areas due to reduced wind mixing and turbidity that could otherwise interfere with microzooplankton foraging success and grazing rates.

Microzooplankton as prey for copepods

In addition to their potential grazing impact, microzooplankton may also be an important food source for copepods and other metazoans, thereby serving as a trophic link between the microbial food web and the classical, metazoan pelagic food web (Sherr et al. 1986, Stoecker and Capuzzo 1990, Gifford 1991). Copepods have been shown to consume protozoans in addition to, and at times in greater amounts than, algal cells in the open subarctic Pacific Ocean (Gifford and Dagg 1991), in upwelling waters off Oregon (Fessenden and Cowles 1994), and the Florida coastal region (Kleppel 1992, Kleppel et al. 1996). Moreover, growing evidence suggests that microzooplankton may also play a crucial role in the trophic processes linking primary production and higher trophic levels in San Francisco Bay and other estuaries.

Field investigations of copepod feeding preferences for non-algal prey in estuaries are limited. One of the few observations of estuarine copepods feeding upon the natural assemblage of planktonic prey was conducted by Gifford and Dagg (1988) in Terrebonne Bay, LA. They found that the ratio of microzooplankton carbon: phytoplankton carbon consumed by *Acartia tonsa* was as high as 0.69, when the ratio of microzooplankton carbon: phytoplankton carbon availability was only 0.03, i.e. microzooplankton were highly preferred over phytoplankton. In San Francisco Bay, Rollwagen Bollens and Penry (submitted) conducted experiments with *Acartia* spp. copepods feeding upon the natural assemblage of <200 µm protistan plankton, using copepods and microplankton collected in the San Pablo Bay channel in February and May 2000.

These results demonstrated that *Acartia* spp. had greater preference for ciliates and dinoflagellates than for diatoms, even when diatoms were present in higher abundance (Fig. 3).

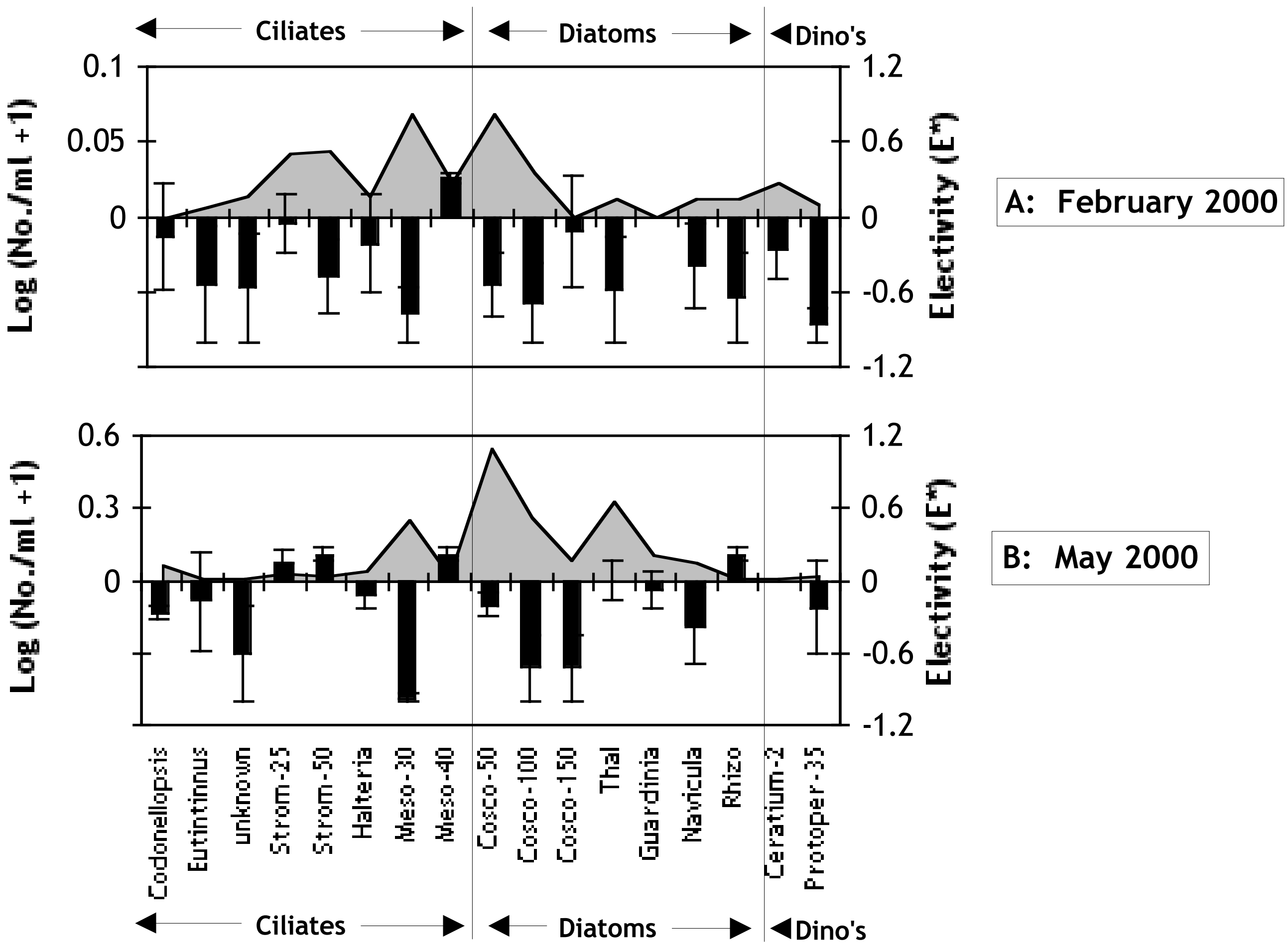

Figure 3. Abundance (shaded area) of planktonic prey taxa <200 µm in the San Pablo Bay channel in February and May 2000. Bars show electivity (means ± S.E.) of *Acartia* spp. copepods for each prey taxa during 12-hour feeding incubations conducted in each month. Positive electivity represents preference, negative electivity represents avoidance of prey. Note differences in abundance scales between months.

These results demonstrate the preference of *Acartia* spp. for ciliates in the San Pablo Bay channel. However, despite predator preference, the initial abundance and biomass of each type of prey available will often determine how much biomass of a particular prey type is ultimately incorporated into predator diet. That is, if a predator prefers ciliates but diatom biomass is very high relative to other types of food resources, diatoms may still comprise the greatest proportion of overall prey ingested, due primarily to its prevalence in the feeding medium. Yet in the same feeding incubations as shown above, not only was *Acartia* spp. preference for non-diatom prey significant, but it led to heterotrophic ciliate and dinoflagellate biomass being consumed at higher proportions than was available in the environment (Fig. 4).

