Guide to this document

- The first 30 pages provide some background, the planned approach for developing a Nutrient Science Plan, and then a brief description of the subset of the proposed projects for FY2015
- The subsequent pages are excerpts from several recent reports, focusing on the recommendations made in those reports that will be rolled into the Science Plan.
- The actual reports can be found by following the links on page 12


November 2012

San Francisco Bay Nutrient Management Strategy

San Francisco Bay Regional Water Quality Control Board

1. Is SFB experiencing nutrient-related impairment, or is it likely to in the future?
   - What types of impairment?
   - What forms of nutrients?
   - What future scenarios?

2. What are the major nutrient sources?
   - POTWs ?
   - stormwater ?
   - agriculture ?

3. What loads/concentrations are protective?
   - most sensitive endpoint ?
   - transport, mixing ?
   - reactions (transformations, losses) ?

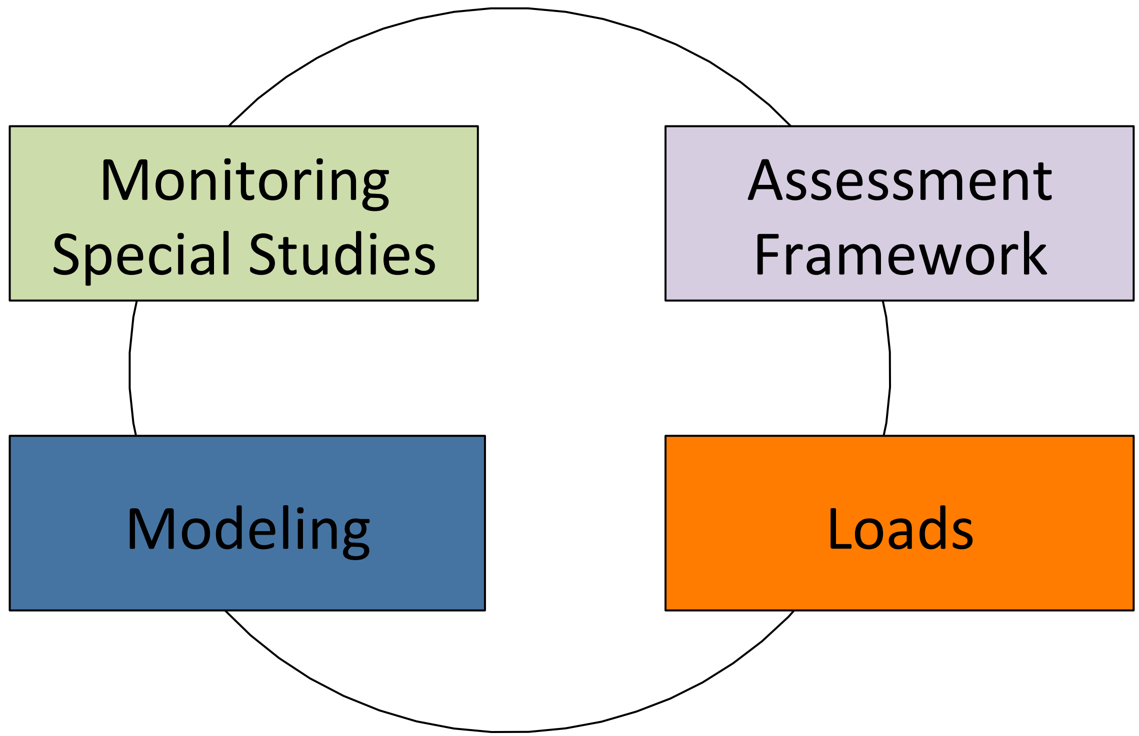
4. What reductions will protect ecosystems?
   - transport, mixing, reactions ?
   - benefit/cost ?

November 2012

San Francisco Bay Nutrient Management Strategy

San Francisco Bay Regional Water Quality Control Board

Nutrient Science Program

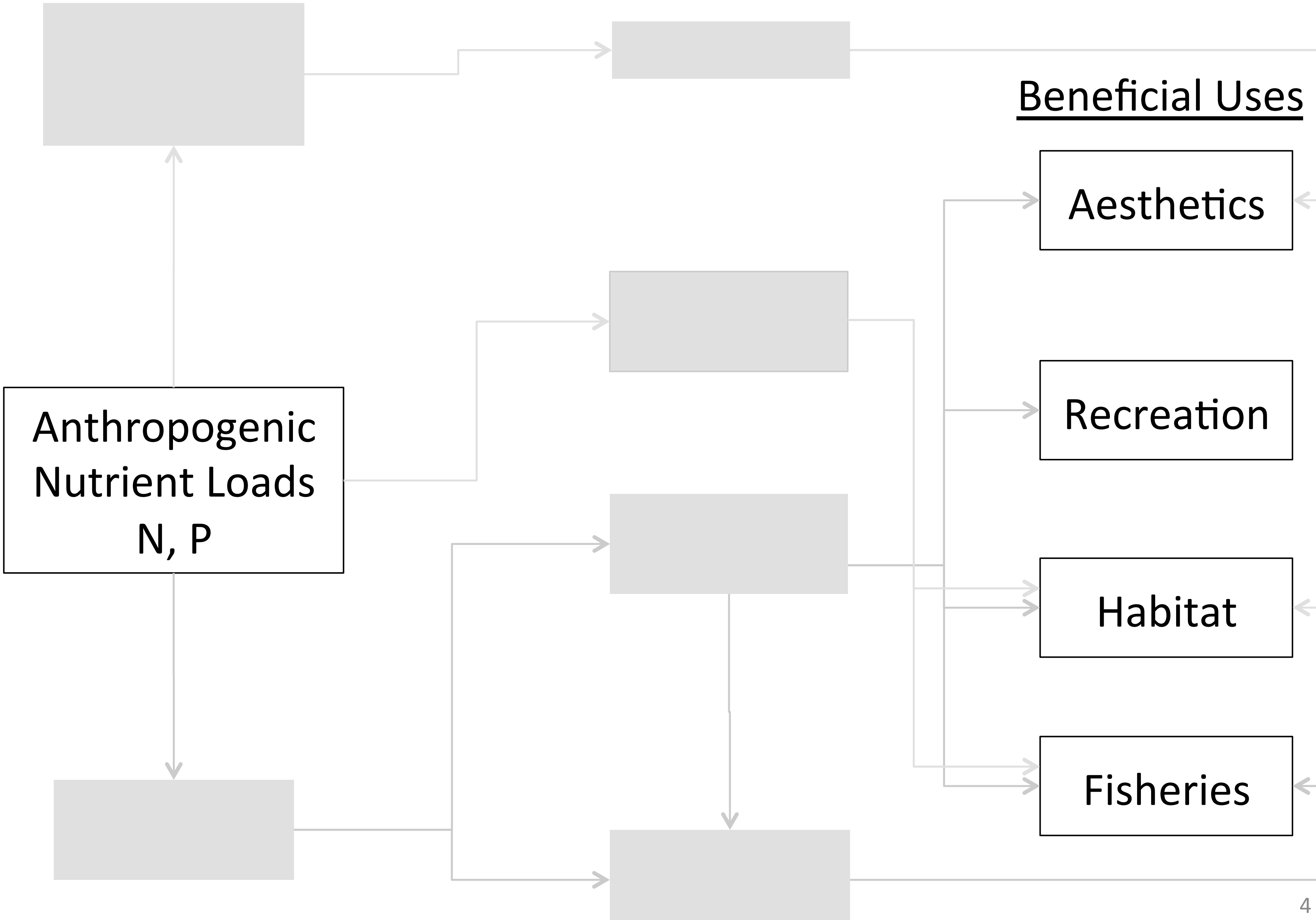


Highest Priority Nutrient Issues in SFB

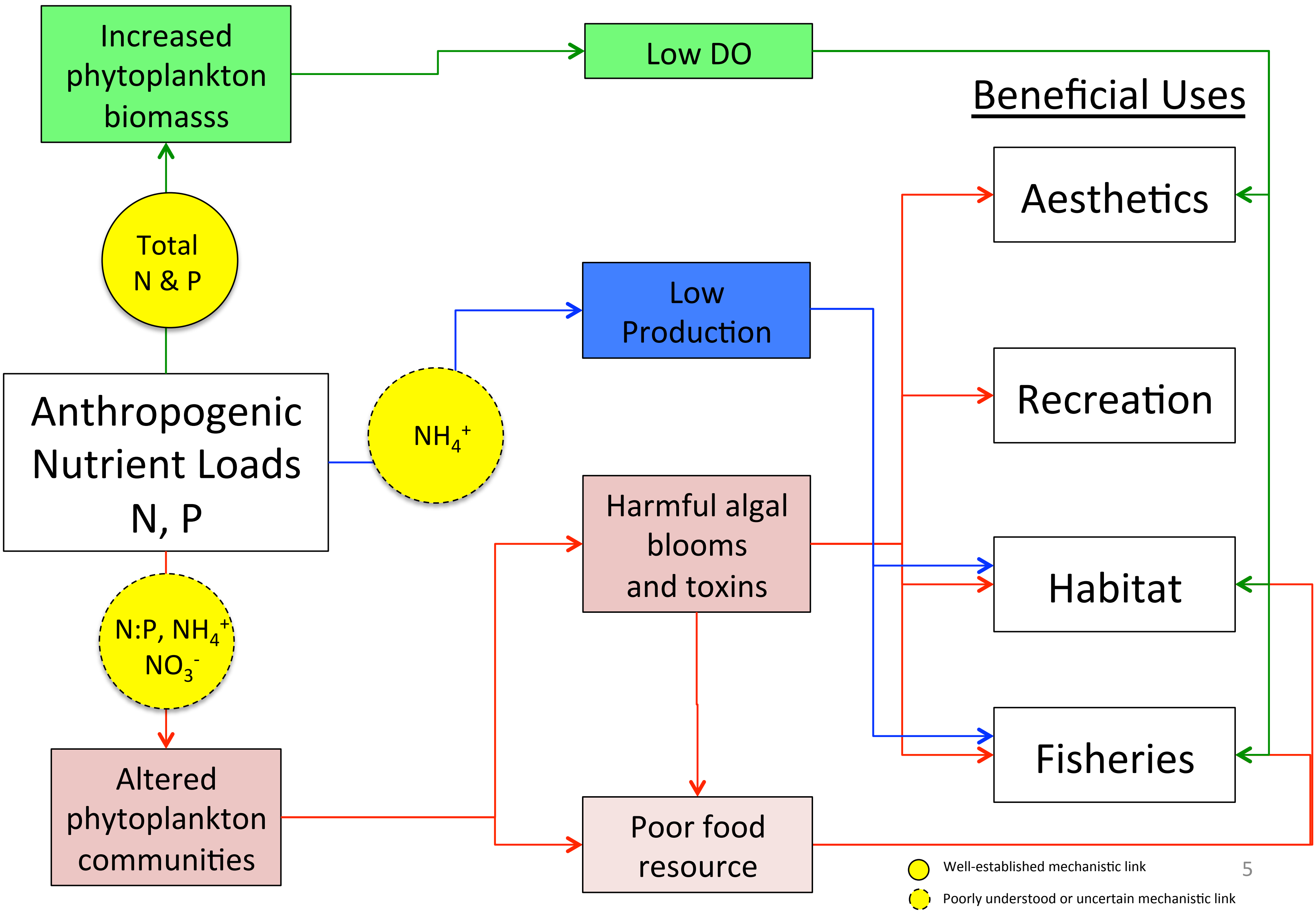
- Determine whether increasing biomass signals future impairment
- Quantify factors that adversely affect phytoplankton composition, including the potential for Harmful Algal Blooms and toxins
- Determine if low DO in shallow habitats causes impairment
  - Quantify role of nutrients
- Test future scenarios that may lead to worsening conditions
- Quantify nutrient contributions to different areas of the Bay
- Test mitigation/prevention scenarios

SFEI 2014b

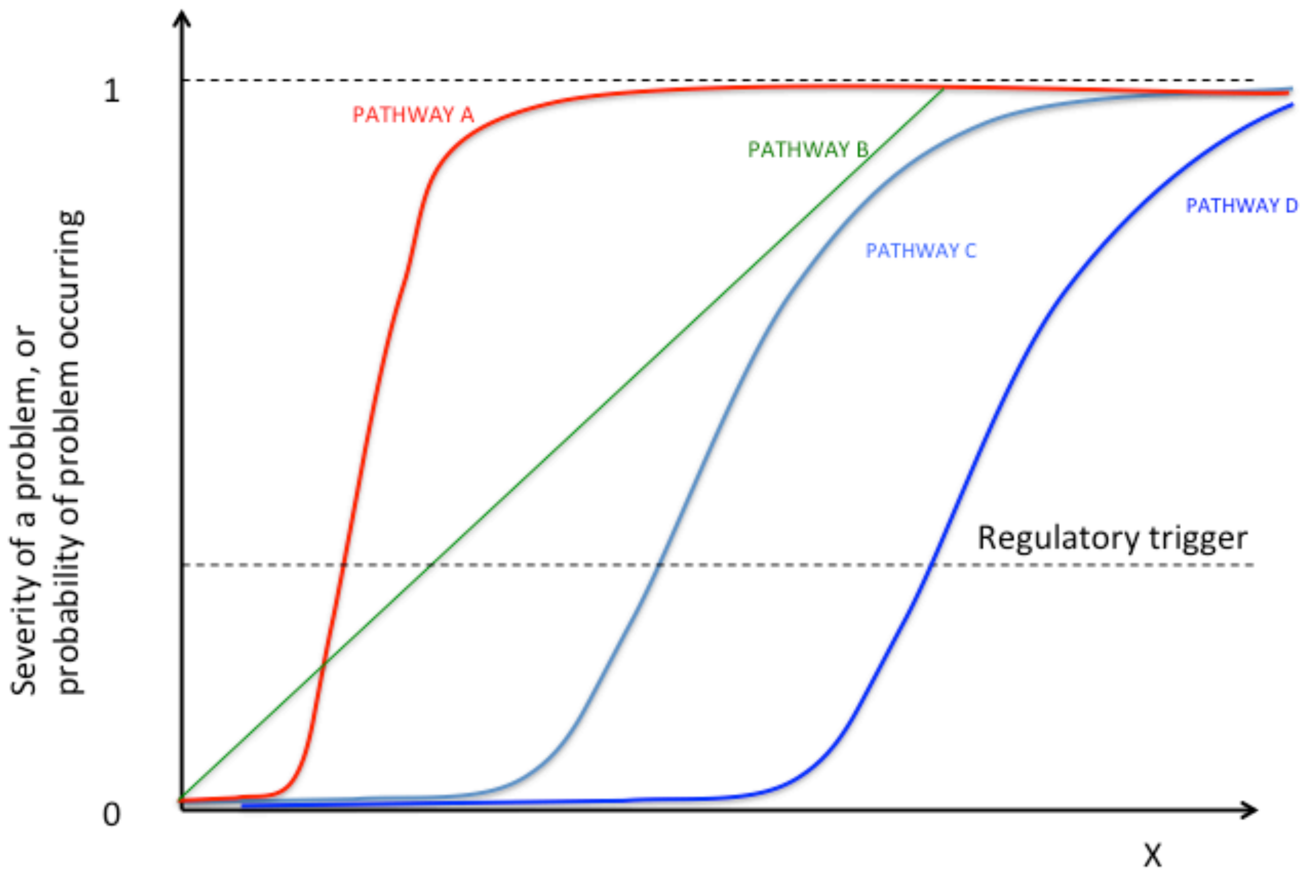
Potential Pathways to Adverse Impacts



Potential Pathways to Adverse Impacts

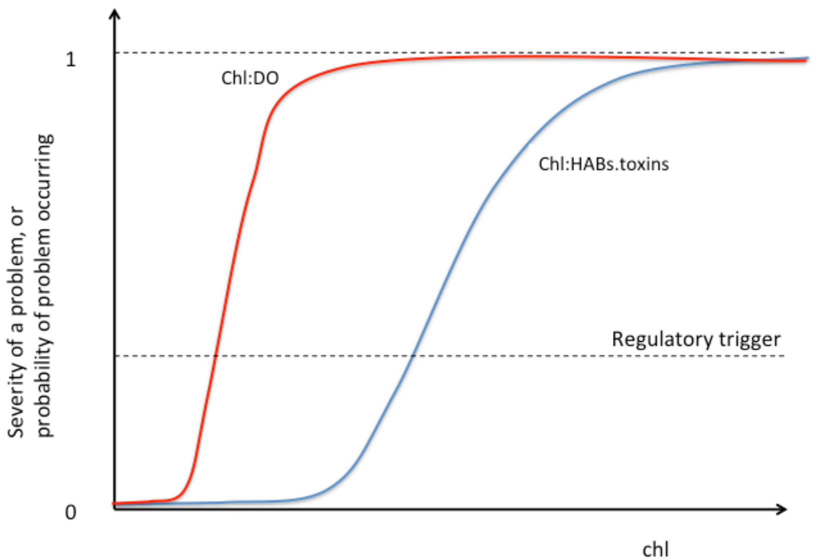


- Multiple Potential Impairment Pathways: i.e., mechanisms through which nutrients could adversely impact ecosystem health (Slide 4)
- Nutrient form and the load/concentration at which impairment develops will differ among pathways.
- Needs for data collection (monitoring), studies, and modeling will also differ among pathways



X = chl
X = loads
X = [DIN], [DIP], [NH4], N:P

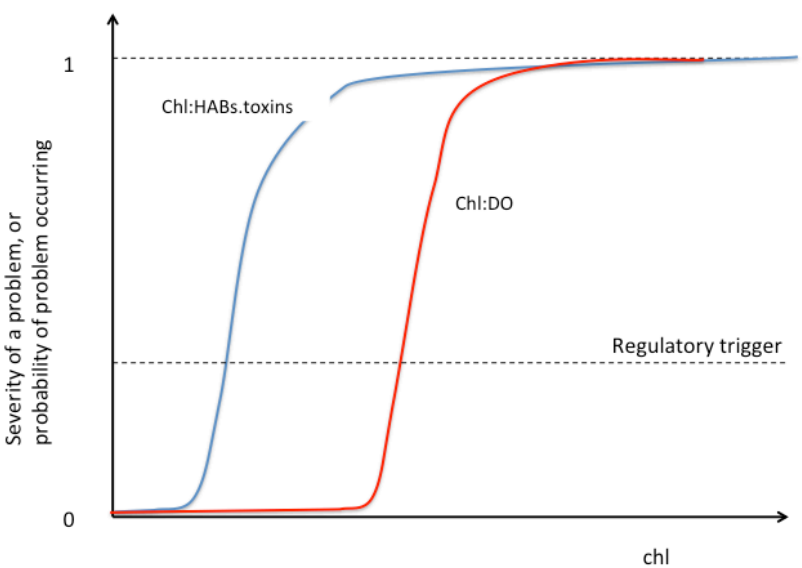
As one example, of how to think about prioritizing, in the assessment framework planning, we are considering chl-a as an indicator of potential problems related to both low DO and HABs in deep subtidal habitats (see Assessment Framework summary report). For this particular habitat type and indicator, our relative focus/investment in scientific investigations and monitoring should be influenced by which of these is likely to be the more sensitive problem and/or the one with the higher probability of occurrence. Initially some of the effort needs to go toward better understanding the mechanisms and levels at which problems could occur. When (if) we identify the more sensitive/probable pathway among these two, it's reasonable to expect that relatively more resources would be directed toward further refining understanding and thresholds for the sensitive pathway. Comparisons among other pathways would also need to be made to inform priorities



If for subembayment X or habitat Y, chl-DO is most likely to be the most sensitive or pronounced problem, focus relatively more of the science effort on:

- phytoplankton composition monitoring,
- toxin monitoring
- Experimentation → toxin:cells
- experimentation → cells:nutrients or toxin:nutrients
- Determination of

toxic thresholds → size/concentration of event → conditions that would cause those events → appropriate monitoring to detect events → management that would prevent/mitigate



If for subembayment X or habitat Y, chl-HABs is likely to be the most sensitive or pronounced problem, focus relatively more of the science effort on:

- Modeling
- Future scenarios (stratification)
- Field studies in margins to better understand both extent and severity of low DO, contributing factors
- Site specific DO objectives, lit reviews or habitat assessment: fish/benthos, avoidance of low DO
- Determinatin of...