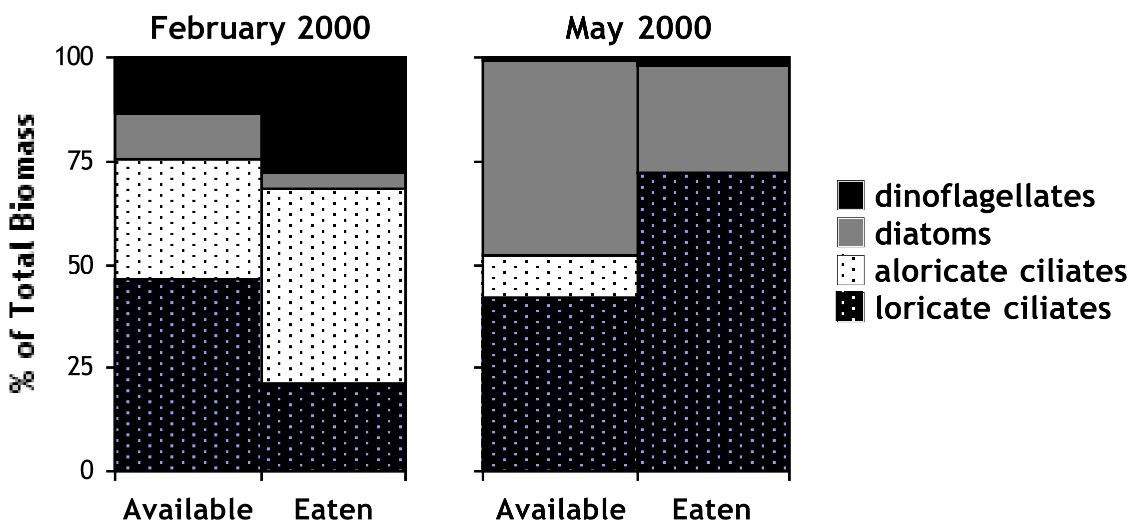

Figure 4. Proportion of prey biomass in the diet of *Acartia* spp. copepods relative to the proportion of total prey biomass available in the surrounding medium during two 12-hour incubation experiments conducted in the San Pablo Bay channel in February and May 2000.

Protozoans (ciliates and heterotrophic flagellates) may be preferred prey for copepods since they can enhance an algal diet by providing important nutritional components, such as essential fatty acids and sterols, and/or by "repackaging" the energy and materials typically retained in the microbial food web (Stoecker and Capuzzo 1990, Klein Breteler et al. 1999). Further, numerous reports have implicated diatoms as negatively affecting copepod fecundity and hatching success, especially during diatom blooms (Ban et al. 1997), but this effect can be reduced when protists are included in the diet (Poulet et al. 1994, Ianora et al. 1995, Miralto et al. 1999).

Clearly, microzooplankton play a significant role in the structure and function of the planktonic food web in marine systems generally, and in estuaries such as San Francisco Bay. In this research project, we will elucidate the structure of the North Bay planktonic food web and quantify the trophic relationships among its important components, in particular the function of microzooplankton dynamics in the system. Such information is required as a basis for all efforts to increase fish production, since the pathways among trophic groups have important implications for energy transfer but also the movement and accumulation of important nutrients and/or toxins that affect fish growth and survival.

3. Approach

We propose to conduct the field and experimental work described below at six stations located in San Pablo Bay and Suisun Bay (Fig. 5). Field observations to characterize the abundance and composition of the protistan microzooplankton standing stocks will be undertaken at each of the stations 15 times per year for two years. Experiments to determine microzooplankton growth rates and grazing rates upon phytoplankton, as well as incubations to measure feeding rates and diet composition of native and introduced copepods upon the natural assemblage of planktonic prey <200 µm, will be conducted at four stations 4 times per year for two years. This sampling plan will give sufficiently broad geographical and temporal coverage to examine several scales of variability.

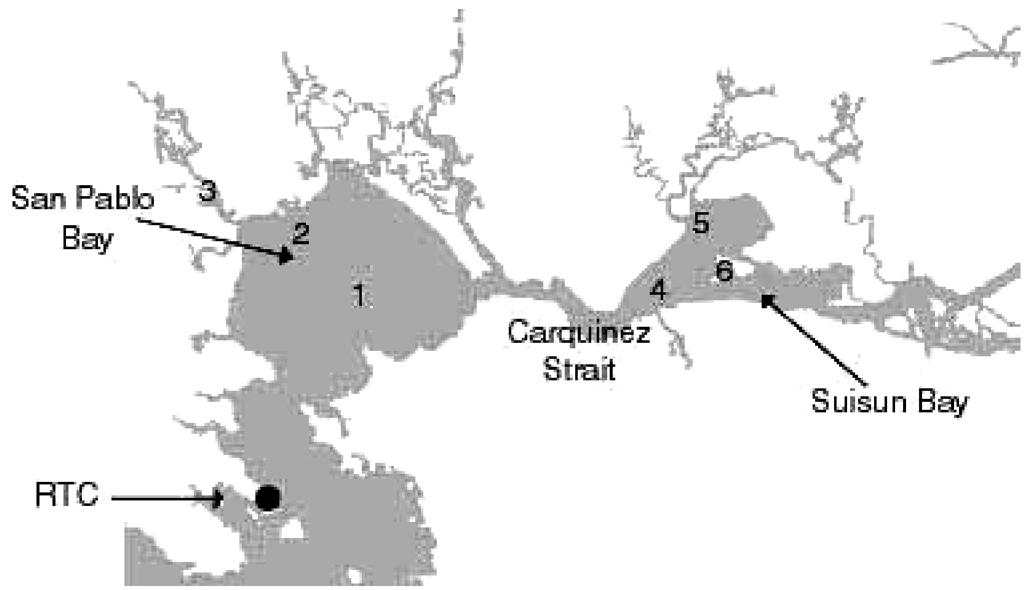

Figure 5. Station locations of proposed field and experimental sampling in North San Francisco Bay.

Task 1: Field sampling for distribution, abundance and taxonomic composition of protistan microzooplankton (Years 1 and 2)

• *Bi-weekly sampling February through July; bi-monthly sampling August through January*

We will conduct regular cruises to six stations in the North Bay every other week between February and July, and every other month between August and January, to collect multiple-depth whole water samples for assessing the protistan microzooplankton community. We will concentrate the sampling effort for microplankton distribution, abundance and composition during this time to better characterize changes in the microplankton community over the spring bloom period and during the period of larval/juvenile fish recruitment in the North Bay. Three of the stations will be in Suisan Bay: one in the deep channel, one in the shoal region, and one at the edge of the fringing marsh. The other three stations will be at comparable sites (channel, shoal, marsh) in San Pablo Bay (Fig. 5).

Water will be collected from three depths at the channel stations in both bays (surface, near bottom and mid-depth), from two depths at the shoal stations (surface and near bottom), and at mid-depth at the marsh stations, using 2.5-l Niskin bottles equipped with teflon springs to avoid metal contamination. Subsamples for microscopical analyses of community composition will be gently siphoned from the Niskin bottles and preserved in 10% acid Lugol's solution for organisms >20 µm (Gifford 1988), and 1% gluteraldehyde followed by staining in FITC for organisms <20 µm (Sherr et al. 1993). Additional subsamples will be filtered onto GF/F glass fiber filters, extracted in 90% acetone, and analyzed via fluorometry for chlorophyll *a* (phytoplankton biomass) concentration.

• *Microscopical analyses of microplankton samples*

Two methods of microscopical analysis will be employed in order to enumerate and identify the protistan plankton <200 µm from North Bay samples. Microplankton (organisms 20-200 μm) will be assessed using the Utermohl method with inverted microscopy. Aliquots of 25 – 50 ml will be settled overnight into Utermohl counting chambers and the entire chamber examined at 100x – 200x using an inverted microscope. All protistan cells will be enumerated, sized and identified to the lowest possible taxonomic level, typically to genus. Cell biovolume will be computed via algorithms from measurements of length and width, and carbon biomass calculated using conversion factors in Menden-Deuer and Lessard (2000).

Nanoplankton (organisms 2 – 20 μm) will be examined via epifluorescence microscopy. Within 24 hours of collection, 10 – 25 ml aliquots from subsamples preserved in 1% gluteraldehyde will be stained in FITC, filtered onto 1-μm black membrane filters, mounted on glass slides and stored at -20°C (Sherr et al. 1993). Filters will then be examined under blue illumination at 400x using an epifluorescent microscope. The first 150 protistan organisms observed will be sized and identified to the lowest taxonomic level, and characterized as being pigmented or non-pigmented. Carbon biomass will be calculated similarly as the microplankton using conversions in Menden-Deuer and Lessard (2000).

In general, the microplankton community will be described by size (2-20 μm, 20-200 μm) and composition with respect to ciliates (loricate and aloricate), diatoms, dinoflagellates, and other flagellates. Morphologically recognizable taxa of ciliates and heterotrophic dinoflagellates will be identified to genus to the maximum extent possible.

Task 2: Grazing: Experimental program to measure protistan microzooplankton growth rates and grazing rates/impact on primary productivity (Years 1 and 2)

- *Monthly experiments March, April, May, and October*.

Dilution experiments to quantify microzooplankton growth rates and grazing impact upon phytoplankton will be conducted using water and organisms collected from the channel and marsh stations in both San Pablo Bay and Suisan Bay in March, April, May and October each year. Because of time and resource constraints, and the considerable existing archive of biological data from channel stations in the North Bay, we have chosen the deep open water (channel) and shallow, protected water (marsh) sites as examples of high and low turbidity, respectively. We will follow modified protocols described by Murrell and Hollibaugh (1998), Landry (1993) and Landry et al. (1995). Natural seawater will be collected from mid-depth using a large volume Niskin bottle equipped with teflon springs. Seawater for dilutions will be collected similarly, and then filtered through glass fiber filters into clean carboys. Each dilution experiment will be set up with four replicated dilution levels (20, 45, 70 and 100%) of natural seawater with filtered seawater, including bottles for initial and seawater controls. Bottles will be incubated for 24 h in the dark inside shore-based incubators with continuously flowing seawater to maintain temperature.

Samples for microzooplankton standing stock will be taken from undiluted water at the beginning and end of the experiments and used to estimate net microzooplankton growth rates. Observed differences in the net growth rates of phytoplankton in the different treatments, measured using fluorometry, will be used to derive estimates of mean instantaneous rates of phytoplankton growth and microzooplankton grazing according to Landry and Hassett (1982). We will determine biomass-specific grazing rates for microzooplankton, and then compare potential grazing impacts based on variations in protist standing stocks.

Task 3: Predation: Experimental program to asses protist microzooplankton as prey for native and introduced copepods (Years 1 and 2)

- *Monthly experiments March, April, May, and October*.

Separate experiments with adult females of representative native (e.g. *Acartia* spp, *Eurytemora affinis*) and introduced (e.g. *Pseudodiaptomus forbesi*, *Limnoithona tetraspina*) copepod species feeding upon the natural assemblage of <200 µm microplankton prey will be run using copepods and microplankton collected from the channel and marsh stations in each bay following the protocols in Rollwagen Bollens and Penry (submitted), modified from Gifford and Dagg (1988). Copepods will be collected via gentle vertical hauls of a 153-µm plankton net, returned to the laboratory and adult females of target species sorted under dim light into holding beakers. 500-ml incubation bottles will be carefully filled with seawater containing the natural assemblage of microplankton prey obtained from mid-depth with a large volume Niskin bottle equipped with teflon springs. Triplicate bottles containing only the natural assemblage will be established as initial controls. Final controls (natural assemblage only) and final treatments (assemblage plus copepod predators) will be prepared in triplicate and incubated in the laboratory for 12 hours in the dark on a slowly rotating (0.5-1 rpm) plankton wheel.

All bottles will be subsampled and analyzed to enumerate and identify the <200 µm microplankton and chlorophyll *a* as described above for field sampling. Copepod clearance and ingestion rates for each category of prey will be estimated using the difference between microplankton abundance at the beginning and end of the incubation, corrected for cell growth determined in the control bottles, according to Marin et al. (1986).

Task 4: Data analysis, interpretation and synthesis (Years 1, 2 and 3)

Microscopical analyses will begin immediately after the first sampling period, and will continue concurrently with field and experimental work throughout the first two years, and half of year three. Data analysis and interpretation of results will also begin as soon after sample collection and microscopical examination as practicable, and continue through year three. The final year will be devoted to statistical analyses, interpretation and integration of results, and preparation of reports. Results from this project will be presented to the scientific and policy-making communities via oral presentations at professional meetings, written CALFED reports and newsletters, and in peer-reviewed journal articles.

Task 5: Project management (Years 1, 2 and 3)

Project management will entail acquisition of materials, supplies, and equipment, supervision of project staff, direction of field and experimental work, participation in and supervision of data analyses and synthesis, and overall management and administration of the project. Management will also include assuring the completion of all tasks in the time allotted, preparation of reports, manuscripts and presentations, and coordination with other Bay/Delta programs.

4. Feasibility

We have designed our approach to sampling, experimental protocol, data analysis, interpretation and preparation of presentations and articles so as to allow completion of all tasks within the three-year time period allotted. All experimental work, analyses and project management will be undertaken in the laboratories of Dr. Stephen Bollens at the SFSU/Romberg Tiburon Center for Environmental Studies, which are well-equipped for this type of research and are conveniently located directly on San Francisco Bay. The Romberg Tiburon Center (RTC) operates the 35-foot research vessel *Questuary*, which is available for our use at reduced cost, and is docked near the Center. We will obtain all necessary collecting permits for the field sampling conducted in years one and two. Since the project does not require special access to protected/private sites, nor does it involve sampling of endangered species, we do not anticipate having to obtain additional permits. As in any field program, weather and equipment failures could cause delays and rescheduling of some planned sampling activities. However, our considerable past experience suggests that all proposed activities are feasible within the time allotted, and that our goals and objectives are tractable.