Protective DO limits → size/concentration of bloom event → conditions that would cause those events → appropriate monitoring to detect events → management that would prevent/ mitigate

Key Points

- Multiple complex science questions – and related data needs and studies – whose answers could point to substantially different management actions
- Issues (solutions?) differ by subembayment
- Finite resources and timeline
- To make the best decisions, need to..
  - Target highest priority science questions
  - Wisely allocate resources
  - Maximize collaboration/coordination among on-going efforts Bay-wide and Bay/Delta
- Need to develop and implement a science plan to prioritize among investigations
  - E.g., 5 year plan with logical sequence of prioritized projects, and budget
  - Under development
  - For year 1, developing a no regrets first part of plan

To prioritize among science needs…*Need to consider*

Institutional Questions

- What are the most efficient ways to allocate resources?
  - Build upon, integrate, and augment on-going efforts…e.g.,
    - Modeling: USGS (CASCaDE II) + Nutrient Program
    - Moored sensors: USGS-Sac + Nutrient Program (+ DWR?)
    - Ship-based monitoring: USGS + RMP + Nutrient Program (+ DWR/IEP?)

- How can we maximize effectiveness and new knowledge through collaboration/coordination among entities carrying out nutrient-related investigations?

2011-2014

Past Studies or Studies Underway

External Loads Study

Effluent Characterization

Effluent Characterization

Delta Loads

Hydrodynamic and Water Quality Modeling

Science Plan

LSB Synthesis

Suisun Synthesis II

NNE Report

Nutrient Strategy

Conceptual Model

Suisun Synthesis I

Assessment Framework Planning

Evaluate Assessment approaches

HAB Toxins

On-going monitoring

Suisun Field Studies

Suisun Field Studies

Pilot: Phyto pigments

Pilot: Moored Sensors

Data Analysis/ Interpretation

Program Design/ Development

On-going monitoring

Suisun phyto studies

Quantify Loads

Load Reductions: Scenarios

Modeling

Synthesis, Science Plan

Assessment Framework

Monitoring, Special Studies

Key Background Documents (and recommendations)

- Nutrient Strategy

http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/Nutrient_Strategy%20November%202012.pdf

- Scientific Foundation for a San Francisco Bay Nutrient Strategy (aka, Conceptual Model Report)

SFEI 2014a
Draft. Final in May 2014
http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/SAG-June-2013/Nutrients_CM_DRAFT_May12013.pdf

- Suisun Bay Ammonium Synthesis

http://www.sfei.org/sites/default/files/SuisunSynthesisI_Final_March2014_0.pdf

- External Nutrient Loads to San Francisco Bay

SFEI 2014b
http://www.sfei.org/sites/default/files/NutrientLoadsFINAL_FINAL_Jan232014_0.pdf

- Approaches to a Nutrient Assessment Framework

SCCWRP 2013
http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/SAG-June-2013/NNE_Framework_White_Paper.pdf

- Characterizing Nutrient Trends, Loads, and Transformations in Suisun Bay and the Delta.

SFEI 2014d
http://www.sfei.org/sites/default/files/IEP%202014%20ENovick%20FINAL.pdf

- Model Development Plan

http://www.sfei.org/sites/default/files/Nutrient_Modeling_Approach_draftFINAL_Jan212014.pdf

- Numeric nutrient endpoint development for San Francisco Bay – Lit review and data gaps analysis

http://www.sfei.org/sites/default/files/644_SFBayNNE_LitReview%20Final.pdf

- Approaches to a Nutrient Assessment Framework, Draft

http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/SAG-June-2013/NNE_Framework_White_Paper.pdf

Updates: subset of current projects

Deliverable	Funding source	Anticipated due	Notes
LSB Synthesis	NSC FY2014	June 2014	Nutrient loads/concentrations, suspended sediments, benthos abundance and filtration rates, DO in deep subtidal and margin habitats, phytoplankton biomass.
Conceptual Model final draft	RMP 2013	June 2014	
Science Plan (skeletal)	NSC FY2014	June 2014	
Suisun Synthesis II	NSC FY2014	Sep 2014	Focus on changes in community composition, N:P, etc. Literature review and conceptual model for phytoplankton response to nutrients under conditions similar to diverse regions of SFB, analysis of historic phytoplankton data in Suisun and Delta, N and P loads and trends in concentrations seasonally/temporally, review of hypotheses on N:P/nutrient drivers of phytoplankton community response in Delta/Suisun
Moored sensor progress report	NSC FY2014, RMP 2014	June 2014	
Monitoring program development plan	State board (SWAMP), NSC FY2014, RMP 2014	Apr 2014	
Monitoring program development progress report	NSC FY2014, RMP 2014	Dec 2014	

NSC = Nutrient Steering Committee

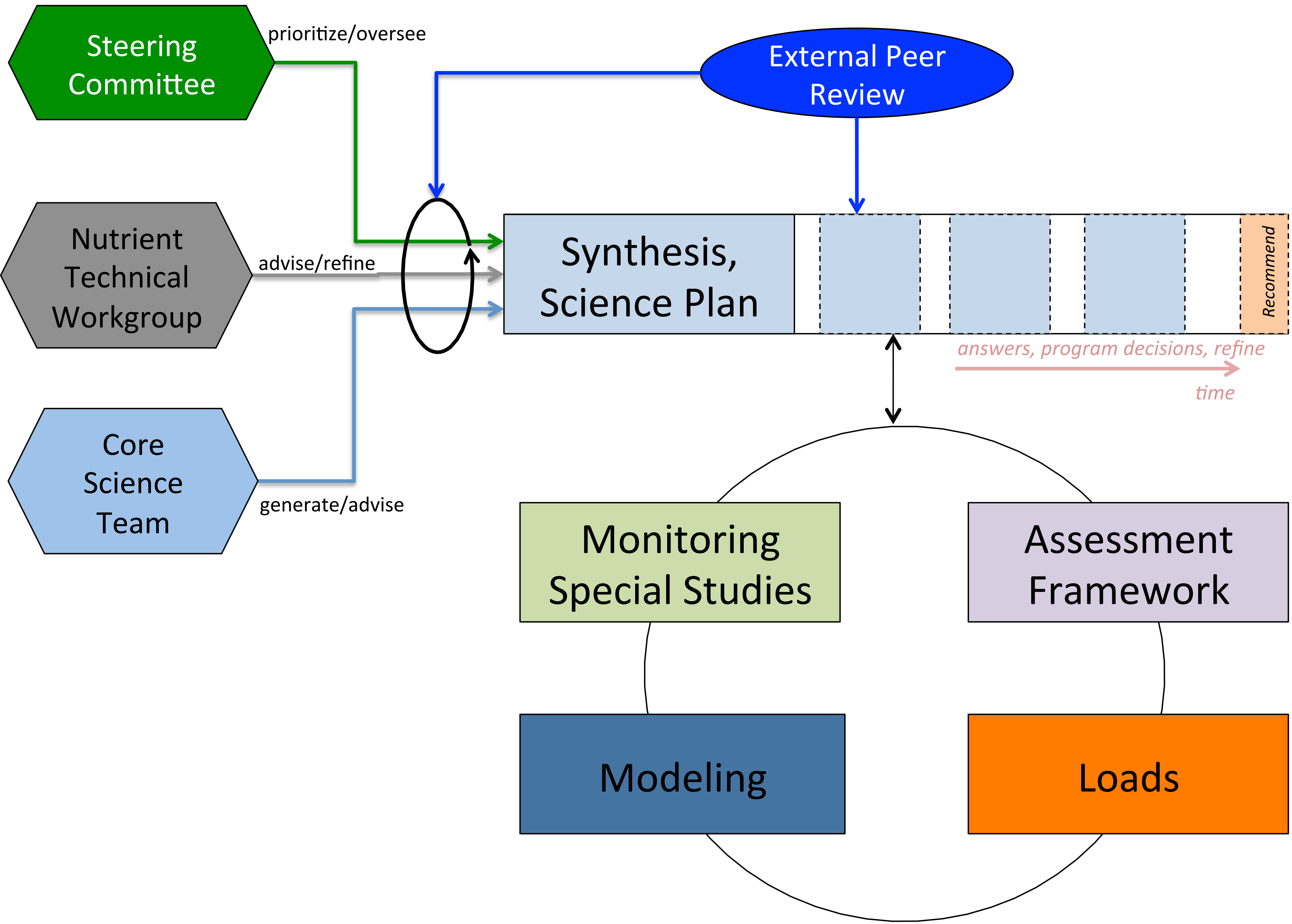
Available Funding for FY2015

Program	Amount	Notes
new		
Nutrient Steering Committee	~$800	
RMP*	$500	moored sensors, modeling
SFB Water Board	$65k	Science Plan Development
SFB Water Board	$100k	Dissolved oxygen objectives
Carry forward		
RMP Modeling	~$300k	From prior years
total	$1.8mill	

*Provisionally allocated

Science Plan

- The science plan will be developed over the coming year and will serve as a guide, prioritization, and workflow/schedule for major activities needed inform nutrient management decisions in SFB.
- Over the past two years, we've been identifying and prioritizing projects based on recommendations from the draft Conceptual Model Report, and recruiting input from technical advisors and stakeholders
- For the FY2015 proposed projects, while developing the longer term (5yr) Science Plan, we are following a similar approach, and ensuring that the proposed projects are "no regrets" studies that will ultimately be part of the Science Plan, and ones that would implemented in its early phases.
- It is expected that the Science Plan will be consistent with the broad recommendations laid out in the Nutrient Strategy. The Science Plan will, however, go into substantially more detail in terms of specific study and data needs, a proposed workflow schedule, and estimated costs. In large part, the Science Plan will actually integrate across recommendations laid out for the major Nutrient Science Program components…monitoring, modeling, special studies, assessment framework.
- While the Science Plan is not yet developed, several of the key reports whose recommendations will inform much of the Science Plan are complete or in draft form. Recommendations for FY2015 are based on recommendations or priorities identified in:
  - Conceptual Model Report
  - Suisun Synthesis I
  - Monitoring Program Development Plan
  - Modeling Plan
  - Assessment framework plan
- Relevant excerpts from those reports are included at the end of this document. The full Monitoring Program Development Plan is also included.


Steering Committee
prioritize/oversee
External Peer Review
Nutrient Technical Workgroup
advise/refine
Synthesis, Science Plan
Recommend
answers, program decisions, refine
time
Core Science Team
generate/advise
Monitoring Special Studies
Assessment Framework
Modeling
Loads

Overview of Potential Projects FY2015

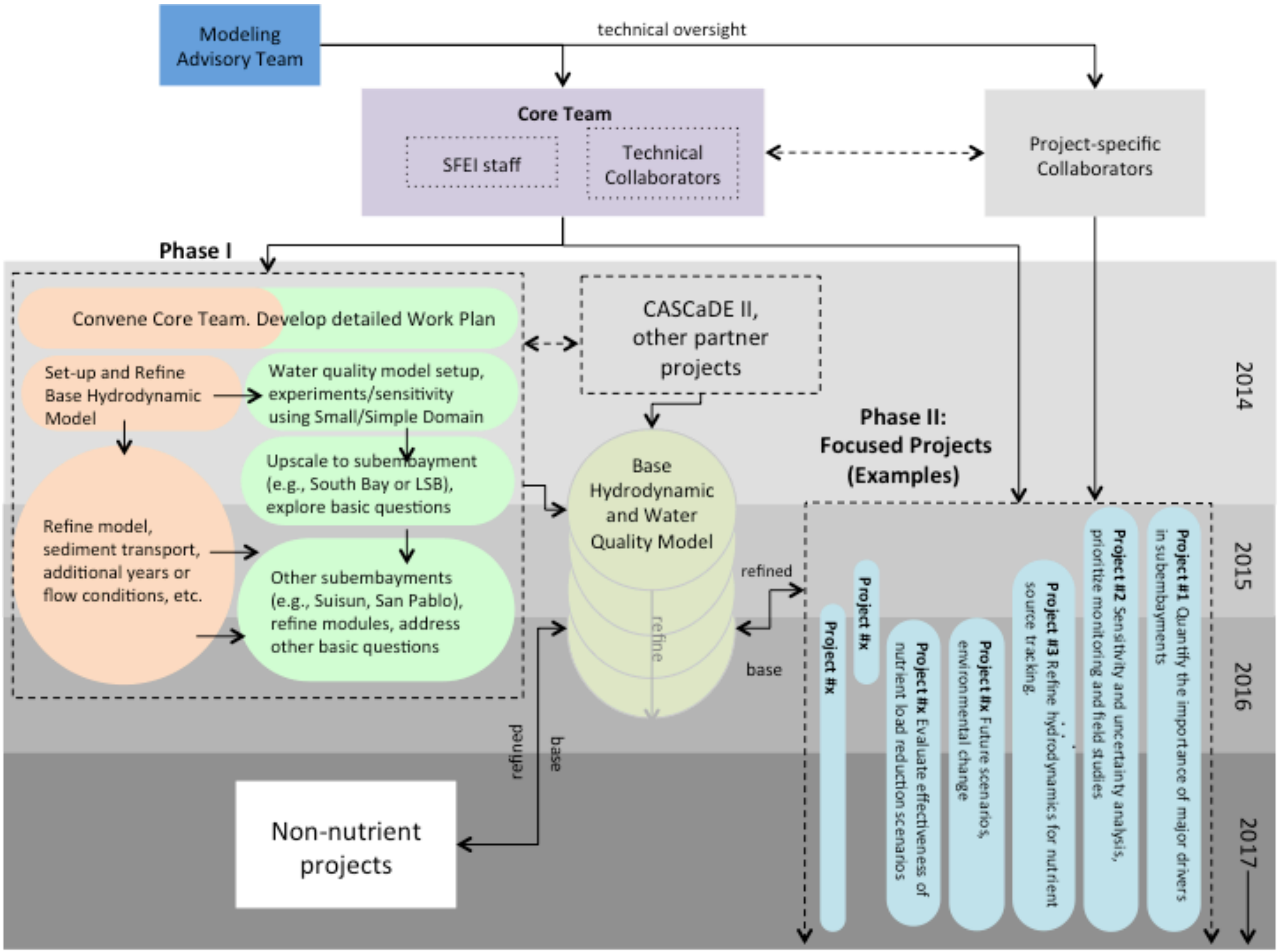
#	Project	Priority for FY2015	Estimated Cost ($1000s) FY2015	Partners/ Collaborators	
1	Modeling	High	470	SFEI, USGS-Menlo, UCBerkeley, Stanford, UCDavis, key consultants	Modeling will be a major component of most pathways and will be used in the process of informing most management decisions. There are numerous hydrodynamic models for the Bay. The focus of Year 1 of this multi-year project is on building regional capacity on water quality modeling within the context of the nutrient work. The overall plan is to collaborate with multiple experts and direct the majority of effort during year 1 toward Water Quality model development, while also investing resources toward a collaborative effort with USGS on developing the appropriate hydrodynamic model input to drive the Water Quality. Water quality focus in Year 1 will be on addressing several key questions related to ecosystem response in simplified-spatial-domain subembayment models (important questions in South/Lower South Bay and Suisun Bay), allowing us to focus more energy on understanding the complex water quality processes, biological response, and physical drivers. In addition to building a solid quantitative-conceptual foundation over that year, the project will also be gathering/building the key input files and setting up higher spatial resolution models at subembayment and whole-bay scales that will be the focus of work in Year 2 and beyond
2	Toxin measurements and phytoplankton composition	High	200	UCSantaCruz, USGS, SFEI	Measure toxin concentrations in ~300 archived water column samples collected throughout the Bay between 2011 and present. Quantify phytoplankton community composiiton using co-located pigment samples. Goals: Substantially increase our understanding about current conditions in SFB with respect to algal toxins: determine how algal toxin concentrations vary seasonally and spatially, and, at select stations, how they vary interannually; assess how toxin concentrations compare to thresholds known to adversely impact ecological health; to the extent possible, develop an improved understanding and testable hypotheses for the physical/chemical/biological factors that contribute to the occurrence of higher/lower toxin abundance. Inform monitoring program requirements for toxin measurements, including: the necessary spatial/temporal sampling resolution to adequately describe variability and to capture "events of concern"; appropriate analytical methods and optimized analytical techniques.
3	Moored sensor program development/expansion	High	340	SFEI, USGS-Sac, USGS-Menlo, SanJose	Add a 4th station in South Bay or Lower South Bay, maintenance of 4 stations, data analysis, data management and web-accessible visualization of real-time and historic data, data analysis to inform planning for future sensor stations, increased emphasis on piloting additional parameters like NO3 and potentially other nutrients (phosphate).
4	Monitoring Program development, assessment framework: Analysis of historic data, program design	High	270	SFEI, UCSantaCruz, USGS-Menlo, RTC, other technical advisors, SCCWRP	Examine the extensive historic monitoring data and other more focused data sets to explore key questions identified by technical advisors to inform monitoring program design and assessment framework development. See questions identified in Section 6.7 of monitoring program development plan
5	Stratification scenarios for DO and HABs	High	110	UCBerkeley, SFEI, SCCWRP, USGS-Menlo	Analysis of high-resolution time-series data at multiple locations, and modeling to asses under what conditions stratification could persist long enough to cause adverse impacts do to low DO or HABs. Stratification, and whether it's likely to change in frequency or duration, will be an important determinant of whether lowDO could be a problem in SouthBay and LowerSouthbay. The potential for more frequent stratification or longer stratification is also important for HAB formation.
6	Using monitoring data in conjunction with existing hydrodynamic modeling output to inform monitoring program design	Medium	110	UCBerekely, UCDavis, SFEI	What events are we actually capturing (what mix of water masses?) at current monthly stations along the Bay's longitudinal axis and at continuous moored stations? Based on hydrodynamics, what placement and frequency of stations would optimally capture important events and best explain processes, both for assessment of bay condition and for calibrating/validatin water quality models
7	DO objectives (lit review, data analysis)	High	100	SCCWRP, SFEI, technical advisors	What organisms/habitats are we aiming to protect? what levels of DO are optimal or protective? What lowDO conditions would adversely impact those habitats/organisms - DO concentration, duration of event, spatial extent, seasonality (eg., relative to critical life stages), specific habitat?
8	Dissolved Oxygen in shallow habitats	High	300	SFEI, SanJose, USGS-Sac	Focused 1-2 year field study to determine the frequency, duration, and spatial extent of lowDO in representative margin habits (sloughs, creeks) using moored sensors complemented by field sampling/calibration. Up to 6 sites, instrumentation, field work/maintenance, data interpretation