5. Performance Measures

Our plan for evaluating the performance of this research project includes a variety of measures. We intend to collect and analyze all data and results with appropriate care and attention to accepted protocols within our scientific discipline. Further, we will submit our results and conclusions for rigorous scrutiny within the scientific and policy-making communities in three forms. First, we will prepare manuscripts for submission to peer-reviewed journals. Second, we plan to present our results to colleagues at both professional scientific meetings (e.g. Estuarine Research Federation biennial meetings, American Society of Limnology and Oceanography annual meetings) and CALFED Science Conferences. Finally, we will update the community as to the status of our research through data reports and newsletter articles to appear periodically throughout the three-year project.

6. Data Handling

All samples collected as part of this research will be preserved and stored appropriately to ensure archival quality. Data will be recorded on data sheets designed specifically for this project and will undergo a series of error checks before archiving. In addition, all the data generated from microscopical analyses, experiments and statistical analyses will be stored on local workstations and backed up onto CD's and/or other appropriate computer storage media. We will also make our data available to various databases/servers being developed by the local scientific community, such as the Bay/Delta Science Consortium, of which one of us (S.M.B) is the representative for SFSU/RTC. We will make our results and interpretations public through articles, presentations and newsletters as described above, and will provide further access to the scientific community upon request.

7. Expected Products/Outcomes

We expect to produce new insights into the structure and magnitude of trophic linkages within the planktonic food web of North San Francisco Bay. In particular, we will quantitatively describe the differences in food web structure and resulting potential for fish production over a range of habitats in the North Bay that will assist in efforts to restore fish populations and their preferred habitats.

As described above, we intend to disseminate our conclusions to the scientific and policy-making communities through the publication of articles in peer-reviewed journals and presentations at professional meetings, as well as through participation in workshops and seminars.

8. Work Schedule

We propose a start date of July 1, 2002 and a completion date of June 30, 2005, although this schedule could easily shift depending on availability of funds. The timeline for completion of all tasks as described above is shown in Table 1.

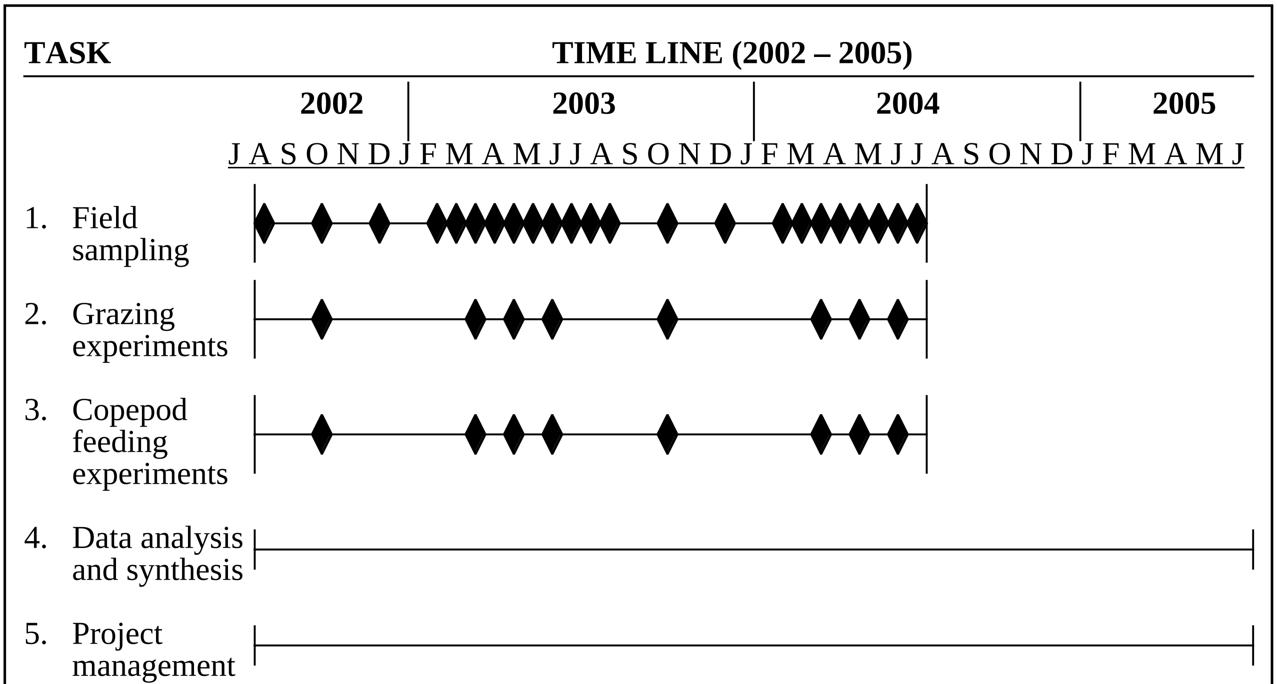

Table 1. Time line for completion of tasks, beginning August 2002 through July 2005.

B. Applicability to CALFED ERP and Science Program Goals and Implementation Plan and CVPIA Priorities

1. ERP, Science Program and CVPIA Priorities

This project will provide information and results relevant to all of the stated ERP goals and objectives, either directly or indirectly. In particular, a quantitative appreciation of the microzooplankton role in the North Bay planktonic food web will directly benefit efforts related to recovery of at-risk fish species (Goal 1), increasing productivity and rehabilitating food web processes to support recovery of native species (Goal 2), enhancing harvestable fisheries (Goal 3), and identifying the competitive relationships between native and non-indigenous species (Goal 5). Clarifying the structure of the lower food web in North Bay will also provide information useful in estimating potential pathways of toxicants such as selenium and mercury to the higher food web.

With respect to the specific goals and restoration priorities of the Bay Region, our results will also help to address a number of issues. This project will provide a better understanding of primary and secondary productivity and linkages within the food webs of San Pablo Bay and Suisun Bay, useful for establishing water management and regulatory approaches to protect both the resident and transient at-risk fish species that utilize these regions (restoration objective #7). In addition, comparing deep channel and shoal/marsh sites will elucidate the potential differences between these locations on fish populations (restoration objective #8).

2. Relationship to other Ecosystem Restoration Projects

The research proposed here will have both direct and indirect applicability to several other CALFED-funded ERP projects. In particular, this research will be directly comparable to the

UC Davis project “Food Resources for Zooplankton in the Sacramento-San Joaquin River Delta”, C. Goldman et al., co-PI’s. Our project will complement their exclusively Delta-based study of the quality of copepod diet by examining the trophic relationships among the actual food resources for copepods further downstream in Suisun and San Pablo Bays. We will identify the structure of the planktonic food web that supports copepods and fish, which will provide valuable context for understanding the controls on secondary production that Goldman et al. are measuring using biochemical techniques.

Our project will also complement the USGS project “Transport, Transformation and Effects of Selenium and Carbon in the Delta: Implications for ERP,” S. Luoma et al., co-PI’s. A major goal of this program is to determine the transfer of Se from phytoplankton through the food web to fish and other predators. We will identify the structure of the planktonic food web and quantify the magnitudes of materials transfer within the system that are essential for predicting the bioaccumulation of Se and potential impacts on higher consumers.

Finally, we also believe that a quantitative understanding of the planktonic food web will provide valuable insights into the potential fate of carbon entering the Bay as measured through the two-part program “Dissolved Organic Carbon Release from Delta Wetlands,” J. Cloern et al., co-PI’s, and will complement the projects listed in B.4. below in which S. Bollens is actively involved. In general, our project will have relevance to all projects whose goals include elucidating the controls on primary and secondary production and improving conditions for harvestable and at-risk fish species.

3. Requests for next-phase funding

This is not applicable to our proposal.

4. Previous Recipients of CALFED Program or CVPIA Funding

The lead investigator of the proposed research (S.M. Bollens) is currently a Co-PI on two CALFED-funded research projects in San Francisco Bay/Delta.

"Effects of Introduced Species of Zooplankton and Clams on the Bay-Delta Food Web" (W. Kimmerer, W. Bennett, and S. Bollens, co-PIs, CALFED 99-N09). This project was begun in 2000 and is 20% complete. Experimental work has been conducted on predation among zooplankton species (both native and introduced), feeding relationships, and zooplankton reproductive and growth rates and their dependence on food supplies. This research will be central to understanding any long-term changes in productivity in the Bay/Delta, especially those that may be due to introduced species, and recovery of at-risk species of fishes.

"Understanding Tidal Marsh Restoration Processes and Patterns: Validating and Extending the BREACH Conceptual Model" (C. Simenstad, D. Reed, P. Williams, S. Bollens, N. Nur, and Z. Hymanson, co-PIs, CALFED 99-B13). This research began in 2000 and is 30% complete. This project is comprised of an extensive set of field studies of biological communities and food webs associated with transitional restoration stages of marshes in San Pablo Bay and Suisun Bay. This research will allow us (and others) to address the feasibility of restoration of shallow water habitat, and any possible differences inherent to different regions of the Bay-Delta, and to evaluate the contribution such restoration may have for the long-term recovery of fisheries.

5. System-Wide Ecosystem Benefits

One of the major factors affecting populations of at-risk fish species is the decline in primary and secondary productivity observed in the North Bay/Delta in recent years. Any efforts to remediate habitat and to improve planktivorous fish production, therefore, must rely on accurate and detailed information regarding the structure of the planktonic food web and how it responds to both biological and physical stressors. The results of our proposed research into the role of microzooplankton in the food web will provide such information and contribute to further research and restoration projects that hope to improve conditions for native at-risk fish species. By targeting San Pablo Bay and Suisun Bay, and a diversity of environments within these bays, we will quantify the structure and function of the planktonic food web across ranges of habitats that encompass a considerable fraction of the North Bay. Thus we anticipate our results to have significance and applicability to projects being conducted across a wide geographic area of the Bay/Delta, and especially to projects whose aim is to increase the fish populations that are supported by the planktonic food web.

C. Qualifications

Dr. Stephen Bollens is Professor, Department of Biology and Romberg Tiburon Center for Environmental Studies, and Assistant Dean, Office of Research and Sponsored Programs, San Francisco State University. He received his Ph.D. in Biological Oceanography from the University of Washington in 1990. Dr. Bollens then spent two years as a Postdoctoral Scholar ('90-92) and 4 years as both tenure-track Assistant Scientist ('92-'96) in the Biology Department, Woods Hole Oceanographic Institution (WHOI), and as faculty member in the joint Ph.D. program at WHOI/Massachusetts Institute of Technology. Dr. Bollens' research interests include behavioral ecology, population dynamics, and community ecology of zooplankton and fishes, and ecosystem dynamics of estuaries and coastal oceans. Recent field sites have included San Francisco Bay, Puget Sound, the central California coast (California Current), Georges Bank, the Bering Sea, the Arabian Sea, and the Antarctic Ocean. Honors include a Young Investigator Award from the Office of Naval Research (ONR) (‘92-’96) and induction into the California Academy of Sciences in 2000. Dr. Bollens has been supported by funding agencies including NSF, ONR, NOAA, and CALFED. He is currently a member of the Interagency Ecological Program's Estuarine Ecology Team, the Romberg Tiburon Center's Board of Directors, the Moss Landing Marine Laboratories Board of Governors, the National Scientific Steering Committee of NSF’s Coastal Ocean Processes Program (CoOP), serves as the SFSU/RTC representative to the newly formed Bay/Delta Science Consortium, and is Co-Chair of the Science Program of the 2003 Estuarine Research Federation biennial meeting. Several on-going and proposed research activities at SFSU-RTC will also benefit the proposed microzooplankton dynamics research (see B.2 and B.4 above). Dr. Bollens has published more than 30 articles in the scientific literature, including journals such as *Nature*, *Limnology & Oceanography*, *Oceologia*, *Journal of Experimental Marine Biology and Ecology*, and *Deep-Sea Research*. Representative publications include Bollens and Frost (1989), Bollens et al. (1993), Speekmann et al. (2000), Bollens et al. (2001), and Bollens et al. (submitted).

Dr. Mary W. Silver is Professor, Department of Ocean Sciences, University of California, Santa Cruz (UCSC). She received her Ph.D. in Oceanography in 1971 from Scripps Institution of Oceanography, University of California, San Diego. Dr. Silver joined the faculty at UCSC in 1972 as an Assistant Professor, was promoted to Associate Professor in 1981, Professor in 1987, and served as Chair of the Marine Sciences (now Ocean Sciences) department from 1982-1984, 1986-1989, and 1992-1995. Dr. Silver has also held an adjunct position with the Monterey Bay Aquarium Research Institute (MBARI) since 1989. Dr. Silver has received numerous awards for both her scientific contributions as well as her teaching excellence. In 1992 Dr. Silver was awarded the prestigious Henry Bryant Bigelow Medal in Oceanography for her pioneering work on the composition, distribution and ecological role of marine snow in pelagic ecosystems. She received the Outstanding Faculty Award from the Division of Natural Sciences at UCSC in 1996, was named Fellow of the California Academy of Sciences in 1997, and in 2001 received the Ricketts Memorial Lecture Award for her exemplary work in the field of marine sciences in Monterey Bay. Dr. Silver’s research interests include marine microbial ecology, pelagic detrital communities (especially marine snow), and the ecology of toxic phytoplankton. Dr. Silver’s research has been supported through awards from NSF, NOAA, DOE, CA Sea Grant, and the UC Water Resources Center. Dr. Silver has published more than 50 articles in peer-reviewed journals, including *Science*, *Nature*, *Limnology & Oceanography*, *Deep-Sea Research*, and *Marine Ecology Progress Series*. Recent publications include Silver et al. (1998a,b), Murrell et al. (1999), Scholin et al. (2000), and Lefebvre et al. (2001).