cont'd

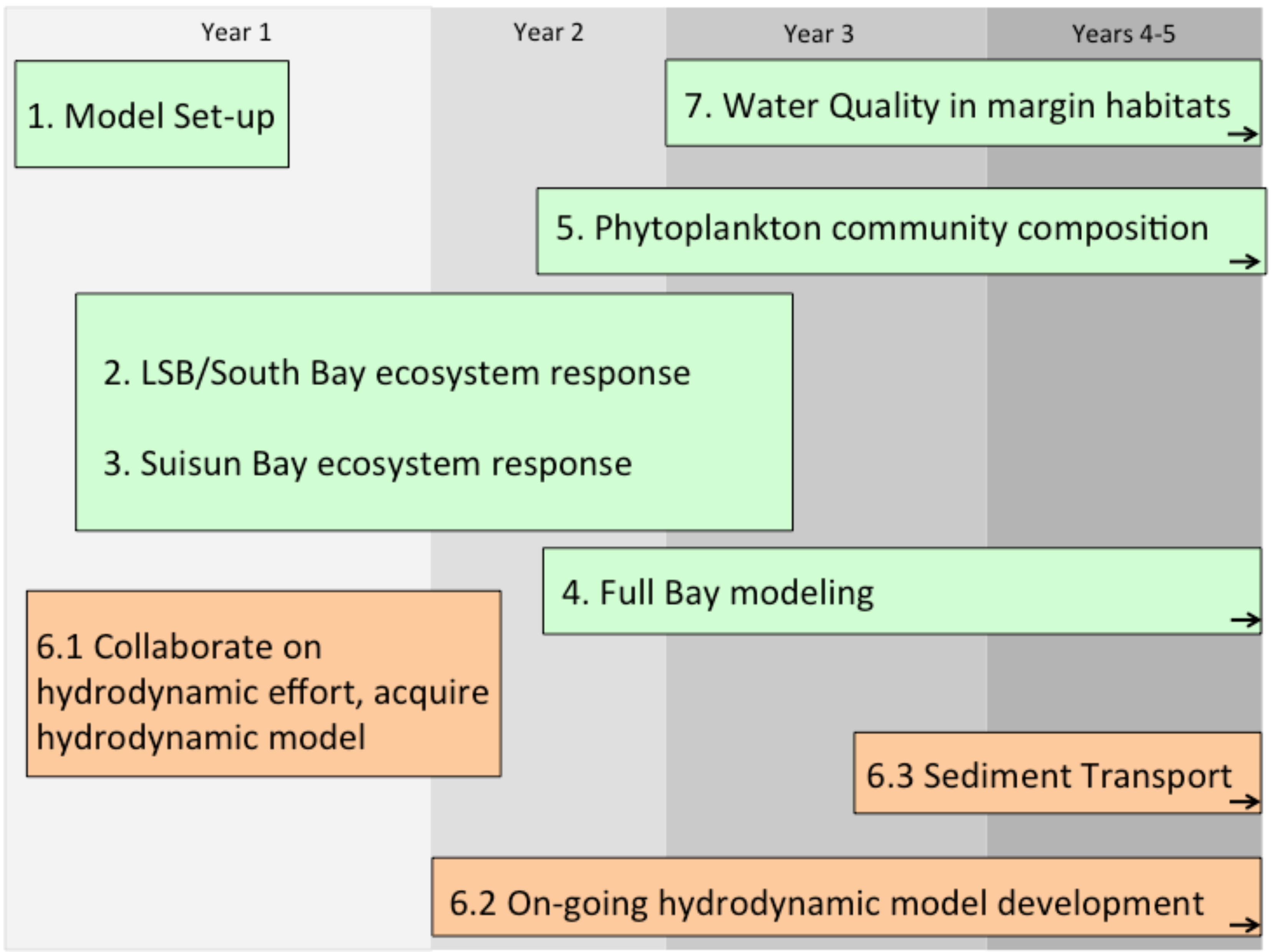
#	Project	Priority for FY2015	Estimated Cost ($1000s) FY2015	Partners/ Collaborators	
9	Additional Monitoring at current main channel stations in SFB, USGS cruises: phytoplankton taxonomy, nutrients	High	75	USGS, SFEI/RMP	Currently phytoplankton composition are collected at limited number of stations and inconsistently (only when chl-a exceeds 5ug/L)nd nutrient measurements. Similarly, nutrients are not a core part of the USGS research program and "optional"; therefore the full suite of analytes is not measured and spatial/temporal frequency is lower than is needed.
11	Suisun Phytoplankton Growth: Continuation of pure culture experiments	High	60	UCSantaCruz, AMS	Continuation/completion of PhaseI of an IEP/SFCWA funded study from 2013/2014 that is carrying field and laboratory investigations to explore the role NH4 plays in phytoplankton growth rates, using isolate pure cultures from Suisun Bay and measuring N uptake rates, growth rates, etc.
10	Contribution to shared Research Vessel Purchase, in collaboration with USGS and other potential partners	High (but may not be possible this year)	400	USGS, SFEI, multiple partners	owned/operated by USGS, ensures otherwise "free" and prioritized use of research vessel over long-term for monitoring and special studies
12	Targeted mechanistic studies of HABs, phytoplankton composition, related to nutrient concentrations, forms	Medium, recommend wait until FY2016	200	xxx	Test hypotheses of N:P, high NH4, and high NO3 on phytoplankton community, individual cell composition, etc. as one step along the path of evaluating the whether these effects are occurring, assessing their relative importance alongside other drivers. Specific project ideas and study design to be determined through Science Plan
13	Fish/benthos studies in margin habitats to inform site specific DO objectives	Medium	200	UCDavis, SCCWRP, SFEI	Targeted studies of fish, important fish prey items (zooplankton, mysids), and benthos along areas that might be considered unimpacted and potentially impacted by low DO to determine abundances, species richness, as a function of space/season, and potentially in response to fluctuating DO.
14	Sediment flux studies: Benthic oxygen demand, nutrient fluxes/transformations	Medium	250	xxx	Focus in Lower South Bay. Provide critical information that will inform conditions related to DO, and related to nutrient cycling and assimilative capacity
12	Program management/science coordination	High	200	SFEI	Science coordination across projects, coordination with Nutrient Steering Committee, regulators and stakeholders, outreach, project management, contract management
13	External Review	Medium/High	50		Convene an external advisory panel to review key aspects of program and key products (science plan, etc.), and hold a meeting with stakeholders and collaborators/experts. Work with advisory panel to summarize findings
	Total		3,335		

Modeling

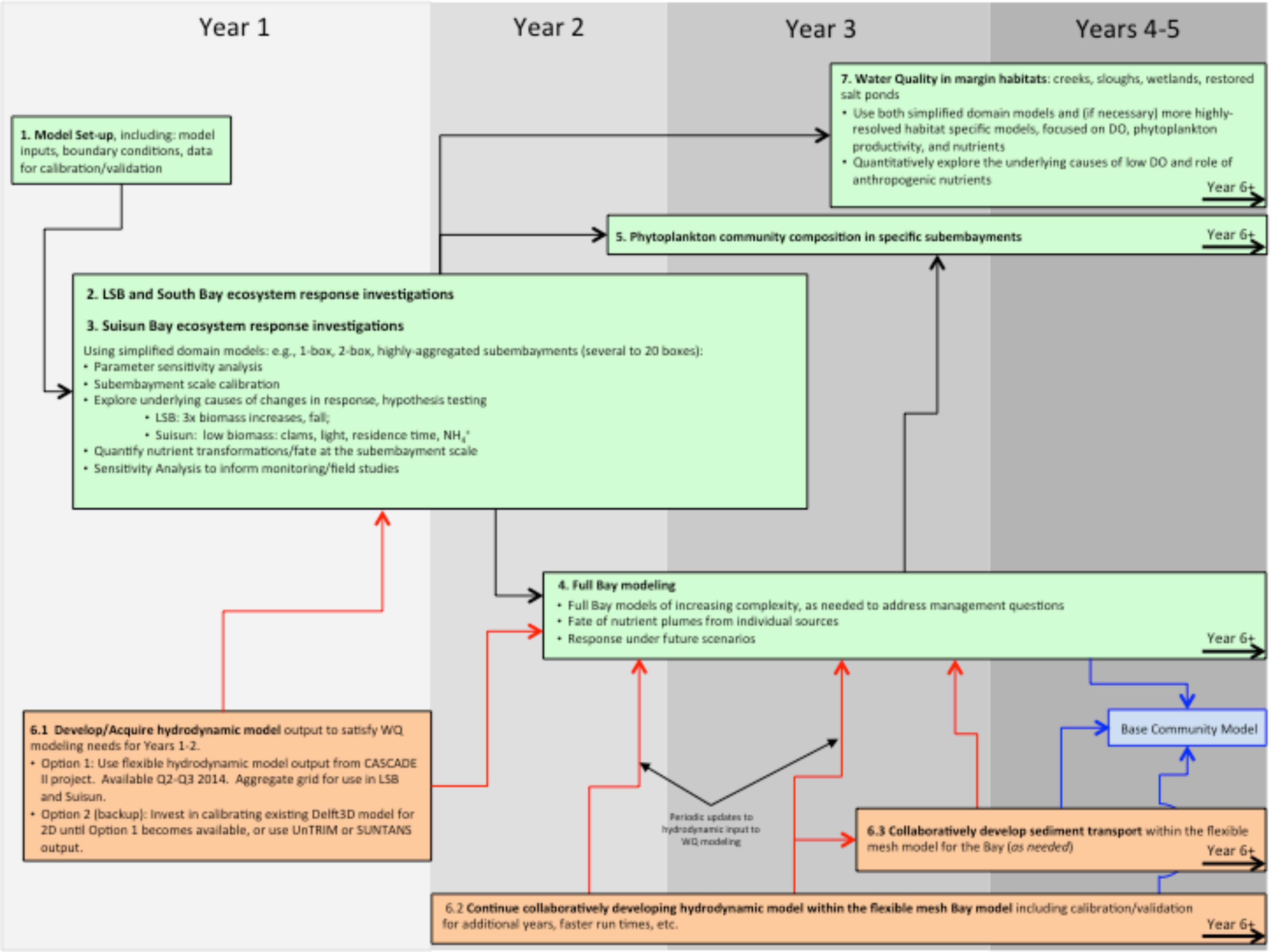
- Overall Plan for Model Development: Work Collaboratively with USGS-led CASCADE project , and in collaboration with a team of regional/national experts
- Focus bullk of nutrient resources toward water quality modeling
- Contribute to and collaborate on CASCADE's hydrodynamic and phytoplankton modeling work
- leverage CASCADE's $1.5-2mill effort and inherit their hydrodynamic/sediment/phytoplankton model



Overview of Modeling Workplan



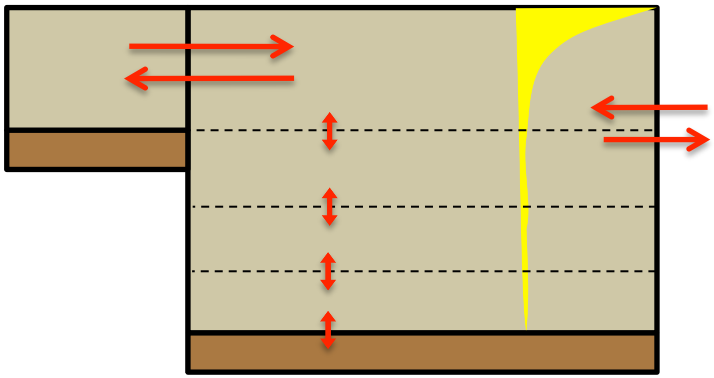
Workplan – Additional Details



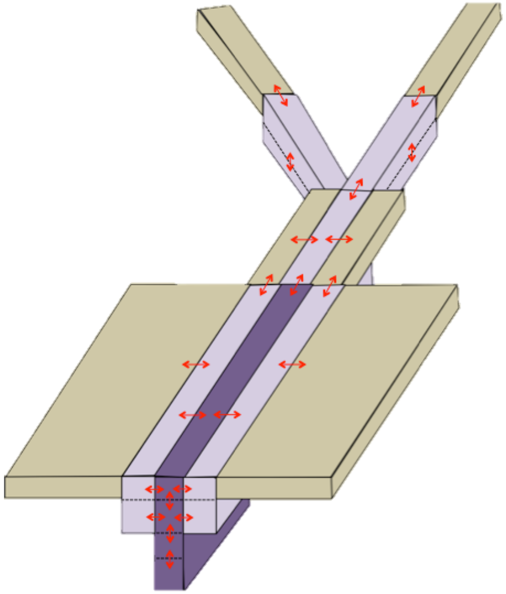
Approach: Focus bulk of effort on Water Quality modeling in a staged fashion

1. Simplified domain (Yr1)

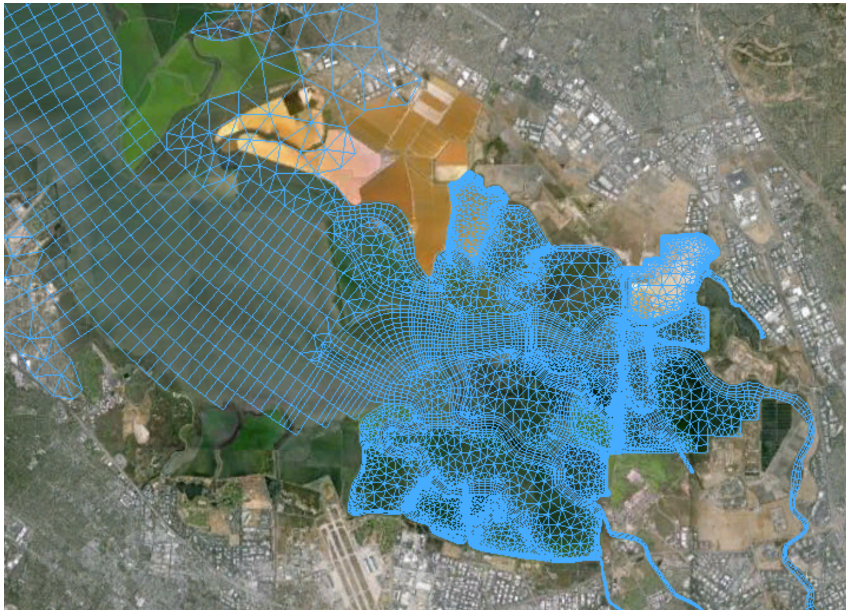
- Hypothesis testing
  - South Bay: changes in biomass
  - Suisun: light vs. clams vs. NH_4^+
- Nutrient budgets: transformations, sources, and sinks
- Parameter estimation
- Sensitivity analysis, key data needs
- Practical Matter/Efficiency: While awaiting hydrodynamic model output, develop expertise within the modeling platform while carrying out the above



2. Aggregated, subembayments (Yr 1-3)



3. Fully-resolved, Bay-wide (Yr 2-5+)



Developing a 4-yr monthly time-series of algal toxins and phytoplankton community composition in San Francisco Bay

- Substantially increase our understanding about current conditions in SFB with respect to algal toxins. Specifically:
  - Determine how algal toxin concentrations vary seasonally and spatially, and, at select stations, how they vary interannually
  - Assess how toxin concentrations compare to thresholds known to adversely impact ecological health
  - To the extent possible, develop an improved understanding and testable hypotheses for the physical/chemical/biological factors that contribute to the occurrence of higher/lower toxin abundance
- Inform monitoring program requirements for toxin measurements, including:
  - the necessary spatial/temporal sampling resolution to adequately describe variability and to capture "events of concern"
  - appropriate analytical methods (e.g., SPATT vs. individual filters) and optimized analytical techniques (e.g., can we extract/measure the relevant spectrum of toxins from a single filter?)

Developing a 4-yr monthly time-series of algal toxins and phytoplankton community composition in San Francisco Bay

- The proposed project would be a major extension of two on-going pilot studies, funded in part by RMP/Nutrients.
  - Subembayment-scale integrated toxin measurements
  - Algal pigment analysis for inferring phytoplankton community composition. A recent poster on this project is summarized on the next slide

Using algal pigments to characterize phytoplankton community composition in San Francisco Bay

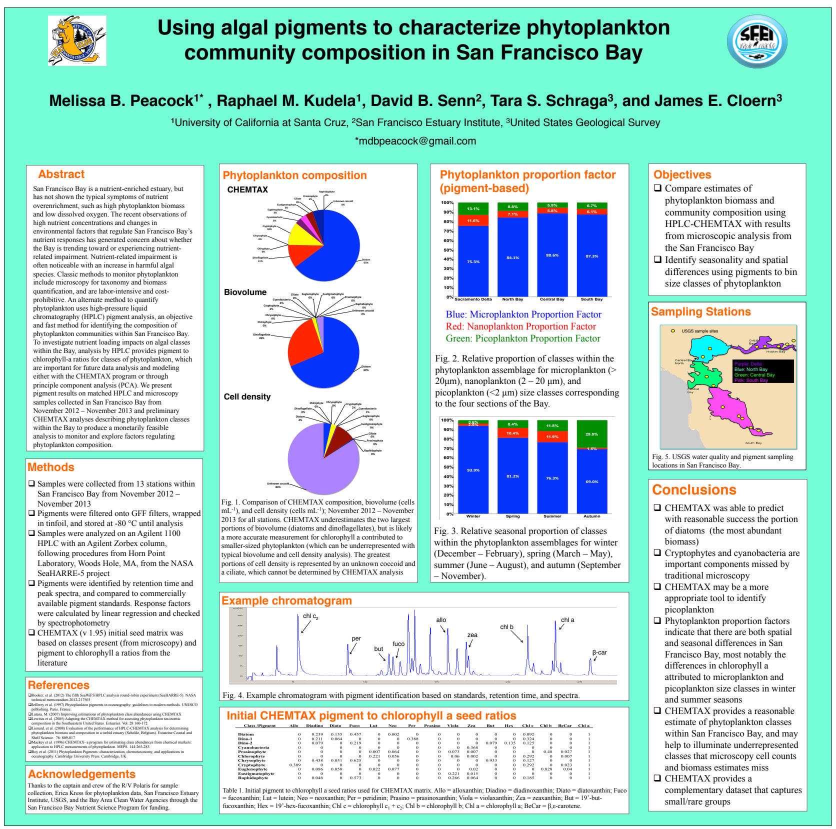
Melissa B. Peacock[1*], Raphael M. Kudela[1], David B. Senn[2], Tara S. Schraga[3], and James E. Cloern[3]

[1]University of California at Santa Cruz, [2]San Francisco Estuary Institute, [3]United States Geological Survey

Presented at ASLO Ocean Sciences Meeting, Feb 2014

Postdoc: Misty Peacock, UCSC

Co-advisors: Raphe Kudela, Dave Senn, Jim Cloern



- ~300 pigment samples analyzed
- ~200 have paired microscopy samples for composition for calibration
- Promising results
- In particular helpful for biovolume (as opposed to counts) and for detecting abundant small organisms that microscopy misses.
- 5-10x less expensive than microscopy.
- Easily paired with measurement of toxin samples

APPROACH…NOTE: This is intended as a list of possible activities. It's likely not feasible to do all this and we should decide the highest priority things to tackle.