Dr. Gretchen Rollwagen Bollens is expected to be Postdoctoral Associate, Department of Ocean Sciences, University of California, Santa Cruz. She will receive her Ph.D. in Integrative Biology from the University of California, Berkeley in early 2002. Dr. Rollwagen Bollens received a B.A. in Biology (with honors) from Harvard University in 1985, and an M.S. in Biological Oceanography from the University of Hawaii in 1994. Publications from her master's research have appeared in *Nature* (Coale et al. 1996) and *Marine Ecology Progress Series* (Rollwagen Bollens and Landry 2000). Dr. Rollwagen Bollens also has one manuscript submitted to *Marine Ecology Progress Series* related to her dissertation research on protozoan-metazoan linkages in San Francisco Bay, and has three other manuscripts in preparation describing the microzooplankton response to the 1998 El Niño and the correlation of microzooplankton and copepod vertical distributions in San Francisco Bay. From 1987 – 1994, prior to her graduate career, Dr. Rollwagen Bollens was Science Program Coordinator and Assistant Scientist with the Sea Education Association (SEA) in Woods Hole, MA, through which she accrued more than 750 days of sea time. Dr. Rollwagen Bollens has an additional 100 days of field experience at sea conducting graduate research aboard oceanographic research vessels in the equatorial Pacific, northwest Atlantic, and San Francisco Bay/coastal California.

D. Cost

The detailed budget for all three years of the proposed research is being submitted through the CALFED website, and therefore is not shown here. There is no cost sharing arrangement with any other institution.

E. Local Involvement

As this is a purely research-based proposal, and our sampling sites and activities do not involve accessing private property, we do not have formal coordination with any county or local entities. However, in addition to its strong commitment to graduate and undergraduate education, the SFSU/Romberg Tiburon Center actively involves the local Marin county community in a variety of programs to increase awareness of the ecology and value of the San Francisco Bay/Delta. These efforts include discussions and demonstrations of RTC scientists' research programs in the Bay, and would include this project as we interpret our results.

F. Compliance with Standard Terms and Conditions

As the lead institution for this proposed research, San Francisco State University (SFSU) agrees to abide by all state and federal contract terms and conditions as stated in Attachments D and E of the 2002 Proposal Solicitation Package.

G. Literature Cited

Alpine, A.E. and J.E. Cloern (1992) Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnol. Oceanogr. 37(5): 946-955.

Ambler, J. W., J. E. Cloern, and A. Hutchinson. (1985) Seasonal cycles of zooplankton from San Francisco Bay. Hydrobiol. 129: 177-197.

Ban, S., C. Burns, J. Castel, Y. Chaudron, E. Christou, R. Escribano, S. Fonda Umani, S. Gasparini, F. Guerrero Ruiz, M. Hoffmeyer, A. Ianora, H. Kang, M. Laabir, A. Lacoste, A.

Miralto, X. Ning, S. Poulet, V. Rodriguez, J. Runge, J. shi, M. Starr, S. Uye, and Y. Wang (1997) The paradox of diatom-copepod interactions. Mar. Ecol. Prog. Ser. 157: 287-293.
Banse, K. (1982) Cell volumes, maximal growth rates of unicellular algae and ciliates, and the role of ciliates in the marine pelagial. Limnol. Oceanogr. 27(6): 1059-1071.
Bautista, B. and R.P. Harris (1992) Copepod gut contents, ingestion rates and grazing impact on phytoplankton in relation to size structure of zooplankton and phytoplankton during a spring bloom. Mar. Ecol. Prog. Ser. 82: 41-50.
Bennett, W.A. and P.B. Moyle (1996) Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: San Francisco Bay: The Ecosystem, J.T. Hollibaugh (ed), American Association for the Advancement of Science, pp. 519-542.
Bollens, S. M. and B. W. Frost (1989) Zooplanktivorous fish and variable diel vertical migration in the marine planktonic copepod *Calanus pacificus*. Limnol. Oceanogr. 34: 1072-1083.
Bollens, S. M., B. W. Frost, K. Osgood, and S. D. Watts. (1993) Vertical distributions and susceptibilities to vertebrate predation of the marine copepods *Metridia lucens* and *Calanus pacificus*. Limnol. Oceanogr. 38: 1841-1851.
Bollens, S. M., S. Avent, J. Cordell, W. Kimmerer, and C. Penalva-Arana (1999) San Francisco Bay zooplankton: interannual and interdecadal variation, with special reference to non-indigenous species and ENSO effects. EOS, Transactions, American Geophysical Union 80: 133.
Bollens, S.M., E., Horgan, S. Concelman, L.P. Madin, S.M. Gallager and M. Butler (2001) Planktonic hydroids on Georges Bank: effects of mixing and food supply on feeding and growth. Deep-Sea Res. 48(1-3): 659-672.
Bollens, S.M., J. R. Cordell, S. Avent, and R. Hooff (Submitted) Occurrences, causes and consequences of zooplankton invasions: A brief review, plus two case studies from the Northeast Pacific Ocean. Submitted to *Hydrobiologia*'s Special Volume on "Progress in Zooplankton Biology: Ecology, Systematics, and Behavior", Commemorating the 60th Birthday of Professor Bruce W. Frost.
Burkill, P.H., R.F.C. Mantoura, C.A. Llewellyn and N.J.P. Owens (1987) Microzooplankton grazing and selectivity of phytoplankton in coastal waters. Mar. Biol. 93: 581-590.
Buskey, E.J. (1993) Annual pattern of micro- and mesozooplankton abundance and biomass in a subtropical estuary. J. Plank. Res. 15(8): 907-924.
Canuel, E.A., J.E. Cloern, D.B. Ringelberg, J.B. Guckert, and G.H. Rau (1995) Molecular and isotopic tracers used to examine sources of organic matter and its incorporation into the food webs of San Francisco Bay. Limnol. Oceanogr. 40(1): 67-81.
Cloern, J.E. (1982) Does the benthos control phytoplankton biomass in South San Francisco Bay? Mar. Ecol. Prog. Ser. 9: 191-202.
Cloern, J.E., B.E. Cole, R.L.J. Wong, and A.E. Alpine (1985) Temporal dynamics of estuarine phytoplankton: A case study of San Francisco Bay. Hydrobiol. 129: 153-176.
Coale, K., Johnson, K., Fitzwater, S., Gordon, R., Tanner, S., Chavez, F., Ferioli, L., Sakamoto, C., Rogers, P., Millero, F., Steinberg, P., Nightingale, P., Cooper, D., Cochlan, W., Landry, M., Constantinou, J., Rollwagen, G., Trasvina, A., Kudela, R. (1996) A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature 383: 495-501.
Dagg, MJ. (1993) Grazing by the copepod community does not control phytoplankton in the subarctic Pacific Ocean. Prog. Oceanogr. 32:163-183.
Dagg, M.J. (1995) Ingestion of phytoplankton by the micro- and mesozooplankton communities in a productive subtropical estuary. J. Plank. Res. 17(4): 845-857.
Dam, H.G., C.A. Miller and S.H. Jonasdottir (1993) The trophic role of mesozooplankton at 47°N, 20°W during the North Atlantic bloom experiment. Deep-Sea Res. 40: 197-212.
Dam, H.G., X. Zhang, M. Butler and M.R. Roman (1995) Mesozooplankton grazing and metabolism at the equator in the central Pacific: implications for carbon and nitrogen fluxes. Deep-Sea Res. 42: 735-756.