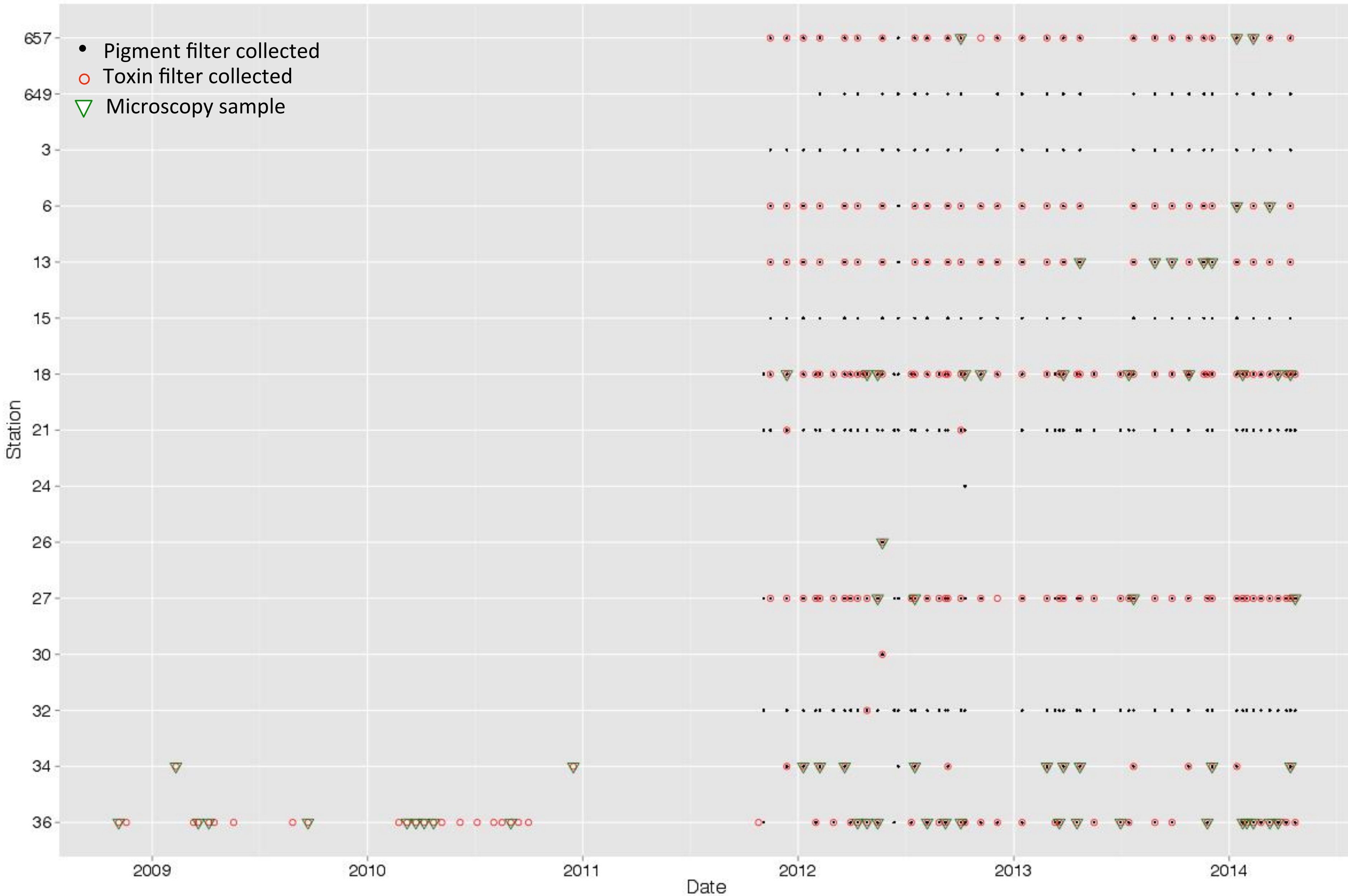
Sample Collection and Measurement

- Measure toxin concentrations in filters collected during past or on-going monitoring at existing USGS sites
  - Archived filters collected beginning in 2008, after salt ponds were breached, through Apr 2014, generally at monthly or greater frequency, at stations in Lower South Bay (60 samples)
  - Archived filters collected monthly from Nov 2011-May 2014 at one station per subembayment on a monthly basis (~240 samples, including ~40 from Lower South Bay noted in 1.a). At all of those stations, pigment filters were also collected and have been recently analyzed in 2013-2014 as part of a related project.
  - Filters collected at 10-15 stations per full-Bay cruise from June 2014-May2015 (~150 samples)
- Measure toxin concentrations in bivalve samples
  - Archived samples from Mussel-watch sites, RMP sampling, and other relevant past sampling activities (12 samples from 2012, 10-15 samples from 2014)
- As part of other planned field activities in Summer/Fall 2014, collect filter samples at 6-9 sites on a monthly basis. (2-3 sloughs, 3 sites per slough, and 1 station at the down-estuary end of Coyote Creek; Aug-Nov = 30-40 samples)
  - These samples could be collected during other fieldwork and would not require its own field campaign (moored sensor maintenance at slough stations, where we would also want/need to collect samples for chl-a calibration).
  - For any newly-collected samples, pigment samples will also be collected and analyzed.

Data Interpretation

- Interpret spatial and seasonal trends
- Discuss concentrations relative to those observed in other systems and relative to thresholds
- Explore relationships between toxin forms/concentrations and phytoplankton composition (using either microscopy or pigment results from past work)

Archived samples available for algal toxin study, along with paired pigment samples and microscopy samples.



Analysis of historic monitoring data and other existing datasets to inform: Monitoring program design, Assessment Framework development, mechanistic interpretations of ecosystem change

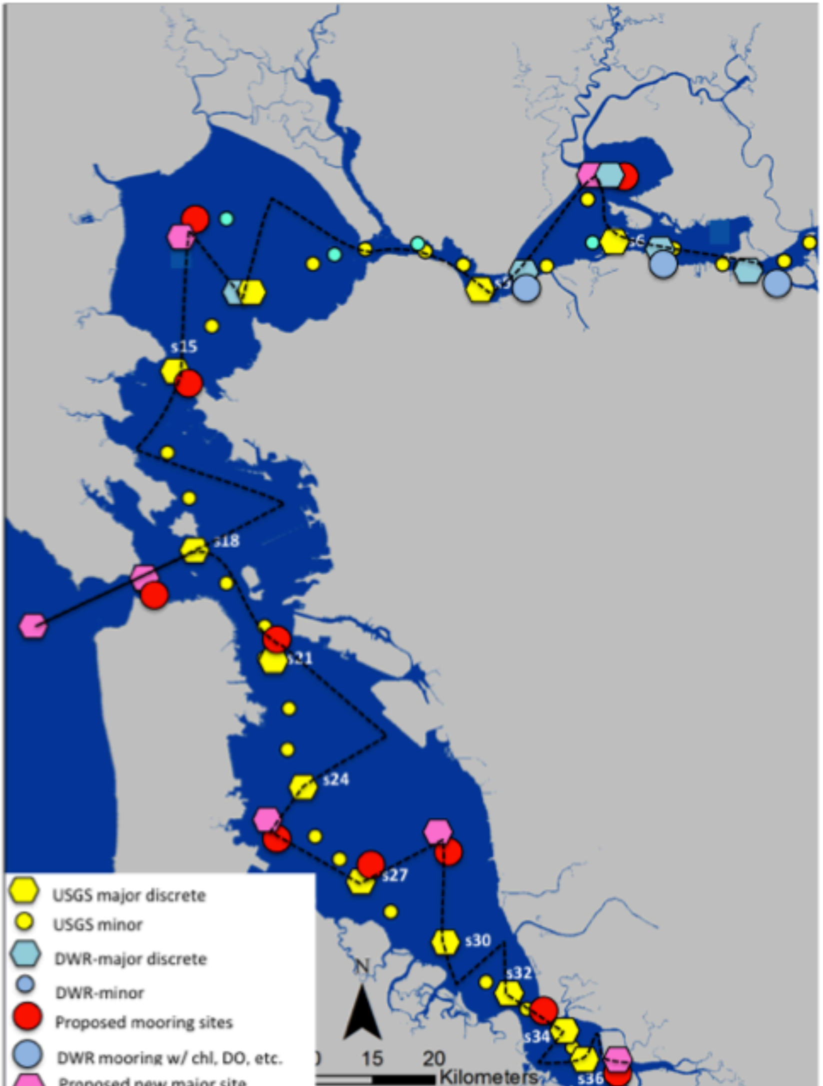


Fig 6.1: Current and hypothesized future monitoring stations for shipboard water column sampling and moored sensor sites. Dashed line illustrates an example cruise track that would allow data to be collected using flow-through system out to the shoals.

Major Questions to be investigated (see monitoring program development plan for specific information)

What is the optimal spatial/temporal resolution of sampling?

- What sampling spatial resolution is needed along the longitudinal axis of the Bay (or what density is redundant)?
- What sampling spatial resolution is needed laterally, as a function of subembayment and season?
- In South Bay, what is the minimum temporal sampling during important periods (e.g., spring blooms)?
- What are characteristic scales (space/time) of phytoplankton blooms in Suisun Bay?
- Where should moored sensors be placed? What is the optimal blend of ship-based sampling and moored sensors?

How frequently (and under what conditions) does the relationship used to estimate productivity in SFB (based on chl-a concentration and PAR, i.e., Cole and Cloern 1987) need to be validated/calibrated?

How has phytoplankton community composition in South Bay, Central Bay, and Lower South Bay changed over the past 20 years? What changes in physical, chemical, or biological drivers can explain those changes?

1. Initial nutrient monitoring recommendations

Draft Nutrient Monitoring Development Plan, March 2014

Development Plan for the San Francisco Bay Nutrient Monitoring Program

March 31, 2014

Prepared by SFEI staff and collaborators

6 Initial Recommendations

Over the subsequent 1-2 years, the overall goal for nutrient monitoring program planning is to develop and broadly vet - through expert teams, technical review, and stakeholder and regulator input - a monitoring program structure that meets the data requirements of the Nutrient Strategy's Assessment Framework and Modeling activities, as illustrated in Figure 2.1. That proposed program structure would undoubtedly include a number of the stations and parameters that are currently part of the USGS or DWR-IEP programs. The ~40-year data record provided by these programs (Table 4.1) has allowed researchers and managers to develop important insights into the mechanisms that regulate SFB's responses to nutrients and other stressors, and how those responses have changed over time. Continuing these programs will be essential for assessing current condition, trends in ecosystem response, and in assessing the effectiveness of any management actions. However, there remain several data gaps, and filling these gaps will be important for a future nutrient-driven monitoring effort (see Tables A.1-A.5). Some of these data gaps may only need to be addressed by one-time or periodic special studies, while others will result in new stations, new parameters, and new methods for data collection augmenting existing USGS and DWR-IEP programs to address specific nutrient-related data needs.

This section summarizes initial recommendations and proposes next steps for monitoring program development, informed by input to date from stakeholders and experts. We begin with a set of monitoring program recommendations from technical experts (Senn et al, 2014a). These recommendations are intended to be provisional and will not necessarily be enacted immediately. Rather, they serve as a starting place for further prioritization based on needs and guidance from the Assessment Framework and Modeling projects. We then identify investigations or special studies needed to address outstanding questions related to program structure, e.g. exact location/timing/methodologies for monitoring (see Sections 6.7, 6.8 and 7). Aside from the technical aspects of monitoring program structure, there are also remain questions around programmatic/institutional considerations, in particular the potential degree of inter-institution collaboration. Those points are discussed in Section 6.11.

6.1 Develop a monitoring program science plan

A monitoring program science plan is needed that lays out a framework for systematically evaluating the numerous data needs emerging from various aspects of the Nutrient Strategy, prioritizing among those needs, identifying the specific analytical approach for measurements, and proposing tiers of program components. Some of the prioritization may happen through other components of the Nutrient Strategy (e.g., sensitivity analysis through modeling). Other prioritization, e.g., the longitudinal spacing of monitoring stations or the balance between moored and shipboard stations, may involve data analysis carried out within monitoring program development.

This current document - including the initial recommendations for additional measurements, data analysis, and special studies below - is a first step in the process of specifying the program's essential components. Initial recommendations about essential program components discussed below are based on a combination of technical expert and stakeholder input gathered from a number of meetings over the prior few years. Fortunately, considerable data resources exist from long-term monitoring in SFB. A major component of the monitoring program design effort should include analyzing this data to inform decisions about program structure (e.g., about spatial and temporal density of sampling). Pilot studies should also be part of planning, to inform which parameters could provide important additional information and to test methods that provide less expensive approaches for essential data collection.

The recommendations presented below are based on the perceived science needs of the nutrient monitoring program. While they are individually all reasonable, non-frivolous recommendations, the combined set of recommendations may exceed available budget. In addition, all the recommendations can not be implemented simultaneously. In the science plan, the rationale for prioritizing among elements and for the phasing-in of new components can be discussed.

6.2 Maintain and augment shipboard monitoring at existing stations along SFB's deep channel

Major portions of the current shipboard water column sampling programs of USGS and DWR-IEP will be important to maintain as part of the nutrient monitoring program. Since much of the cost associated with shipboard sampling is related to boat use/maintenance, adding new parameters to already existing stations could be a relatively low-cost way to gain additional data. This subsection outlines several recommended sets of important additional data that could be collected at existing stations.

6.2.1 Additional basic water quality parameters

These parameters are relatively straightforward to measure, but nonetheless have costs associated with sample collection/processing, sample analysis, and data management.

TN and TP, and potentially TDN and TDP: Total N (TN) and total P (TP) are necessary parameters for nutrient mass balances and for modeling. Total dissolved N and total dissolved P could be considered somewhat lower priority than TN and TP, but nonetheless provide valuable information. By subtracting the relevant inorganic nutrient forms from TN and TP, estimates for total organic N and P (TON, TOP) can be obtained. Similarly, by subtracting the inorganic forms from total dissolved N and P (TDN and TDP), concentrations of dissolved organic N and P (DON, DOP) be can be obtained. In both cases, the additional effort for sample collection is trivial, and the analysis method is fairly routine.

Inorganic nutrients: Inorganic nutrient samples (primarily NO_3^-, NH_4^+, and o-PO_4) need to be collected at all major stations and analyzed with comparable methods. Inorganic nutrients have been collected consistently at DWR-IEP stations, but the USGS data has some gaps in space or time for these parameters as a result of changing research focus and limited funding. Comparing methods, detection limits, and QA/QC between USGS and DWR-IEP would be worthwhile.

Phytoplankton C, N, chl-a, size-fractionated chl-a: These parameters, and their ratios, provide important information about the physiological state of phytoplankton, the types of organisms that are making up the bulk of their biomass, and their nutrient requirements. C:chl-a can be highly variable among species and among physiological states within a species. Since chl-a is the most commonly used parameter for measuring phytoplankton biomass, knowledge of this ratio is essential for accurately translating measured chl-a into actual biomass; uncertainty associated with C:chl-a can be among the most important/sensitive uncertainties in modeling phytoplankton response. C:N is subject to similar inter-species and physiological state variability, but it varies over a narrower range than C:chl-a. Size-fractionated chl-a provides information on both the types of phytoplankton that are growing and serves as an indicator of the community's value as a food resource (phytoplankton < 5µm are generally considered lower food quality).

While the basic measurements of C, N, chl-a, and size-fractionated are chl-a are straightforward, they require additional filtering effort in the field. In addition, they are subject to some bias because some portion of the particulate organic matter will be detrital or vascular plant-derived as opposed to viable phytoplankton cells. In some cases stable C isotope rates can be used to verify whether the majority of the organic matter is derived from phytoplankton (i.e., produced within the Bay).

While this data will be valuable, it may not be needed at the same spatial or temporal frequency as other parameters.

6.2.2 Primary Production rates (e.g., ^{14}C uptake incubations)

Rates of primary productivity (PP, g C m^{-2} d^{-1}) provide important information on phytoplankton growth. When coupled with chl *a*, the relationship between phytoplankton biomass and productivity can be used to inform ecosystem models. While a number of PP rate measurements have been done in SFB, the bulk of those were completed prior to the 1990s (except a modest number completed in the past 10 years; Kimmerer et al. 2012, Parker et al. 2012). It is possible to estimate PP in SFB based on the amount of phytoplankton present (e.g., as measured by chl-a), incident light, and light attenuation as a function of depth, using a conversion factor referred to as ψ obtained experimentally via ^{14}C incubations (Cole and Cloern 1984). ψ varies depending on T and community composition; therefore, ^{14}C incubations need to be repeated to capture a range of conditions in space and time to calibrate the SFB-specific ψ, but only at low frequency because the incubations require substantial effort (e.g., quarterly or twice per year, at only several stations across a range of conditions). To inform how frequently updates/calibration-checks are needed, historic data could be analyzed to determine how sensitive ψ is to differences in T and phytoplankton community composition.

6.2.3 Phytoplankton community composition and algal toxins

Given the prevalence of HAB-forming organisms in SFB, increased frequency in *Microcystis* blooms in the northern estuary, SFB-wide detections of algal toxins, and other hypothesized shifts in phytoplankton community composition, phytoplankton community composition and related parameters need to be more systematically monitored. Currently, the USGS program only performs taxonomical analysis of phytoplankton at its main stations when phytoplankton biomass is elevated (i.e., chl-a > 5 µg L^{-1}) because of budgetary constraints. DWR-IEP sampling sites have a long phytoplankton composition record, collected independent of biomass on a monthly basis. However, the DWR-IEP counting methodology differs appreciably from that employed by USGS, and limits the comparability across the two data sets. Algal toxin samples are currently not part of routine monitoring, although samples have been collected more recently as part of pilot studies by USGS, in collaboration with UC Santa Cruz and the RMP. To date, most algal toxin measurements have been either space-integrated samples at the sub-embayment scale, or time-integrated samples at fixed stations over a the period of ~1month, using a solid phase extraction (SPE) approach that extracts a portion of toxin from the surrounding fluid. While these pilot studies have provided important results, the sampling technique limits the interpretability of the results in terms of the size or duration of a toxin plume and plume concentration, because of both the integrated nature of the technique and uncertainty in the correspondence between measured (i.e., extracted) and ambient concentrations.

The factors that regulate phytoplankton community composition and toxin production in SFB are poorly understood. Higher spatial and temporal monitoring of phytoplankton composition and toxin levels, in combination with special studies, will be needed to better understand these mechanisms and assess potential linkages to nutrients. However, determining community composition by microscopy is expensive ($175-500/sample). Pilot studies are needed to help inform which techniques, beyond microscopy, provide the most valuable and cost-effective information (see Section 6.8). The bullets below identify important data needs, but do not recommend specific techniques.

- Collect samples at multiple stations Bay-wide on at least a monthly basis, independent of phytoplankton biomass (i.e., chl-a) concentration. The major USGS historic stations, plus continuation of the DWR-IEP stations in San Pablo and Suisun Bays, can serve as a reasonable initial set of stations. Other stations, or more frequent sample collection during some times of the year, may be needed, and the exact sampling program will need to be determined by on-going data analysis. Both cell numbers and dimensions (for determining biovolume) are needed.
- Determine taxonomy in surface and bottom samples at some locations or times. Gradients in light and density can result in vertical gradients in phytoplankton. In addition, dense coastal waters can enter SFB as bottom layers and carry coastal organisms (including some potentially harmful species) into SFB where, when mixed to the surface, could take advantage of warmer waters and high nutrient concentrations.
- If data collected from both USGS and DWR-IEP are going to be used as part of the nutrient monitoring program, the approach to counting and dimensioning cells needs to be harmonized among the programs.
- Incorporate algal toxin measurements into the routine monitoring program. Current toxin monitoring is funded on a pilot basis, and needs to be sustained.