Edwards, E.S., P.H. Burkill and C.E. Stelfox (1999) Zooplankton herbivory in the Arabian Sea during and after the SW monsoon, 1994. Deep-Sea Res. 46: 843-863.
Fessenden, L. and T.J. Cowles (1994) Copepod predation on phagotrophic ciliates in Oregon coastal waters. Mar. Ecol. Prog. Ser. 107: 103-111.
Froneman, P.W. and C.D. McQuaid (1997) Preliminary investigation of the ecological role of microzooplankton in the Kariega Estuary, South Africa. Estuar. Coast. Shelf Sci. 45: 689-695.
Gallegos, C.L. (1989) Microzooplankton grazing on phytoplankton in the Rhode River, Maryland (USA): Nonlinear feeding kinetics. Mar. Ecol. Prog. Ser. 57(1): 23-34.
Gifford, D.J. (1988) Impact of grazing by microzooplankton in the northwest arm of Halifax Harbor, Nova Scotia. Mar. Ecol. Prog. Ser. 47: 249-259.
Gifford, D.J. (1991) The protozoan-metazoan trophic link in pelagic ecosystems. J. Protozool. 38: 81-86.
Gifford, D.J. and M.J. Dagg (1988) Feeding of the estuarine copepod *Acartia tonsa* Dana: carnivory vs. herbivory in natural microplankton assemblages. Bull. Mar. Sci. 43: 458-468.
Gifford, D.J. and M.J. Dagg (1991) The microzooplankton-mesozooplankton link: consumption of planktonic protozoa by the calanoid copepods *Acartia tonsa* Dana *and Neocalanus plumchrus* Murukawa. Mar. Microb. Food Webs 5(1): 161-177.
Ianora, A., S.A. Poulet and A. Miralto (1995) A comparative study of the inhibitory effect of diatoms on the reproductive biology of the copepod *Temora stylifera*. Mar. Biol. 121: 533-539.
Jassby, A.D. and J.E. Cloern (2000) Organic matter sources and rehabilitation of the Sacramento – San Joaquin Delta (California, USA). Aquatic conserv: Mar. Freshw. Ecosyst. 10: 323-352.
Jassby, A.D., J.E. Cloern, and T.M. Powell (1993) Organic carbon sources and sinks in San Francisco Bay: variability induced by river flow. Mar. Ecol. Prog. Ser. 95: 39-54.
Jassby, A.D. and T.M. Powell (1994) Hydrodynamic influences on interannual chlorophyll variability in an estuary: Upper San Francisco Bay-Delta (California, USA). Estuar. Coast. Shelf Sci. 39: 595-618.
Jassby, A.D., W.J. Kimmerer, S.G. Monismith, C. Armor, J.E. Cloern, T.M. Powell, J.R. Schubel and T.J. Vendlinksi (1995) Isohaline position as a habitat indicator for estuarine populations. Ecol. Appl. 5(1): 272-289.
Kimmerer, W.J., E. Gartside and J.J. Orsi (1994) Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Mar. Ecol. Prog. Ser. 113: 81-93.
Kimmerer, W.J. and J.J. Orsi (1996) Changes in the zooplankton of the San Francisco Bay estuary since the introduction of the clam *Potamocorbula amurensis*. In: San Francisco Bay: The Ecosystem, J.T. Hollibaugh (ed), American Association for the Advancement of Science, pp. 403-424.
Kirk, K.L. (1991) Inorganic particles alter competition in grazing plankton: the role of selective feeding. Ecology 72(3): 915-923.
Kirk, K.L. and J.J. Gilbert (1990) Suspended clay and the population dynamics of planktonic rotifers and cladocerans. Ecology 71(5): 1741-1755.
Klein Breteler, W.C.M., N. Schogt, M. Baas, S. Schouten and G.W. Kraay (1999) Trophic upgrading of food quality by protozoans enhancing copepod growth: role of essential lipids. Mar. Biol. 135: 191-198.
Kleppel, G.S. (1992) Environmental regulation of feeding and egg production by *Acartia tonsa* off southern California. Mar. Biol. 112: 57-65.
Kleppel, G.S., C.A, Burkart, K. Carter and C. Tomas (1996) Diets of calanoid copepods on the West Florida shelf: relationships between food concentration, food composition and feeding activity. Mar. Biol. 127: 209-217.
Kurth R. and M. Nobriga (2001) Food habits of larval splittail. IEP Newsletter (California Department of Water Resources, Sacramento, CA, USA) 14(3): 40-42.

Landry, M.R. (1993) Estimating rates of growth and grazing mortality of phytoplankton by the dilution method, pp. 715-722. In: Methods in Aquatic Microbial Ecology, P. Kemp, B. Sherr, E. Sherr and J. Cole (eds), Lewis Publ, NY.
Landry, M.R. and R.P. Hassett (1982) Estimating the grazing impact of marine microzooplankton. Mar. Biol. 67: 283-288.
Landry, M. R., C. J. Lorenzen and W. K. Peterson (1994) Mesozooplankton grazing in the Southern California Bight. II. Grazing impact and particulate flux. Mar. Ecol. Prog. Ser. 115: 73-85.
Landry, M.R., J. Constantinou and J. Kirshtein (1995) Microzooplankton grazing in the central equatorial Pacific during February and August, 1992. Deep-Sea Res. 42: 657-671.
Landry, M.R., J. Constantinou, M. Latasa , S.L. Brown, R.R. Bidigare and M.E. Ondrusek (2000) Biological response to iron fertilization in the eastern equatorial Pacific (IronEx II). III. Dynamics of phytoplankton growth and microzooplankton grazing. Mar. Ecol. Prog. Ser. 201: 73-83.
Lefebvre, K.A., S.L. Dovel and M.W. Silver (2001) Tissue distribution and neurotoxic effects of domoic acid in a prominent vector species, the northern anchovy *Engraulis mordax*. Mar. Biol. 138(4): 693-700.
Lehman, P.W. (2000) The influence of climate on phytoplankton community biomass in San Francisco Bay Estuary. Limnol. Oceanogr. 45(3): 580-590.
Lessard, E.J. and M.C. Murrell (1998) Microzooplankton herbivory and phytoplankton growth in the northwestern Sargasso Sea. Aquat. Microb. Ecol. 16: 173-188.
Lougheed, V.L. and P. Chow-Fraser (1998) Factors that regulate the zooplankton community structure of a turbid, hypereutrophic Great Lakes wetland. Can. J. Fish. Aquat. Sci. 55: 150-161.
Lovejoy, C., W.F. Vincent, J.J. Frenette, and J.J. Dodson (1993) Microbial gradients in turbid estuary: Application of a new method for protozoan community analysis. Limnol. Oceanogr. 38(6): 1295-1303.
Marin, V., M.E. Huntley and B. Frost (1986) Measuring feeding rates of pelagic herbivores: analysis of experimental design and methods. Mar. Biol. 93: 49-58.
McManus, G.B. and M.C. Ederington-Cantrell (1992) Phytoplankton pigments and growth rates and microzooplankton grazing in a large temperate estuary. Mar. Ecol. Prog. Ser. 87(1-2): 77-85.
Menden-Deuer, S. and E.J. Lessard (2000) Carbon to volume relationships for dinoflagellates, diatoms, and other protist plankton. Limnol. Oceanogr. 45: 569-579.
Meng, L. and J.J. Orsi (1991) Selective predation by larval striped bass on native and introduced copepods. Trans. Amer. Fish. Soc. 120: 187-192.
Miquelis, A., C. Rougier, and R. Pourriot (1998) Impact of turbulence and turbidity on grazing rate of the rotifer *Brachionus calyciflorus* (Pallas). Hydrobiol. 386: 203-211.
Miralto, A., G. Barone, G. Romano, S.A. Poulet, A. Ianora, G.L. Russo, I. Buttino, G. Mazzarella, M. Laabir, M. Cabrini and M.G. Giacobbe (1999) The insidious effect of diatoms on copepod reproduction. Nature 402: 173-176.
Moyle, P.B., B. Herbold, D.E. Stevens and L.W. Miller (1992) Life history and status of delta smelt in the Sacramento-San Joaquin estuary, California. Trans. Amer. Fish. Soc. 121(1): 67-77.
Murrell, M.C. and J.T. Hollibaugh (1998) Microzooplankton grazing in northern San Francisco Bay measured by the dilution method. Aquat. Microb. Ecol. 15: 53-63.
Murrell, M.C., J.T. Hollibaugh, M.W. Silver and P.S. Wong (1999) Bacterioplankton dynamics in northern San Francisco Bay: role of particle association and seasonal freshwater flow. Limnol. Oceanogr. 44(2): 295-308.
Neuer, S. and T.J. Cowles (1994) Protist herbivory in the Oregon upwelling system. Mar. Ecol. Prog. Ser. 113: 147-162.
Obrepski, S., J.J. Orsi and W.J. Kimmerer (1992) Long-term trends in zooplankton distribution and abundance in the Sacramento-San Joaquin estuary of California. California Interagency Ecol. Studies Progr. Tech Rept. 32. Sacramento, CA 42 pp.