6.2.4 Zooplankton abundance/composition

Zooplankton abundance and composition serve as important indicators of food supply and quality for higher trophic levels and are also used to calculate basin-wide pelagic grazing rates. Long-term zooplankton monitoring has been carried out by DWR-IEP at several stations in Suisun Bay, one station in San Pablo Bay, and multiple stations in the Delta. However, zooplankton abundance and composition are not currently measured as part of routine monitoring in other subembayments. Monitoring for both macro- and microzooplankton may be important, because microzooplankton grazing rates may exceed those of macrozooplankton.

The actual experimental quantification of grazing rates is an additional activity, and if needed would be considered a special study, not part of routine monitoring. However, the systematic monitoring of zooplankton (species, size, and abundance) would be essential information for extrapolating lab-derived grazing rates to field-scale grazing estimates.

6.3 Expand shipboard monitoring to shoal sites

Sampling along the shoals is needed to improve understanding of phytoplankton and nutrient processes, and for model calibration. Most of the water quality data available in SFB is from stations along the deep channel. The shoals are important areas for phytoplankton and MPB production, and large lateral heterogeneities in phytoplankton biomass are common in SFB (e.g., Thompson et al., 2008, Huzzey et al. 1990). In addition, suspended particulate matter, which influences light availability and growth rates, exhibits strong lateral variability. Shoal monitoring can be accomplished both through shipboard or small boat transects, although a vessel with a shallow draft is needed. Moored sensors can also be useful for some parameters. Using autonomous underwater vehicles (AUVs) outfitted with sensors may also be a possibility. AUVs are commonly employed in research studies, and some are commercially available. The pros and cons of the different approaches need to be considered in detail, potentially including pilot studies.

To the extent that monitoring along the shoals is carried out using a fully-equipped research vessel (i.e., if a new vessel was obtained with shallow draft), the data gathered using its flow-through system during transects would be of additional value.

6.4 Utilize moored stations for continuous data collection

Data collection at higher temporal resolution for chl-a, DO, nutrients, turbidity, and other parameters is needed at multiple locations to identify the onset of events (e.g., large blooms) and to calibrate water quality models so that processes can be better understood and effects under future scenarios can be forecasted. Continuous monitoring with moored sensor systems is feasible for a wide range of water quality parameters. Techniques for some parameters are becoming increasingly well-established and reliable (e.g., salinity, T, turbidity, chl-a, DO), while others are advancing (e.g., nitrate, phosphate, ammonium, phytoplankton composition using flow-through digital imaging and flow cytometry). Moored sensor systems can also telemeter data, allowing for near real-time assessment of conditions.

Although moored sensors may address some questions better than shipboard sampling, they are not a substitute, but rather a strong complement that provides important additional information about processes operating on shorter time-scales. While there are currently multiple stations in Suisun Bay and the Delta that measure some of these parameters (e.g., DO, salinity, T, chl-a), there are only 2-3 pilot stations south of the Bay Bridge for measuring chl-a or nutrients, funded by the RMP and recently installed as part of the nutrient monitoring effort. Specific data needs include:

- High temporal resolution DO, chl-a, turbidity, and ancillary data (e.g., T, conductivity) at key sites and multiple depths (minimum of surface and bottom) along main channel
- High temporal resolution DO, chl-a, turbidity, and ancillary data at key sites along the shoals
- Additional sensors at a subset of sites may be warranted, including nitrate, phosphate, ammonium (when reliable sensors become available), phytoplankton community composition, and, if possible, algal toxins

6.5 Benthos Monitoring

Zoobenthos: Grazing by benthic filter feeders is considered to be one of the main controls on phytoplankton biomass accumulation in several subembayments. To estimate the influence of benthic grazing, and track its changes in space and time, benthic surveys are needed on a regular basis in some subembayments, i.e., Lower South Bay, South Bay, San Pablo Bay, and Suisun Bay. In recent years there has been ample zoobenthos monitoring in Suisun Bay and the Delta, and some in San Pablo Bay, although the future of that program is not known. Sampling in other subembayments has been less consistent or absent entirely. However, there are some years during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008), and some opportunistic semi-continuous sampling efforts in South Bay (in some cases, samples have been archived but not yet analyzed for biomass; J Thompson, personal communication).

Benthos monitoring could occur less frequently than water quality monitoring, e.g., three times per year (spring, summer, fall). Sorting, counting, and weighing benthos samples is time consuming and thus costly. In designing a benthos sampling program, the use of benthic cameras could be considered (alongside some traditional sample collection for calibration/validation), and be the focus of a pilot study, since its use could potentially allow for more cost-effective benthic surveys.

Microphytobenthos: Microphytobenthos (MPB) may account for a substantial fraction of primary production in some habitats of SFB, in particular along the broad intertidal mudflats of some subembayments. As such, MPB production could influence the nutrient, carbon, and oxygen cycles or budgets in those habitats. The abundance of MPB is poorly known, and some level of systemic sampling, either as part of routine monitoring or special studies, may be needed.

6.6 Provisional recommendations for station locations

Expert input was solicited on the geographic structure of the future monitoring program at a February 2014 technical team meeting related to assessment and monitoring. The group was asked: 'If you had to select stations on a map today, what is your best estimate of how the network would look?' The team generated a first-draft hypothesized structure, taking into consideration the existing USGS shipboard stations and the DWR-IEP shipboard and moored stations, based on what is known about SFB's hydrodynamics and ecosystem response, and on current (albeit incomplete) knowledge about data requirements for assessment and modeling (Fig 5.1).

Figure 6.1 illustrates the proposed program structure. The structure was intended as a hypothesis, and one that would be tested and adjusted through data analysis and pilot studies such as those identified in Sections 6.7, 6.8, and 6.10. Currently, USGS monthly cruises travel along the spine of SFB and occupy all of the yellow stations. At the minor stations, an instrument package (CTD, DO, chl-a, turbidity, PAR, etc.) is lowered through the water column and a profile of data is collected, but no discrete samples are collected. At the major stations, the instrument package is lowered and discrete samples are collected for multiple analytes. The hypothesized new structure would include all the USGS major stations, and augment those with up to 7 new stations, 5 of which are along the shoals and 2 of which would provide a clearer picture of water quality at stations more influenced by the coastal ocean. Some of the USGS minor stations might not be essential components of the nutrient monitoring program, in particular if the cruise track (dashed line) follows a zig-zag pattern in order to perform underway measurements along the shoals. Up to 10 moored stations were also included, with most of those in regions that currently have few or no nutrient-related sensors. Co-locating new major shipboard monitoring sites with these moored sensor sites would maximize the value of sensor servicing trips. In setting this station distribution, it was assumed that DWR-IEP shipboard and moored stations would continue, and that the data collected at those sites could be used as part of the nutrient monitoring program. As discussed above, for that to be the case, methods would need to be harmonized across the programs.

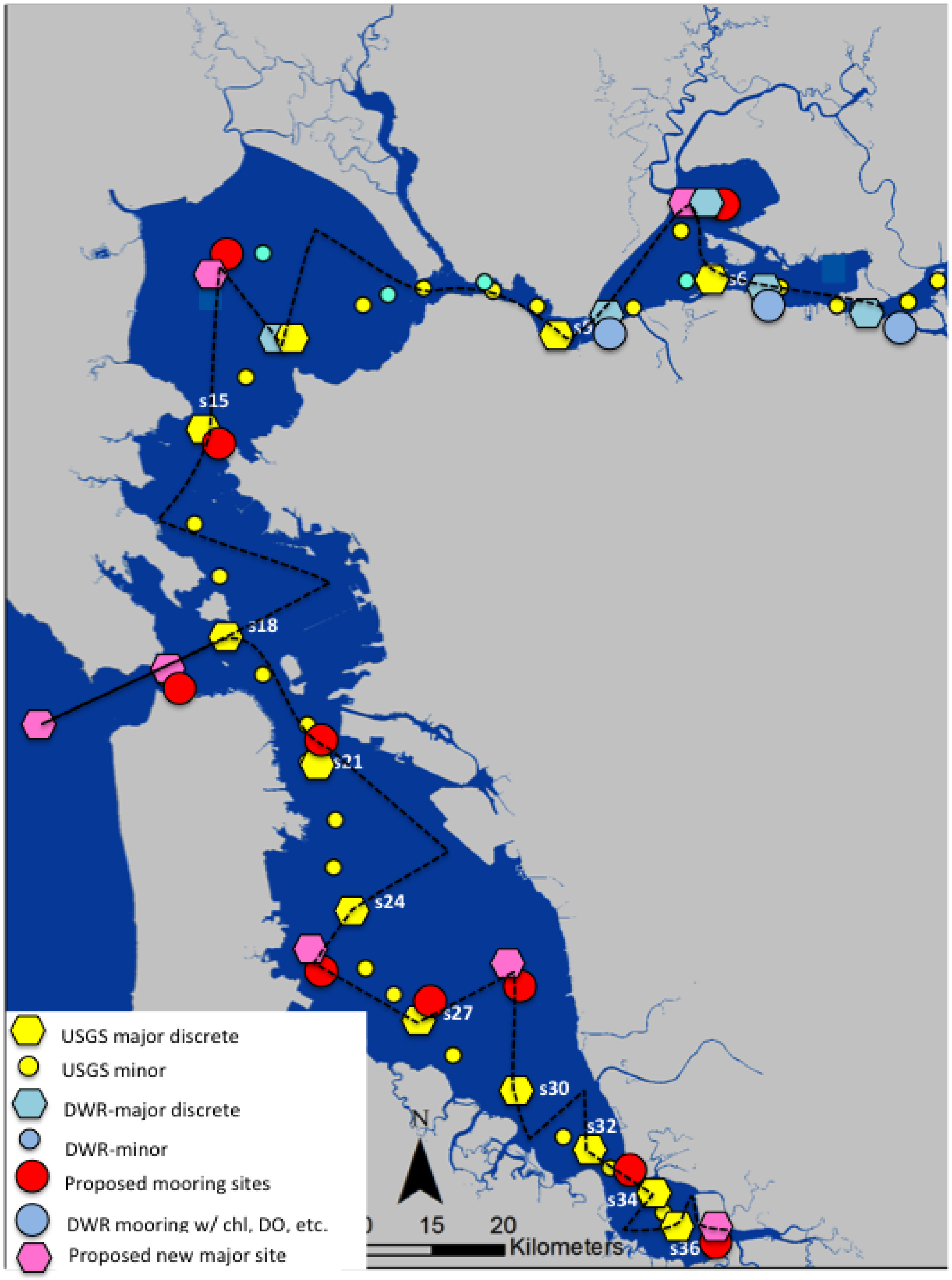


Fig 6.1: Current and hypothesized future monitoring stations for shipboard water column sampling and moored sensor sites. Dashed line illustrates an example cruise track that would allow data to be collected using flow-through system out to the shoals.

6.7 Recommended Data Analysis to inform Program Structure

This section identifies recommended data analysis activities that could be pursued in the near term to inform nutrient monitoring program structure.

6.7.1 Identifying spatial/temporal resolution of priority "events"

One major requirement of the nutrient monitoring program is that it assess condition based on parameters determined to be key indicators of ecosystem health (e.g., chl-a, DO, phytoplankton community composition, algal toxins) and determine when conditions are meeting standards and when they are below standards. The program's spatial and temporal sampling frequency must be sufficient to detect an "event" during which standards are not met. Exactly what constitutes an event will be informed by both science and policy, and will be developed through the Nutrient Strategy's Assessment Framework. The questions below are intended to help frame the discussion from the science side, inform the data requirements, and illustrate the close relationship between the monitoring program and assessment framework. While the assessment-related issues will have a strong influence over the monitoring program, it should be noted that they are not the only requirements.

6.7.1.1 What level of production/chl-a would lead to DO-related adverse impacts?

Measurements to date indicate that SFB does not experience low DO in subtidal, open water areas. Thus, unlike in some other estuaries, it is not possible to draw inferences from periods of low DO and antecedent phytoplankton biomass. Instead, it is recommended that basic estimates be made about the magnitude of a potential bloom (concentration of chl-a, area and depth of the bloom), that, when it settles into a bottom layer of the water column, could result in DO consumption down to levels that could have adverse impacts. Initial calculations could be quite basic (e.g., 1-2 box mass balance) to determine under what conditions a problem is feasible. If warranted, additional layers of complexity could be added to these calculations (up to a coupled hydrodynamic/water quality model).

In the end, these calculations would reveal the concentration and spatial extent of a bloom that could cause low DO to develop, which would inform the spatial and temporal resolution of monitoring that would be needed to detect such a bloom.

6.7.1.2 What duration/severity/frequency of low dissolved oxygen would adversely impact biota?

The answer to this question would provide information about the spatial and temporal frequency of DO sampling needed to identify a problematic low DO event. In addition, the answer would also inform calculations in 6.7.1.1. Experiments are not needed to begin address this question. There is sufficient information available in the scientific literature about effect-levels of low DO; instead, the DO standards can be specified based on the DO requirements of the organism(s) one is aiming to protect.

6.7.1.3 What levels of toxin concentration are problematic? How do these translate into spatial, concentration, and duration scales?

This question is similar to 6.7.1.2 in that it requires identifying the toxicity thresholds for organisms of concern, and working backward (including factors such as bio-concentration in the food web) to ambient concentrations and necessary spatial extent in the water column that would result in exceedence of those thresholds.

6.7.2 Optimizing spatial/temporal resolution of sampling

6.7.2.1 What sampling spatial resolution is needed along the longitudinal axis of the Bay (or what density is redundant)?

To explore this question, USGS data collected over the past 10-20 years at stations along SFB's deep channel, and flow-through underway data between these stations, can be analyzed to identify the degree of similarity/dissimilarity among stations, and identify the optimal placement of stations. The analysis can be performed for individual parameters and for multiple parameters simultaneously. A similar analysis was done by Jassby et al. (1997), but that work did not include nutrient parameters, and did not capture changes in biomass and other parameters that became evident beginning in the late 1990s. DWR-IEP data may also be relevant for this type of calculation for San Pablo Bay, Suisun Bay, and Delta.

Once the calibration/validation of the SFB biogeochemical model is complete, we could perform simulations to inform the suitability of the placement of stations, particularly for potential future conditions or parameters not historically monitored.

6.7.2.2 What sampling spatial resolution is needed laterally, as a function of subembayment and season?

Less lateral data exists than longitudinal data in SFB. However, there are several datasets that can be used to explore this question, notably 1 year of monthly continuous lateral transects collected in 1980 by USGS for the full Bay. Additional lateral data collected by the USGS is available for periods in the 1990s. Underway data is also available from multiple spring, summer, and fall sampling campaigns in San Pablo Bay and Suisun Bay by SFSU-RTC researchers aboard *R/V Questuary*. As noted above, model output could also be used to explore these questions, once that output data becomes available.

6.7.2.3 In South Bay, what is the minimum temporal sampling during important periods (e.g., spring blooms)?

During spring months, USGS typically samples on a weekly basis in South Bay to capture bloom events. This data could be analyzed to determine if similar observations would have been made if sampling had occurred at lower frequency (e.g., monthly, or every two weeks). The year 1982 could be a particularly interesting period because of weekly sampling in the deep channel plus sampling in shallow areas.

6.7.2.4 What are characteristic scales (space/time) of phytoplankton blooms in Suisun Bay?

To explore this issue, underway data from SFSU-RTC spring and fall sampling campaigns aboard the *R/V Questuary* could be used. Data from DWR-IEP moored sensors (outfitted with chl-a fluorometers) in Suisun Bay could also be used.

6.7.2.5 What spatial and temporal scales are integrated by measurements made at current monitoring stations? What spatial distribution of stations would maximize our ability to capture events (e.g., a bloom of certain magnitude, or a plume of algal toxin) or efficiently capture as much variance in condition as possible?

Monitoring at current stations in SFB does not measure conditions in a static water volume at those locations. Instead, the water volumes at those stations are actually changing mixtures of water that originated from multiple locations. In that sense, measurements made at monitoring stations throughout SFB are actually integrated biogeochemical signals from a range of locations. To explore this range, existing hydrodynamic model output data could be used to "backtrack", and identify which water masses contributed to the observed concentrations on a particular date when measurements were taken. In addition, by running such a model forward again, it would be possible to determine where sampling stations would need to be placed to capture events of specified magnitudes.

6.7.2.6 Where should moored sensors be placed? What is the optimal blend of ship-based sampling and moored sensors?

Moored sensors provide high-frequency data at a single point in space, and this location should appropriate for identifying problematic events in SFB (section 6.7.1) and, in combination with shipboard sampling, should capture the greatest ecosystem variability. While some aspects may be answered through analysis of existing data, the use of model output combined with monitoring data may be most informative.

6.7.2.7 What parameters are most important to measure in terms of their quantitative influence on predictions or model interpretations?

Sensitivity analysis of water quality parameters need to be performed using water quality models. The results of these analyses will help prioritize which parameters are more important to monitor for model development.

6.7.2.8 How frequently (and under what conditions) does the relationship used to estimate productivity in SFB (based on chl-a concentration and PAR, i.e., Cole and Cloern 1987) need to be validated/calibrated?

This relationship, while often assumed to be a constant, may actually be sensitive to changes in phytoplankton community composition, temperature, light intensity, and potentially other factors. There is ample data from a number of studies within different subembayments and the Delta that could be used to explore these sensitivities and inform calibration procedures.

6.8 Pilot studies

Pilot studies should be carried out throughout the program development period to identify the best techniques

6.8.1.1 What combination of techniques represents the best approach to measuring phytoplankton community composition for the needs of SFB?

Currently, a pigment-based approach is being piloted (CHEMTAX), with results being compared to samples analyzed by microscopy for method validation. In addition, a grant proposal was recently submitted to obtain 2 Imaging Flow Cytobots. If the proposal is successful, one of these instruments would be deployed aboard the USGS research vessel and used while underway to measure phytoplankton composition at high frequency. The second instrument would be deployed at a moored station, for example, at Dumbarton Bridge (Lower South Bay).

6.8.1.2 What approaches and spatial/temporal resolution are needed for measuring algal toxins?

Pilot studies are currently underway that employ solid-phase extraction to obtain subembayment-scale integrated measures of toxin. This technique is attractive in that it provides an integrated impression of toxin abundance. However, the correspondence of these measurements to ambient concentrations remains highly uncertain. In addition, the subembayment-scale measurements do not provide sufficient spatial resolution to identify localized toxin plumes. This limitation could be addressed through doing finer-scale integrated samples.

As part of another pilot project, USGS collected filter samples for toxin measurements, co-located with phytoplankton composition sample collection (both pigments and microscopy). There are currently ~2 years of monthly samples collected at ~10 or more stations per cruise, amounting to 200-250 samples. Analyzing these samples will provide high-spatial resolution toxin concentration along with the dominant phytoplankton communities, and will provide valuable information about both the spatial resolution of toxin plumes and factors that may explain their varying levels. In addition, it will provide a valuable complement to the spatially-integrated samples, and allow for consideration of what spatial aggregation is appropriate for this indicator.

6.8.1.3 Deploy pilot moored stations

The goal of this set of pilot studies is to inform where to best place sensors, and to begin developing the maintenance program and local-knowledge for sensor maintenance and data interpretation. Work on this topic is underway, with 3 stations deployed in South Bay and Lower South Bay, and needs to continue for another 2-3 years.

6.9 Coordinated monitoring needed in shallow margin habitats, including sloughs, creeks, and wetlands.

Some agencies (e.g., stormwater, wastewater) carry out monitoring in shallow habitats, and several studies have been conducted in Lower South Bay systems (Thebault et al. 2008, Shellenbarger 2008, Topping 2009). However, there is currently no Bay-wide systematic approach to monitoring in shallow marsh habitats. Data collection on productivity and DO concentrations in select systems may help inform whether impairment is occurring in these systems due to low DO, and to help ascertain the causes of any impairment. Before embarking on this effort, it may be helpful to examine existing data from current or recent studies (e.g., studies in LSB) to assess the need for monitoring and identify the best approaches to pursue.

6.10 Allocate sufficient funding for data interpretation and synthesis

Data analysis and data synthesis are essential components of a monitoring program. Allocating sufficient funds for these activities will allow field results to be efficiently translated into management-relevant observations that inform decisions, and allow the monitoring program to nimbly evolve to address emerging data requirements. Annual reports will be needed that not only compile and present data, but that also evaluate and interpret trends. More detailed special studies will also be needed periodically to generate scientific synthesis reports on complex data sets (e.g., spatial and seasonal trends in phytoplankton community composition).

6.11 Broad considerations about ecosystem change

During discussions of monitoring needs with technical advisors, four so-called "Grand Challenges" related to understanding and managing SFB ecosystem health were identified. These Grand Challenges represent a somewhat different perspective or framework for considering science and data collection needs than the considerations already outlined in this report. In so doing they highlight connections between nutrient issues and other ecosystem health concerns, and provide an additional impetus for addressing those data collection needs.

6.11.1 Grand Challenge #1:

What do we need to know in 10-20 years to make improved decisions water quality management or ecosystem health issues, including those related to nutrients?

1-2 decades is approximately the time scale over which large capital improvement projects are planned and implemented. 1-2 decades 10-20 years is also a long enough time period for trends to become evident, e.g., the changes in phytoplankton biomass in South Bay and LSB since the late 1990s.

What information needs to be collected now, to serve as baseline condition data, so that changes in important indicators can be confidently identified and attributed to the correct causal agent(s), whether those changes show improved or worsened condition?

6.11.2 Grand Challenge #2

The northern estuary is poised to experience major changes due to management actions and environmental change. Anticipated changes include:

- Nitrification of effluent combined with N removal at Sacramento Regional County Sanitation District wastewater treatment plant, which will change both the form of N and total N concentrations discharged
- Numerous large scale restoration projects in the Delta
- Changes in water withdrawals and flow routing
- Changing climate patterns altering the timing, residence time, and amount of water passing through the Delta.

What do we need to be measuring now in order to determine if these changes have positive, negative, or no impacts on ecological health in SFB and the Delta? How will phytoplankton respond to changes in nutrient loads/speciation? How will the food web respond?

6.11.3 Grand Challenge #3

Large areas along the margins of South Bay and LSB are slated to undergo restoration. Given the size of these areas compared to the adjacent water surface area (Figure 5.1), it is reasonable to expect that effects will extend to the open water. Some of these effects may be positive, including increased habitat for fish, birds and other organisms. It will be desirable to document those changes; in order to do so, baseline data is needed for indicators of ecosystem health. Those changes may also encourage much higher rates of denitrification, which should be considered as part of an integrated nutrient management plan.

As discussed earlier, there may also be unintended and undesirable consequences of this restoration, including salt ponds acting incubators for HAB-forming phytoplankton species, exceedingly high primary production and low DO environments in light-rich, long-residence time habitats, and increased duration of stratification due to dampening of tidal mixing energy. What hypotheses of adverse impacts need to be tested so that the risks of severe unintended consequences are minimized?

6.11.4 Grand Challenge #4

While the exact ways that climate change will manifest itself in SFB habitats are unknown, the scientific consensus is that some of those changes have already started arriving, and that combinations of others are on the way. Changes to multiple climate-related drivers are feasible, and the combined effects are uncertain. Similar to Grand Challenges 1-3, what baseline observational data is needed in order to see these changes and disentangle them from other anthropogenic drivers? What types of modeling simulations should be done to anticipate effects?

The CASCaDE II project is exploring these issues, largely focused in the Delta.[1] Similar approaches may be worth considering for the Bay.

6.12 Program management considerations

Implementing a regional nutrient monitoring program will be a major undertaking in terms of logistics and cost. Long-term institutional support will be needed. As discussed above, there are several entities currently involved in ship-based and continuous (moored sensors) monitoring (e.g., USGS, DWR-IEP). To avoid unnecessary duplication of effort and maximize what can be accomplished with available resources, when developing the future nutrient monitoring program there will likely be considerable advantage to fostering close coordination among on-going programs toward achieving some of the monitoring program goals, and augmenting those efforts with additional monitoring as needed. In addition to broad institutional cooperation, there needs to be coordination at the level of sampling and analytical methodologies, data QA/QC, data sharing, synthesis, and reporting.

Along these lines, in the relatively near term (next 1-3 years), the USGS plans to replace its research vessel. The purchase of a new vessel represents an interesting opportunity for collaboration and joint funding between regional entities and the USGS. Based on initial estimates, it may also prove a wise investment on the part of the region, and a highly cost-effective way of ensuring ship access and sustaining the underlying program upon which the nutrient monitoring program will likely be built.

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[1] http://cascade.wr.usgs.gov/

2. Recommendations for addressing priority knowledge gaps about nutrients in SF Bay

Scientific Foundation for a San Francisco Bay Nutrient Strategy, April 2013

Scientific Foundation for a San Francisco Bay Nutrient Strategy

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12.2 Recommendations for Addressing Priority Knowledge Gaps

Section 12.2.1 provides an overview of the recommended highest priority work efforts over the next 1-5 years to address knowledge gaps and inform nutrient management decisions in SFB. The process we followed (outlined in Figure 1.1) consisted of

- Identifying the highest priority scenarios (Section 11, and Tables 11.3-11.5) for potential impairment along one or more pathways, and the outstanding science questions that need to be addressed related to those scenarios;
- Prioritizing data or knowledge gaps related to key processes that control ecosystem response to nutrients along the pathways of the near-term highest priority scenarios, developed within conceptual module descriptions in Sections 6-10 and identified in Tables 6.1, 7.1, 8.1, and 9.1.

Recommendations presented in Section 12.2.1 are organized around several major themes or types of work. Not all high priority data gaps are discussed below, and the reader is also referred to Tables 6.1, 7.1, 8.1, and 9.1 and Tables 11.3-11.5. Section 12.2.2 takes a broader view, and describes knowledge gaps and data needs in terms of a set of ecological and management challenges that lie ahead.

12.2.1 Recommendations

R.1 Develop a regionally-administered and sustainably-funded nutrient monitoring program

On-going monitoring efforts include the USGS research program[1] and the IEP Environmental Monitoring Program (Figure 5.3).[2] The data generated through these programs, and the related discoveries, form much of the foundation for current understanding of SFB's response to nutrients. However, the focus and mandates of these programs are not necessarily aligned with those of a nutrient monitoring program to inform management decisions. Furthermore, future funding of the USGS program is highly uncertain.

Developing a regionally-administered and sustainably-funded nutrient monitoring program needs to be a major priority over the next 1-2 years. Effort needs to be directed toward both developing the institutional and funding framework and the scientific program. Several initial recommendations are presented below.

R.1.1 Program development

R.1.1.1 Develop institutional and funding agreements

Developing and implementing a regional nutrient monitoring program will be a major undertaking in terms of logistics and cost, and long-term institutional support will be needed. There are several entities currently involved in ship-based and continuous (moored sensors) monitoring (e.g., USGS, IEP, CA Department of Water Resources, CA Department of Fish and Game). To avoid unnecessary duplication of effort and maximize resources, when developing the future nutrient monitoring program there may considerable advantage to achieving some monitoring program goals through fostering close coordination among on-going programs, and

[1] http://sfbay.wr.usgs.gov/access/wqdata/

[2] http://www.water.ca.gov/iep/activities/emp.cfm

augmenting those efforts with additional monitoring. The efforts need to be well-coordinated, in particular in terms of methods, data QA/QC, and data sharing, synthesis, and reporting.

R.1.1.2 Develop monitoring program science plan: management questions, goals, priorities, and approaches

A monitoring program science plan needs to be developed that lays out the management questions, and the program's goals and priorities relative to those management questions. Detailed plans for achieving those goals also need to be developed. A number of the future nutrient monitoring program's specific goals and data needs of the future may differ considerably from those of the current research and monitoring activities. When evaluating future program's needs relative to current efforts, particular attention needs to be given to the following issues:

- The necessary degree of emphasis among broad monitoring categories for monitoring (water column, benthos, physical/hydrodynamic, biological, chemical)
- Key parameters or processes to be measured within these categories;
- Spatial and temporal resolution of sampling; and
- The distribution of monitoring effort between ship-based sampling and moored sensors for continuous monitoring.

For some of these issues, considerable data resources exist from long-term monitoring in SFB. a major component of the monitoring program design effort should include analyzing this data to inform decisions (e.g., about spatial and temporal density of sampling). Pilot studies should also be part of planning, to inform which parameters provide important additional information (e.g., should TN and TP be measured?), test methods that provide less expensive approaches for essential data collection, and select moored sensor sites and parameters.

R.1.2. Initial monitoring program science recommendations

Several clear monitoring program recommendations emerged through developing the conceptual modules, and identifying data/conceptual gaps in light of the priority impairment scenarios (Tables 6.1, 7.1, 8.1, and 9.1). They are described briefly below.

R.1.2.1 Continue shipped-based monitoring along SFB's deep channel

The long-term record provided by the USGS research program has yielded insights into the mechanisms of SFB's response to nutrients and other stressors, and how the response (and the underlying stressors) have changed over time. Continuing this program will be critical for anticipating future changes, and in assessing the effectiveness of any management actions. Adding new parameters may be highly informative, such as size-fractionated chl-a and C:chl-a, as well as others noted below.

R.1.2.2 Develop a moored sensor sub-program for high temporal resolution data

Data collection at higher temporal resolution for chl-a, DO, nutrients, turbidity, and other parameters is needed at multiple locations to identify the onset of events (e.g., large blooms) and to: improve understanding about the processes that influence phytoplankton blooms; assess oxygen budgets; and quantify nutrient fate. High temporal resolution data will also be essential for accurately calibrating water quality models. Continuous monitoring with moored sensor systems is feasible for a wide range of water quality parameters. Techniques for some parameters are becoming increasingly well-established and reliable (e.g., salinity, T, turbidity, chl-a, DO, and more recently nitrate), while others are advancing (e.g., phosphate, ammonium, phytoplankton composition using flow-through digital imaging). Moored sensor systems can telemeter data, allowing for near real-time assessment of conditions.

Although moored sensors may address some questions better than ship-based sampling, they are not a substitute for ship-based sampling, but rather a strong complement that provides important additional information about processes operating on shorter time-scales. While there are currently multiple stations in Suisun Bay and the Delta that measure some of these parameters (e.g., DO, salinity, T, chl-a), there are no stations south of the Bay Bridge for measuring chl-a or nutrients.

R.1.2.3 In addition to monitoring along the channel, monitoring is needed in shoal environments, including lateral transects

Sampling along the shoals is needed for improved understanding of phytoplankton and nutrient processes, and for model calibration. Most of the water quality data available in SFB is from stations along the deep channel. The shoals are important areas for phytoplankton and MPB production, and large lateral heterogeneities in phytoplankton biomass (and SPM, which influences light availability and growth rates) are common in SFB (Thompson et al., 2008; Cloern, 1995). In addition, a substantial proportion of nutrient transformations likely take place along the shoals (benthic nitrification and denitrification). Shoal monitoring can be accomplished both through ship-based transects or using moored sensors, and the best approach will vary depending on the question being addressed. Using autonomous underwater vehicles (AUVs) outfitted with sensors may also be a possibility. AUVs are commonly employed in research studies, and some AUV-sensor systems are already commercially-available. Pilot studies that test the utility of AUVs would useful to assess feasibility and cost effectiveness, and to inform planning.

R.1.2.4 Coordinated monitoring in shallow subtidal habitats.

Some agencies (e.g., stormwater, wastewater) carry out monitoring in shallow habitats, and several studies have been conducted in Lower South Bay systems (Thebault et al., 2008; Shellenbarger et al. 2008; Topping et al., 2009). However, there is currently no Bay-wide systematic approach to monitoring in shallow subtidal habitats. Data collection on productivity and DO concentrations in select systems may help inform whether impairment is occurring in these systems due to low DO, and to help ascertain the causes of any impairment. Before embarking on this effort, it may be helpful to examine existing data from current or recent studies (e.g., studies in LSB) to assess the need for monitoring and identify the best approaches to pursue.

R.1.2.5 Increased focus on phytoplankton community composition, including HAB/NAB-forming species, and algal toxins

Given the prevalence of HAB-forming organisms in the Bay, the dramatic increase in blooms of *Microcystis*, and other hypothesized nutrient-related shifts in phytoplankton community composition, it would be prudent to more closely monitor phytoplankton composition, occurrence of HAB-forming organisms, and algal toxins within San Francisco Bay.

The relative importance of factors that regulate phytoplankton community composition in SFB are poorly understood, in particular those that may shift assemblages toward compositions that inadequately support food webs. More frequent (in space and time) analysis of phytoplankton composition, in combination with special studies, (see Recommendation 4.1) will be needed to better understand these mechanisms and assess potential linkages to nutrients. Determining taxonomy and biomass by microscopy is expensive and time consuming, which limits the amount of data that can be collected. Some amount of manual microscopy ground-truthing will always be needed. However, other techniques, in combination with microscopy, may allow for increased data collection of at lower costs.

Carrying out pilot studies will help inform which techniques provide valuable and cost-effective information. Measuring phytoplankton-derived pigments is one such approach. Different classes of phytoplankton have distinct pigment fingerprints. It is possible, with sufficient calibration (relative to microscopy) and training of software to quantify phytoplankton biomass within specific classes

Digital imaging tools are also available. These systems, which are essentially flow-through microscopes with digital cameras, can be deployed at moored stations for continuous monitoring, used on a monitoring vessel as it cruises along a transect, or used in the laboratory. After "training" the software, the system can continuously sample the water column, count individual cells, and enumerate species. Moored applications can telemeter data, allowing for near real-time information. One such system provided early warning of a toxic algal bloom in the Gulf of Mexico.[3] An additional advantage of digital imaging approaches is that an archive of phytoplankton image data would be developed: if a phytoplankton species eventually becomes important, the digital archive could be mined to determine when that species first appeared.

Pilot projects have begun to measure algal toxins in SFB (Figure 3.8). Continuation of similar pilot studies, and testing a variety of methods, will help identify the most informative and cost-effective options, all the while establishing baseline concentration data against which future data can be compared. The feasibility of measuring algal toxins in archived benthos samples should also be considered in order to generate longer time series of algal toxins and look for changes over the past decade or more (if well preserved samples exist).

R.1.2.6 Benthos monitoring to quantify spatial, seasonal, and interannual variability in grazer abundance

Grazing by benthic filter feeders is considered to be one of the main controls on phytoplankton biomass accumulation in several subembayments. To estimate the influence of the benthic grazing, and track its changes in space and time, benthos surveys are needed on a regular basis in some subembayments, most importantly Lower South Bay, South Bay, San Pablo Bay, and Suisun Bay.

In recent years there has been ample benthos monitoring in Suisun Bay and the Delta (and some in San Pablo Bay), although the fate of this program is not known. There are currently no sustained programs in the other subembayments. However, there are some years during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008; see Figure 7.4.b), and

[3] http://www.whoi.edu/oceanus/viewArticle.do?id=46486

along with opportunistic sampling efforts (in some cases, samples have been archived but not yet analyzed for biomass; J Thompson, personal communication).

Benthos monitoring could occur less frequent than water quality monitoring, e.g., three times per year (spring, summer, fall). Sorting, counting, and weighing benthos samples is time consuming and thus costly. In designing a benthos sampling program, the use of benthic cameras could be considered (alongside some traditional sample collection for calibration/validation), and be the focus of a pilot study, since its use could potentially allow for more cost-effective benthos surveys.

R.1.2.7 Zooplankton abundance/composition
Monitoring data on zooplankton are needed to quantify pelagic grazing rates. Zooplankton abundance and composition may also serve as an important indicator of food supply and quality for higher trophic levels. Long term zooplankton monitoring has been carried out in Suisun Bay and the Delta. However, zooplankton abundance and composition are not currently measured in other subembayments.

R.1.2.8 Allocate sufficient funding for data interpretation and synthesis
Data analysis and data synthesis are essential components of a monitoring program. Allocating sufficient funds for these activities will allow field results to be efficiently translated into management-relevant observations that inform decisions, and allow the monitoring program to nimbly evolve to address emerging data requirements. Annual reports will be needed that not only compile and present data, but that also evaluate and interpret trends. More detailed special studies will also be needed periodically to generate scientific synthesis reports on complex data sets (e.g., spatial and seasonal trends in phytoplankton community composition).

R.2. Develop and implement science plans for SFB that target the highest priority management and science questions
The size of SFB, and the complexity of nutrient-response issues in this system, create a situation in which there are numerous relevant science questions that need to be addressed to improve our understanding of the system. Addressing the management and science questions will require a combination of field studies, controlled experiments, monitoring, and modeling across the topics of nutrient cycling, phytoplankton response (biomass and community composition), and hydrodynamics.

It will not be feasible to explore all the relevant science questions – that would take longer than management decisions can wait, and would outstrip any reasonable budget. To best target science efforts, there would be considerable benefit to developing and implementing science plans that

- Identify the highest priority management issues, and associated science questions
- Identify sets of studies and data collection/monitoring needs that efficiently target those questions

For some management issues and science questions, a Bay-wide science plan may be appropriate. Other questions, related to geographically specific issues, may be best addressed with subembayment-specific modules. The science questions listed in Tables 11.3-11.5 could serve as an early step in what would be an iterative refinement process.

Analysis of existing data from SFB, combined with broader critical literature review, would be useful early steps in science plan development, to articulate what is well-understood (in other estuaries and SFB) and focus on critical knowledge gaps.

R.3. Develop hydrodynamic, nutrient cycling, and ecosystem response models
Tables 11.3-11.4 illustrate that modeling will play an important and central role in addressing a diverse set of science questions. Modeling can also help prioritize data collection needs. While there are numerous hydrodynamic models available for SFB, and several phytoplankton growth models (that are decoupled from nutrients), there are currently no coupled hydrodynamic-phytoplankton-nutrient models.