Orsi, J.J. and W.L. Mecum (1986) Zooplankton distribution and abundance in the Sacramento-San Joaquin Delta in relation to certain environmental factors. Estuaries 9(4B): 326-339.
Peters, F. and T. Gross (1994) Increased grazing rates of microplankton in response to small-scale turbulence. Mar. Ecol. Prog. Ser. 115: 299-307.
Poulet, S.A., A. Ianora, A. Miralto and L. Meijer (1994) Do diatoms arrest embryonic development in copepods? Mar. Ecol. Prog. Ser. 111: 79-86.
Purkerson, D.G., M.A. Doblin, S.M. Bollens, S.N. Luoma and G.A. Cutter (Submitted) Selenium in San Francisco Bay zooplankton: Potential effects of hydrodynamics and food web interactions. Submitted to Limnol. Oceanogr.
Rollwagen Bollens, G.C. and M.R. Landry (2000) The biological response to iron fertilization in the eastern equatorial Pacific (IronEx II). II. Mesozooplankton abundance, biomass, depth distribution and grazing. Mar. Ecol. Prog. Ser. 201: 43-56.
Rollwagen Bollens, G.C. and D.L. Penry (Submitted) Ingestion rates and prey preferences of *Acartia* spp. copepods feeding on natural microplankton in San Francisco Bay. Submitted to Mar. Ecol. Prog. Ser.
Ruiz, A. J. Franco and F. Villate (1998) Microzooplankton grazing in the Estuary of Mundaka, Spain, and its impact on phytoplankton distribution along the salinity gradient. Aquat. Microb. Ecol. 14: 281-288.
Saiz, E., M. Alcaraz, and G-A. Paffenhofer (1992) Effects of small-scale turbulence on the feeding rates and gross-growth efficiency of three Acartia species (Copepoda: Calanoida). J. Plank. Res. 14(8): 1085-1097.
Sautour, B., L.F. Artigas, D. Delmas, A. Herbland and P. Laborde (2000) Grazing impact of micro- and mesozooplankton during a spring situation in coastal waters off the Gironde estuary. J. Plank. Res. 22(3): 531-552.
Sherr, E.B., D.A. Caron, and B.F. Sherr (1993) Staining of heterotrophic protists for visualization via epifluorescence microscopy. In: Methods in Aquatic Microbial Ecology, P. Kemp, B. Sherr, E. Sherr and J. Cole (eds), Lewis Publ, NY. pp. 213-228.
Sherr, E.B. and B.F. Sherr (1994) Bacterivory and herbivory: Key roles of phagotrophic protists in pelagic food webs. Microb. Ecol. 28: 223-235.
Sherr, E.B., B.F. Sherr and G.A. Paffenhofer (1986) Phagotrophic protozoa as food for metazoans: a “missing” trophic link in marine pelagic food webs? Mar. Microb. Food Webs 1: 61-80.
Shimeta, J. P.A. Jumars, and E.J. Lessard (1995) Influences of turbulence on suspension feeding by planktonic protozoa; experiments in laminar shear fields. Limnol. Oceanogr. 40(5): 845-859.
Silver, M.W., S.L. Coale, C.H. Pilskaln and F.P. Chavez (1998) Exploratory observations of marine aggregates at sub-euphotic depths. Deep-Sea Res. 45(8-9): 1839-1861.
Silver, M.W., S.L. Coale, C.H. Pilskaln and D. R. Stienberg (1998) Giant aggregates: importance as microbial centers and agents of material flux in the mesopelagic zone. Limnol. Oceanogr. 43(3): 498-507.
Speekmann, C.L., S.M. Bollens and S.R. Avent (2000) The effect of ultraviolet radiation on the vertical distribution and mortality of estuarine zooplankton. J. Plank. Res. 22(12): 2325-2350.
Stoecker, D.K. and J. McDowell Capuzzo (1990) Predation on protozoa: its importance to zooplankton. J. Plank. Res. 12: 891-908.
Strom, S.L. and N.A. Welchmeyer (1991) Pigment-specific rates of phytoplankton growth and microzooplankton grazing in the open subarctic Pacific Ocean. Limnol. Oceanogr. 36: 50-63.
Tamigneaux, E., M. Mingelbier, B. Klein and L. Legendre (1997) Grazing by protists and seasonal changes in the size structure of the protozooplankton and phytoplankton in a temperate nearshore environment (western Gulf of St. Lawrence, Canada). Mar. Ecol. Prog. Ser. 146: 231-247.
Verity, P.G., D.K. Stoecker, M.E. Sieracki and J.R. Nelson (1993) Grazing, growth and mortality of microzooplankton during the 1989 North Atlantic spring bloom at 47°N, 18°W. Deep-Sea Res. 40: 1793-1814.