Considerable progress could be made toward addressing several sets of science questions through using relatively "basic" models that that are built upon simplified (aggregated), but still accurate, hydrodynamics. Recommended model applications include (not an exhaustive list):

R.3.1 Quantitative analysis of nutrient budgets (including losses/transformations of nutrients) to determine the Bay's natural assimilative capacity;
R.3.2 Assessing the relative importance of major processes that control primary production (light, clams, flushing, NH_4^+ inhibition);
R.3.3 Forecasting ecosystem response under future scenarios, and narrowing the list of high priority scenarios;
R.3.4 Performing sensitivity/uncertainty analysis, and identifying highest priority monitoring activities, process level studies, or rate measurements to minimize model uncertainty.
R.3.5 Determine the amount of turbulent energy dampening (due to salt pond restoration) that would be required to prolong stratification for a period of time that could potentially lead to impairment in South Bay or LSB.

In developing such models, there is a benefit to "starting simple", and adding complexity as needed. Suisun Bay and LSB/South Bay could serve as good focus areas for basic model development and application, both because of the abundance of data and the fact that these areas are among those where concerns about impairment are greatest. Lessons learned through applying basic models will be useful for informing larger-scale or more complex model development.

Higher spatial resolution models, or larger spatial scale models (e.g., full Bay as opposed to individual subembayments) will be needed to evaluate some important questions. Many of these are related to the management scenarios identified in Table 11.5:

R.3.6 Assess the hydrodynamic changes that would result from salt pond and wetland restoration around the margins of LSB, and determine if the altered physics could amplify nutrient-related impacts (related to *R.3.5*).
R.3.7 Determine the zones of influence of individual POTWs under a range of hydrodynamic forcings and estimated transformations/losses

R.3.8 Quantify loads from the Delta to Suisun Bay under seasonally- and interannually-varying hydrological conditions, and the influence of these loads in Suisun and down-estuary subembayments under a range of forcings.
R.3.9 Evaluate the effectiveness of different nutrient control strategies for achieving desired reductions in ambient concentrations as a function of space and time.
R.3.10 Quantify the importance of net nutrient loads from the coastal ocean to SFB under a range of commonly-occurring forcing scenarios.
R.3.11 Explore the fate of the nutrient-rich SFB plume leaving the Golden Gate, and the potential influence of those nutrients on coastal ecosystems.

R.4. Carry out special studies to address key knowledge gaps about mechanisms that regulate ecosystem response, and inform whether or not impairment is occurring
The draft list of priority science questions in Tables 11.3-11.5, viewed alongside the data/knowledge gap priorities in Tables 6.1, 7.1, 8.1, and 9.1, present an initial picture of the types of data collection and studies that are the most important in the near term. A number of priorities have been discussed above in the context of monitoring program development (*R.1.2.1-1.2.8*) and modeling (*R.3.1-R.3.11*). An overview of special study priorities is provided below; however, the reader is also referred to the tables noted above.

Nutrient cycling
R.4.1 Controlled field/lab experiments to measure pelagic nutrient transformations (pelagic nitrification, nutrient uptake rates)
R.4.2 Controlled field/lab experiments to measure benthic nutrient transformations (benthic nitrification, denitrification, mineralization and N and P fluxes from sediments)
R.4.3 Quantify the importance of internal nutrient transformations using models.

Phytoplankton and MPB productivity
R.4.4 Controlled experiments that further test the proposed "NH_4^+-paradox" mechanism of lower productivity when NH_4^+ is elevated, determine relevant thresholds, and allow its effect to be better parameterized and compared to other regulating factors in models (*R.3.2*) .
R.4.5 Through analysis of existing data or through field studies, test whether the Cole and Cloern (1987) productivity relationship continues to hold, or if changes to the "efficiency factor", ψ, or C:chl-a necessitate additional field surveys of productivity.
R.4.6 Field measurements to quantify MPB primary production rates and biomass.
R.4.7 Compare MPB production and biomass with phytoplankton production and biomass, consider how MPB's relative importance would change (or already has changed) due to ecosystem change (lower suspended sediments, benthic grazers), and explore how those changes influence nutrient cycling, oxygen budgets, and food webs.

Dissolved O_2
R.4.8 Controlled field experiments to quantify sediment oxygen demand in a range of depositional environments. These can be carried out in conjunction with the benthic nutrient transformation special studies as part of the same experimental protocol (*R.4.2*).
R.4.9 Analysis of DO data in shallow margin habitats and development of criteria for determining whether or not impairment is occurring

R.4.10 Through field experiments and modeling, quantify the contribution of anthropogenic nutrients to current sediment oxygen demand (through production of new phytoplankton biomass or MPB biomass that undergoes mineralization in the sediments).

Phytoplankton community composition and HABs

R.4.12 Rigorous analysis of existing phytoplankton community composition data to test qualitative and quantitative agreement with various conceptual models

R.4.13 Field studies (collecting phytoplankton composition data at higher temporal or spatial resolution) to test mechanisms of phytoplankton community succession in response to physical, chemical, and biological drivers.

R.4.14 Field studies to evaluate the potential importance of salt ponds as incubators of HAB-forming species.

R.4.15 Controlled experiments, using phytoplankton assemblages and monocultures from SFB, that mechanistically explore the interactive effects of nutrient availability (including variability in concentrations and forms), light, and temperature. The goals of such studies would be to identify conditions that favor some classes or species of phytoplankton over others under the prevailing conditions in SFB (light limitation, excess nutrients), and enable predictions about assemblage response;

R.4.16 Apply the information from R.4.1.5 using basic models to, among other issues, evaluate the magnitude of the nutrient component of stress, and explore potential composition responses to changing conditions, including those due to potential management actions (e.g., nutrient load reductions).

Table 6.1 N and P loads and cycling: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of Knowledge about magnitude, composition, or controls	Need for <u>additional or continued</u> data collection, process studies, modeling	Priority for study in next 1-5 years
Loads				
POTWs	**High**	**Moderate: C**omprehensive effluent monitoring is currently underway. Prior to 2012, data availability varies by POTW and in general is fairly sparse for several nutrient forms (NO_3^-, o-PO4, TN, TP)	**Very High**	**Very High**
Stormwater runoff	**Uncertain**	**Low**: Limited stormwater data and limited modeling effort	**High**	**High**
Delta	**High**	**Low:** Initial estimates suggest Delta loads may be a large source but they need to be validated, and time-series of loads are needed.	**Very High**	**Very High**
Groundwater	**Low**	**Low:** Poorly quantified but not expected to be major source because of relatively high loads from other sources	**Low**	**Low**
Direct atmospheric deposition	**Low**	**Low**: Poorly quantified but not expected to be major source because of relatively high loads from other sources, including from the large Central Valley watershed	**Low**	**Low**
Exchange through GG	**Uncertain**	**Low:** Has the potential to be large, but highly uncertain	**High**	**High**
Processes				
Benthic denitrification	**High**	**Low**: see OM mineralization and NH4 and PO4 release below	**Very High**	**Very High**
Pelagic denitrication	**Low**	**Low**: not expected to be important because of oxic water column	**Low**	**Low**
Benthic nitrification	**High**	**Low**: see OM mineralization and NH4 and PO4 release below. Potentially large, but limited field measurements, and need for both field and model-based estimates.	**Very High**	**Very High**
Pelagic nitrification	**High**	**Low**: Potentially large, but limited field measurements, and need for both field and model-based estimates.	**Very High**	**Very High**
N fixation	**Low/Uncertain**	**Low**	**Moderate**	**Low**

Process or Parameters	Importance for quantitative understanding	Current Level of Knowledge about magnitude, composition, or controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
OM mineralization and release of NH4 and o-PO4 from sediments, and in the water column	**High**	**Low**: Potentially a substantial source from the sediments to the water column. Limited data from two studies in SFB, but well-studied in other systems and at least initially may be able to use that information. Field studies aimed at exploring this issue will also inform sediment oxygen demand, benthic primary production, benthic denitrification, and benthic nitrification.	**Very High**	**Very High**
Settling/burial of N and P	**High**	**Low/Moderate**: limited field estimates to date, although could be estimated based on other sedimentation data.	**Moderate**	**Low**
Rates of NH4, NO3, and o-PO4 uptake by phytoplankton	**High**	**Moderate**: field measurements exist for NH4 and NO3 in northern estuary, limited data in South Bay and LSB. Uptake rates for P are not well-studied. Both N and P uptake rates can be partially constrained by knowing phytoplankton C:N:P and productivity	**Moderate**	**Moderate**
Other processes: DNRA, ANAMOX	**Low**	**Low**: but expected to be relatively small	**Low**	**Low**
N and P budgets for subembayments: loads, transformations, sources/sinks, export	**High**	**Low**: The ability to quantify these will provide important information on the subembayments' ability to process/assimilate N and P. Basic modeling work needed.	**Very High**	**Very High**
Ambient concentration data				
Phytoplankton C:N:P	**High**	**Low**: Currently not routinely measured during monitoring	**Very High**	**Very High**
Concentration of NO3, NH4, and PO4	**High**	**Moderate**: monthly data available at ~15 stations Bay-wide but finer spatial and temporal resolution needed to inform process level understanding and modeling	**Very High**	**Very High**
Concentrations of NO_2^- and N_2O	**Low/Moderate**	**Moderate**: not needed for nutrient budgets, but informative as diagnostic of processes	**Moderate**	**Moderate**
Concentration of DON, PON, DOP, POP within and loaded to the system	**Moderate/ uncertain**	**Low:** Little current data, and information is needed. Given the high DIN and DIP concentrations, abundance organic forms may be relatively low.	**High**	**High**

Table 7.1 Phytoplankton productivity and biomass accumulation: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Processes				
Primary production rates	**High**	**Low/Moderate**: Basic understanding about light limitated production is well modeled. Recent studies suggest that the relationship may have shifted, and revisiting this may be important for estimating system productivity.	**Very High**	**High**
Pelagic grazing	**High**	**Low**: Long-term program in Suisun Bay and Delta for macrozooplankton, but limited micro-zooplankton data, which may be more quantitatively important in terms of overall grazing rate. No systematic zooplankton sampling in LSB, South Bay, Central Bay.	**Very High**	**High**
Benthic grazing	**High**	**Low**: good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	**Very HIgh**	**Very High**
Sinking, respiration, burial	**High**	**Moderate**: Discussed within context of Dissolved Oxygen	**Low**	**Low**
Inhibition of primary production rates by elevated NH_4^+	**High/ Uncertain**	**Low**: Several studies have been completed and others are underway. Uncertainty remains about mechanism and relative importance of the process. Field/lab studies and modeling work can be done in parallel, with the former designed to further elucidate the mechanism and thresholds and the latter to quantify its role relative to other factors.	**Very High**	**Very High**
Production in the shoals vs. channels (during stratification), and physical or biological controls on bloom growth/propagation	**High**	**Low**: Considered to be an important process but limited data available. Data needed to better predict bloom magnitudes.	**Very High**	**Very High**
Germination of resting stages	**Low**	**Low:** Not considered among the highest priority processes to study	**Low**	**Low**
Phytoplankton – Ambient concentration data				
High temporal resolution data in channel	**High**	**Low**: Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	**Very High**	**Very High**
High temporal resolution data in shoals	**High**	**Low:** Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	**Very High**	**Very High**
Biomass data along the Bay's deep channel	**High**	**Moderate/High**: USGS program has been collecting monthly data at along the channel for the past 35 years, and needs to be continued.	**Very High**	**Very High**
Phytoplankton C:N ,C:chl-a, and size-fractionated chl-a	**High**	**Low:** Valuable information to inform understanding of processes and for modeling	**Very High**	**Very High**

Table 7.2 Microphytobenthos productivity and biomass: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Microphytobenthos - Processes				
Primary production rates	**Moderate**	**Low:** may be able to predict productivity based on light levels and chl-a, although needs to be confirmed	**Moderate**	**Moderate**
Grazing	**Moderate/ Unknown**	**Low:** Potentially important as a sink, but difficult to study.	**Low**	**Low**
Microphytobenthos – Ambient abundance data				
Basic biomass information, seasonal, spatial	**High**	**Low:** Very limited data on MPB abundance and productivity, despite the fact that MPB productivity may be comparable in magnitude to phytoplankton productivity.	**Very High**	**Very High**

Table 8.1 Dissolved Oxygen: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Processes or loads				
Atmospheric exchange	**High**	**Moderate**: Difficult to measure but readily modeled (albeit with substantial uncertainty)	**Low**	**Low**
Pelagic and benthic nitrification (for O2 budget)	**Low/Moderate**	**Moderate**: NH4 loads/concentrations provide an upper bound on this oxygen sink. It is not expected to be a major DO sink, or	**Low**	**Low**
Sediment oxygen demand (Benthic respiration + oxidation of reduced compounds).	**High**	**Low**: This set of processes is particularly important for understanding O_2 budget in shallow margin environments. The mechanisms are well understood but rates are poorly constrained and likely are highly variable in space/time. Field experiments are possible. Increased (high spatial/temporal resolution) monitoring of DO will also allow "average" demand to be quantified by difference/modeling.	**Very High**	**Very High**
Pelagic and benthic primary production rates	**High**	**Low**: Benthic production rates, in particular are particularly poorly constrained and would require field surveys. Pelagic rates can be reasonably well-estimated based on phytoplankton biomass and light. As noted above, high spatial/temporal resolution monitoring of chl-a will help refine estimates	**Very High**	**Very High**
Pelagic respiration	**Moderate**	**Moderate**: In shallow areas, sediment oxygen demand will be of much greater importance than pelagic respiration. Pelagic respiration rates by viable phytoplankton can be reasonably well-estimated based on biomass. Respiration of dead OM is a function of OM abundance and quality, and water temperature.. In deep channel areas of the Bay, where pelagic respiration will be more important than sediment oxygen demand, low DO does not appear to be a major issue, and thus constraining these rates are not among the highest priorities.	**Low**	**Low**
DO – Ambient concentration data				
High spatial resolution DO data in deep channel	High	**Low**: USGS research program provides an excellent long-term record along the Bay's spine. This work needs to be continued.	**Very High**	**Very High**
High temporal resolution DO data in deep channel	High	**Low**: Limited DO data available from continuous sensors, in particular in South Bay and LSB. A network of sensors is installed in Suisun Bay and the Delta.	**Very High**	**Very High**
High temporal resolution data in shoals and shallow margin habitats	High	**Low**: Some special studies have been performed, and some on-going monitoring by POTWs and others (e.g., USGS studies in salt ponds). While these individual efforts have valuable information and some reports are available, a meta-analysis of this data has not been completed, and there is currently no overarching regional program.	**Very High**	**Very High**

Table 9.1 Phytoplankton community composition and HABs: current state of knowledge for key processes and parameters

Process or Parameters	Importance for quantitative understanding	Current Level of Certainty about magnitude, composition, or controls	Need for additional or on-going data collection or process studies	Priority for study in next 1-5 years
Processes				
Pelagic grazing rates (size-selective)	**High**	**Low**: No systematic zooplankton sampling in LSB, South Bay, Central Bay. Only 1 station in San Pablo.	**Moderate**	**Moderate**
Size-selective benthic grazing rates	**High**	**Low**: Good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	**Very High**	**Very High**
Temperature, light, and nutrient (concentration, N:P, form of N) preferences of phytoplankton PFTs specific to SFB subembayments	**High**	**Low**: Limited understanding of how these factors/preferences may shape phytoplankton community composition, in particular in a light-limited nutrient-replete system.	**Very High**	**Very High**
Effects of trace metals, organics or pesticides	**Moderate/ Uncertain**	**Low:** Limited information on vitamins, trace-metals, and the influence of anthropogenic contaminants such as pesticides that may be influencing community composition. competition with diatoms.	**Moderate**	**Moderate**
Effect of physical forcings, including exchange between subembayments, oceanic and terrestrial (including wetlands, salt ponds) end-member inputs, large scale climate forcings	**High**	**Moderate:** Data on community composition over the past 20 years (Bay wide) and up to 40 years (Suisun and Delta) to explore different explanations.	**Very High**	**Very High**
NH4 inhibition: diatom productivity	**High/ Uncertain**	**Low:** Several studies completed, others underway.	**Very high**	**Very high**
Ambient composition data				
Size-fractionated chl-a	**High**	**Low:** Provides a coarse measure of in which classes phytoplankton biomass resides, which is a useful albeit coarse surrogate for food quality. Not currently being collected but could be easily added to monitoring.	**HIgh**	**High**
Phytoplankton community composition, monthly time-scales, at sufficiently high spatial resolution, and higher temporal/spatial resolution to test mechanisms	**High**	**Moderate:** 20 year near-monthly Bay-wide record from USGS and ~40 year record for Suisun and Delta. But few higher resolution data sets or special studies.	**Very high**	**Very high**

Process or Parameters	Importance for quantitative understanding	Current Level of Certainty about magnitude, composition, or controls	Need for additional or on-going data collection or process studies	Priority for study in next 1-5 years
Frequency and magnitude of detection of HABs or HAB toxins	**High**	**Low**: Limited data on HABs and toxins, and	**Very high**	**Very high**
Phytoplankton community composition in salt ponds, particularly HAB-forming species	**High**	**Low:** Limited data to date, but of high concern.	**Very High**	**Very High**
Surrogate measures for phytoplankton composition	**Low**	**Low:** The use of phytoplankton pigments or digital image recognition approaches could be piloted that would eventually increase the amount of composition data that could be collected	**Very High**	**Very High**

Table 11.3 Highest priority *current trend* scenarios and associated science questions

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling: basic or small scale	Watershed Modeling: complex or large scale	Assessment Framework	Technology, cost-benefit analysis
CT.1 High biomass in LSB and South Bay										
a. What are the relative importances of the fundamental drivers that underlie recent changes in phytoplankton biomass in LSB (decreased SPM, loss of benthic grazers, other)?		x	x		x					
b. Based on this analysis, what are likely future trajectories in LSB and South Bay? Will biomass concentrations level off or continue increasing? What will be the response of DO?		x	x		x					
c. What levels of phytoplankton biomass and DO would represent impaired conditions, and how do predictions compare with the impairment thresholds?	x	x							x	
CT.2 Low DO in margin habitats in LSB and South Bay (as test cases for other subembayments)										
a. With what frequency is low DO detected in these habitats?		x	x							
b. Are the low DO occurrences entirely (or mostly) natural or are they more severe (longer duration, more frequent, lower levels), and is this increased severity due to anthropogenic nutrient loads?		x		x	x					
c. Is impairment occurring, and to what degree is it related to anthropogenic nutrients?					x				x	
CT.3 HABs and NABs in all subembayments										
a. What frequency and abundance of HABs/toxins and NABs would be considered as impairing beneficial uses?	x	x							x	
b. How frequent are potentially harmful and nuisance algal species observed?		x	x							
c. What is their source?		x	x	x						
d. How do HAB toxin abundances vary in space and time?		x	x							
e. What factors might lead these species to form harmful or nuisance blooms? Are current nutrient concentrations among the factors that favor these blooms (or the production of toxins) or allow the blooms to expand in size/duration?	x	x	x	x	x					
f. If current nutrient concentrations potentially play an important role, what decreases in ambient concentrations are needed to lower the risk of impairment?	x			x	x					
CT.4 Suboptimal phytoplankton community composition in all subembayments										
a. How have phytoplankton community compositions changed within SFB subembayments over recent years?		x	x							
b. What constitute optimal, or at least healthy, phytoplankton assemblages in SFB's subembayments? Conversely, recognizing the first question is difficult to address, what assemblages would be considered as poorly supporting desirable food webs?	x	x							x	
c. What role can nutrients (concentrations, forms, N:P) play in shaping phytoplankton community composition? What is known from other systems or from prior experimental work? What controlled experiments or observations in SFB are needed to further inform this issue?	x			x						

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling: basic or small scale	Watershed Modeling: complex or large scale	Assessment Framework	Technology, cost-benefit analysis
d. What is the magnitude of the role, or relative importance of the role, that current ambient nutrient concentrations play in shaping SFP community composition?	x	x		x	x					
e. If nutrients play an important role, what changes to nutrient availability would mitigate or prevent impairment?	x	x		x	x					
CT.5 Low phytoplankton biomass in Suisun Bay										
a. What is the underlying mechanism by which NH_4^+ slows or inhibits primary production?	x			x						
b. At what NH_4^+ concentrations are primary production rates substantially impacted?		x		x						
c. What is the relative contribution of elevated NH_4^+ compared to other factors that maintain low phytoplankton biomass in Suisun Bay (clam grazing, light limitation, flushing)?					x					
d. Are current NH4 loads or concentrations impairing beneficial uses?		x							x	

Table 11.4 Highest priority change scenarios leading to impairment, and associated science questions

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling: basic or small scale	Watershed Modeling: complex or large scale	Assessment Framework	Technology, cost-benefit analysis
CS.1 High phytoplankton biomass in LSB and South Bay										
a. What level of phytoplankton biomass (and over what area, for what period of time) would constitute impairment in LSB and South Bay habitats?									x	
b. What will be the response of phytoplankton biomass and DO if suspended sediments continue decreasing at rates similar to the past 10-20 years?			x		x	x				
c. Does impairment become increasingly likely at environmentally-relevant SPM values? Or is impairment unlikely along this pathway under this scenario?			x		x	x				
d. Could salt pond and wetland restoration efforts lead to longer periods of stratification that could translate into extended periods of higher primary production rates, greater biomass accumulation, and impairment?			x		x	x				
e. Similarly, could changes in climate patterns lead to sufficiently longer periods of stratification that impairment develops?		x			x	x				
f. What would be the response to lower SPM and longer stratification combined?			x		x					
g. If these scenarios emerge as quantitatively plausible paths to impairment, what reductions in ambient nutrient concentrations are necessary to prevent impairment?			x		x					
CS.2 Increased frequency of HABs and NABs in all subembayments										
a. What frequency or magnitude of HABs/NABs or HAB-toxins would be considered an impaired state?	x	x							x	
b. To what extent may restoration and reconnection of salt ponds allow them to act as high-light, warm, nutrient-replete incubators for HABs and NABs to LSB and South Bay?		x	x	x	x					
c. In Suisun Bay, what is the potential role of future water management practices in the Delta (withdrawals, longer residence times) in terms of fostering HABs?		x	x	x	x					
d. Similar to S6, what changes in climate patterns would be necessary to permit HABs or NABs to proliferate? e.g., increased frequency of conditions that allow for several days of thermal stratification in fall (such as the Fall 2004 red tide bloom)? Are these possible in the 20-30 yr time horizon?	x	x		x	x					
Changes that would lead to suboptimal phytoplankton composition										
Since so little is understood about the factors that currently regulate phytoplankton composition, the change scenarios are not considered among the early priorities to consider. Instead, effort should be focused on the status quo issues with composition (Table X.X CT.4)										

Table 11.5 Highest priority mitigation scenarios and related science questions

	Literature Review	Analysis of existing data and synthesis	Data collection and monitoring	Field or laboratory experiments	Bay Modeling: Basic	Bay Modeling: Complex or full bay	Watershed Modeling: basic or small scale	Watershed Modeling: complex or large scale	Assessment Framework	Technology, cost-benefit analysis
MS.1 Reductions in nutrient loads from POTWs and nutrient loads from the Delta										
a. What are the magnitudes of loads from individual POTWs?		x	x							
b. How do Delta loads to Suisun Bay vary seasonally and interannually?					x	x	x	x		
c. What portions of the loads that enter Suisun Bay from the Delta originate from SacRegional, others POTWs?		x	x				x	x		
d. What portions of the loads come from Central Valley and Delta agriculture?								x		
e. What will the loads to Suisun Bay be under future scenarios, e.g., changes at SacRegional, restoration or water management practices in the Delta, changes in agricultural practices?					x	x	x	x		
f. What are the zones of influence of individual POTWs that discharge to SFB, and of Delta loads, and how do these vary seasonally and interannually?						x				
g. What is SFB's assimilative capacity for nutrients: mixing/flushing and nutrient cycling (losses and transformations) as a function of space and time?				x	x	x				
h. What is the range of options for achieving various levels of nutrient load reductions from POTWs?										x
i. Considering areas of influence, zones where impairment may be occurring, and internal processes, what combination of load reductions would be effective at mitigating or preventing impairment?					x	x				
j. What are the costs and multiple benefits (beyond nutrients) of individual POTW efforts, and of longer-term integrated sub-regional plans?										x
MS.2 Reductions in stormwater nutrient loads										
a. Are stormwater nutrient loads important sources to some margin habitats in some subembayments, and do they warrant major consideration?	x	x	x		x	x	x			
b. If yes, what are the loads from priority watersheds, and how do they mix with the rest of the subembayment?		x	x				x	x		
MS.3 Influence of nitrification at SacRegional and Suisun direct POTWs on NH4 inhibition of primary production										
a. What is NH4 fate within the Delta and how does this change as a function of season, flow, etc.?					x	x	x	x		
b. What load reductions are necessary to reduce NH4 to concentrations that would not inhibit production?					x	x				
MS.4 Other mitigation strategies: wetland restoration/treatment and shellfish beds										
a. What is the mitigation potential of wetland restoration/treatment for removal of nutrients?	x				x	x				
b. What is the mitigation potential of cultivating shellfish beds?	x				x	x				

3. Executive Summary of Suisun Bay Ammonium issues

Suisun Bay Ammonium Synthesis Report, March 2014

Suisun Bay Ammonium Synthesis Report

FINAL

March 14 2014

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Executive Summary

Observations made since the early 2000's have noted declining abundances of important, pelagic members of the Suisun Bay and Sacramento/San Joaquin Delta food webs. In response, numerous investigations have been launched, aimed at identifying the underlying cause(s) of what is referred to regionally as the Pelagic Organism Decline (POD). The conceptual model for the POD recognizes that multiple factors may act in concert to degrade habitat and contribute to the POD (Baxter et al., 2010; NRC 2012), including: changes in flow regime, physical alterations to habitat, land use changes, invasive species, contaminants, and nutrients. Understanding the underlying causes of habitat degradation and the POD in Suisun Bay and the Delta requires an integrated analysis across the range of potential drivers. This report focuses on one set of these issues: elevated loadings and concentrations of ammonium (NH_4^+) in Suisun Bay and a subset of the proposed mechanisms by which NH_4^+ may adversely impact ecosystem health.

Recent studies have hypothesized that anthropogenic nutrient loads over the past few decades, in particular NH_4^+, are negatively impacting food webs in Suisun Bay and the Delta. Elevated NH_4^+ concentrations are hypothesized to be inhibiting primary productivity in Suisun Bay, San Pablo Bay, and the Sacramento River (Dugdale et al., 2007; Parker et al., 2012), and indirectly contributing to the POD by decreasing the potential food supply. Other investigators hypothesize that changes in nutrient ratios and forms of N are exerting additional bottom-up pressures on Delta and Suisun food webs by altering the phytoplankton community composition and the N:P composition of individual cells (e.g., Glibert et al., 2011; Glibert et al, 2012). In addition, a recent study reported evidence that NH_4^+, at concentrations observed in some areas of the Delta and Sacramento River, can exert chronic toxicity on a copepod species (*Pseudodiaptomus forbesi*) that is an important food resource (Teh et al., 2011).

The purpose of this report is to provide an overview of the state of the science and identify science gaps related to a subset of the hypothesized adverse impacts of NH_4^+ in Suisun Bay, and characterize NH_4^+ loads, concentrations, and fate. The report's specific goals are to

1. Synthesize the scientific literature on nitrogen utilization by marine and estuarine phytoplankton, with a particular focus on factors and mechanisms that regulate the N form utilized by phytoplankton, and the effect of different N sources on primary production rates. (Section 2)
2. Through the perspective of the broader scientific literature, evaluate the results and interpretations of recent studies that hypothesize that elevated NH_4^+ levels inhibit primary production rates. (Section 3)

3. Summarize the scientific literature related to NH_4^+ toxicity to copepods. (Section 4)
4. Synthesize the scientific literature on copepod ecology and changes in community composition and abundance in Suisun Bay (Section 5)
5. Quantify NH_4^+ loads to Suisun Bay, evaluate long-term changes and seasonal variations in ambient NH_4^+ concentrations, and characterize NH_4^+ fate. (Section 6)
6. Summarize key observations and identify next steps. (Section 7)

Although additional pathways of nutrient-related impairment have been proposed in Suisun Bay and the Delta, this report is narrowly focused on the above goals. The report was developed under the assumption that it would be used in conjunction with complementary reports (including reports already developed, e.g., Baxter et al., 2010; Meyer et al, 2009) that address other factors affecting ecosystem health in Suisun Bay and the Delta to help identify the outstanding science questions whose answers will informed management decisions. For additional background and context on nutrient related issues in San Francisco Bay, the reader is referred a recent nutrient conceptual model report (Senn et al. 2014).

The report is organized into individual sections that address each of the six main goals, and the overall findings are summarized below.

NH_4^+ inhibition of primary production

The NH_4^+ inhibition hypothesis was developed through multiple studies by researchers at San Francisco State University's Romberg Tiburon Center (RTC) for Environmental Studies over the past decade (e.g., Wilkerson et al., 2006; Dugdale et al., 2007; Parker et al., 2012a, 2012b; Dugdale et al., 2012). The conceptual model for the ecological impacts of the NH_4^+ inhibition hypothesis is built around three main points:

P.1 The presence of NH_4^+ at elevated levels (>1-4 µmol L^{-1}) inhibits the uptake of nitrate by phytoplankton.

P.2 The rate of NO_3^- uptake (when NH_4^+ is absent or less than 1-4 uM) is greater than the rate of NH_4^+ uptake. Thus, when NO_3^- uptake is suppressed, and only NH_4^+ is being taken up by phytoplankton, the overall rate of N uptake is lower.

P.3 The lower rate of N uptake resulting from this mechanism translates into lower rates of primary production.

Dugdale et al (2012) refer to the suppression of bloom development by elevated NH_4^+ as "the NH_4^+ paradox". The NH_4^+-inhibition conceptual model that is based on P.1-P.3 argues that phytoplankton uptake of NO_3^-, the largest pool of N in the San Francisco

Estuary, is necessary for phytoplankton bloom development. Under this model, bloom initiation is dependent on lower NH_4^+ concentrations combined with certain river flow and loading conditions (assuming sufficient irradiance), and three criteria must be met: 1) NH_4^+ loading must not exceed the capacity of the phytoplankton to assimilate the inflow of NH_4^+; 2) NH_4^+ concentration must be equal to or less than 4 μmol L^{-1} to enable phytoplankton NO_3^- uptake; 3) The dilution rate of the phytoplankton biomass, set by river flow, must not exceed the phytoplankton growth rate to avoid washout.

There is strong support in the scientific literature for P.1, with numerous studies demonstrating either that multiple species of phytoplankton exhibit a strong preference for NH_4^+ or that NO_3^- uptake is actively inhibited by elevated NH_4^+ concentrations. RTC studies offer convincing support for P.1, with NO_3^- uptake by phytoplankton strongly inhibited when NH_4^+ concentrations exceed 1-4 μmol L^{-1}.

P.2 is not well-supported by the broader scientific literature on N uptake rates by phytoplankton. Few well-controlled studies have actually investigated N uptake rates during experiments in which both NO_3^- and NH_4^+ were available over a range of concentrations. Thus, there remains a critical gap in the literature on this topic. While there are limited studies that explicitly compare NO_3^- vs. NH_4^+ uptake kinetics, the more broadly accepted conceptual model is that, when nutrients are abundant, cells access whichever N source is most readily available, and that uptake rates of NO_3^- and NH_4^+ are similar. The RTC studies provide some support for P.2 through enclosure experiments carried out with Bay water and using ambient phytoplankton community assemblages (Parker et al., 2012a), and with one set of uptake kinetic experiments using ambient community assemblages. However, RTC studies also yield some experimental evidence that suggests NH_4^+ uptake rates can be comparable to or even greater than NO_3^- uptake rates. In addition, uncertainty remains about whether experimental artifacts or other reasonable explanations could explain some of the observations used as evidence in support of P.2. While P.2 remains a plausible hypothesis, additional research is needed to more rigorously establish NO_3^- and NH_4^+ kinetics under a range of conditions (temperature, light levels), including experiments carried out with mono-cultures of phytoplankton species or taxa commonly present in Suisun Bay. .

P3 is not well supported by the broader scientific literature. As with P2, the more broadly accepted concept is that most phytoplankton taxa grow equally well when using NH_4^+ or NO_3^- as their nitrogen source (see Section 2 for further discussion). Multiple studies have found similar growth rates (rates of carbon fixation) across a range of taxa when using NH_4^+ or NO_3^-. While the rate of growth varies with different levels of light, experiments in which monocultures of phytoplankton were grown under different light regimes and different N sources found that growth rate was not strongly dependent on whether NO_3^- or NH_4^+ was provided (see Section 2). As with P.2, few studies have done growth experiments in which phytoplankton have the choice between NH_4^+ and NO_3^-, so there also remains a critical gap in the literature on this related topic. RTC field and enclosure experiments provide some evidence that is consistent with the the hypothesis that primary production rates (using rates of C uptake) are slower at high NH_4^+ levels, and that growth rates increase when NH_4^+ is depleted and phytoplankton begin utilizing NO_3^- (Parker et al., 2012a, 2012b). In other studies, primary production rates are inferred from changes in chl-a or assumed to be proportional to the N uptake rate, both of which are prone to considerable uncertainty (due to variations in C:chl-a and C:N). In addition, in some components of RTC studies, experimental artifacts (e.g., acclimation time to light conditions in enclosures) or competing explanations have not been sufficiently ruled out, including the potential role of other contaminants, either co-occurring in treated wastewater effluent, or other sources such as agricultural runoff. Even if P.2 and P.3 are occurring, N uptake and primary production in Suisun Bay appear to behave differently compared to the conceptual model, which was developed largely based on observations in San Pablo and Central Bay (Dugdale et al., 2007; Parker et al., 2012). Dugdale et al. (2007) and Parker et al (2012a) acknowledge the potential role of other factors, such as other contaminants. However, their conclusions about Suisun Bay do not sufficiently address this nuance, or the extent to which the NH_4^+-based explanations can be readily applied in Suisun Bay. Finally, NH_4^+ levels are present at comparable levels in South San Francisco Bay, and examples of NH_4^+ inhibition of primary production rates have not been documented there.

Similar to P.2, P.3 remains a plausible hypothesis. Inhibition of primary production by elevated NH_4^+ has been proposed as one possible mechanism to explain lower production rates elsewhere (e.g., Delaware Bay; Yoshihama and Sharp, 2006). The RTC studies have tackled the issue with field observations and experimental studies using ambient phytoplankton assemblages, as opposed to pure culture experiments. Their field studies and simulation of field conditions through enclosure experiments with Bay water and ambient phytoplankton communities provide an important perspective on net effects at the field scale. However, the complexity introduced by field conditions or simulated-field conditions, when multiple underlying factors are changing over space or time (e.g., phytoplankton community composition, grazing, acclimation to experimental light conditions, increases or decrease in light attenuation as a function of space in field studies, stratification) can make it difficult to directly evaluate the role of the NH_4^+ inhibition mechanism. Additional research is needed to:

- Determine whether statistically significant differences in primary production rates occur due to the N form utilized. Effort should be directed toward establishing NO_3^- and NH_4^+ uptake kinetics and phytoplankton growth kinetics under a range of conditions (e.g., varying temperature and light levels, varying proportions of

NO_3^- and NH_4^+), including experiments carried out with mono-cultures of phytoplankton species or taxa commonly present in Suisun Bay.

- Determine the ecological significance of this mechanism at the ecosystem scale, including improved understanding of the conditions under which differences in growth rates occur, and the magnitude of the effect.
- Rule out competing explanations and experimental artifacts in field observations and enclosure experiments.

Some of these research needs are the focus of on-going or proposed studies by RTC researchers, their collaborators, and other research. Those studies have not been discussed in this report; therefore, this review may need to be revisited as that data becomes available.

Independent of whether the set of processes laid out in the NH_4^+-inhibition conceptual model occur as proposed, their potential importance at the ecosystem scale has not been adequately investigated. Other factors are known to play important, if not dominant, roles in limiting primary production rates (e.g., light limitiation) or biomass accumulation (clam grazing, residence time) in Suisun Bay. The RTC studies acknowledge the roles of light limitation and clam grazing; they point out that NH_4^+ inhibition of primary production is an additional factor that limits production when conditions might otherwise allow for blooms to occur. However, this important point sometimes gets lost when the NH_4^+-inhibition conceptual model is discussed in the context of its management implications. The potential ecosystem-scale importance of the NH_4^+-inhibition conceptual model could be assessed using relatively basic biogeochemical models and existing data. Such modeling efforts would have benefits far beyond testing the NH_4^+ hypothesis, in that they will yield tools for quantitatively synthesizing existing nutrient and phytoplankton data in Suisun Bay and other embayments, identifying data and monitoring needs, and informing the broader modeling strategy for the Bay.

NH_4^+ toxicity to copepods

Changes in quality and abundance of food for pelagic fishes has been identified as one potential factor contributing to POD in the Delta and Suisun Bay. Zooplankton abundance and size have decreased over the last four decades, and these declines in food availability may be exerting bottom-up pressure on the food web (Baxter et al., 2010), since zooplankton are the primary prey for Delta smelt and other pelagic fishes whose decline lie at the center of the POD. High grazing rates by invasive benthos, low food abundance (i.e., low phytoplankton biomass), and direct toxicity of contaminants have been hypothesized to be acting in concert to keep zooplankton populations low. The unionized form, ammonia (NH_3), is the form that has most commonly been considered to be toxic to aquatic organisms. However, Teh et al. (2011) recently reported on chronic toxicity to the copepod *Pseudodiaptomus forbesi* at fairly low NH_4^+ concentrations. *P. forbesi* is of particular interest because during most times of the year, *P. forbesi* is considered the most important food source for all fish that have shown declining populations.

Teh et al. (2011) found that the survival of *P. forbesi* from early life stages to adult stages was reduced at NH_4^+ concentrations as low as 26 µmol L^{-1}. The toxicity mechanism was hypothesized to be related to the fact that copepods excrete N waste as NH_4^+, and that elevated NH_4^+ levels in the ambient surrounding water interfere with NH_4^+ excretion rates. Since NH_4^+ levels exceed 26 µmol L^{-1} in some parts of the northern Delta and the Sacramento River, it has been suggested that *P. forbesi* population levels may be impacted by elevated NH_4^+ loads to the system.

If toxicity to copepods from NH_4^+ may be among the issues that will inform nutrient management decisions in Suisun Bay, it would worthwhile to conduct further investigations. While the copepod toxicity study by Teh et al. (2011) was carefully executed, it has not yet been replicated. Furthermore, although there is some support for the proposed toxicity mechanism in the literature, only a handful of studies have been published on NH_4^+ toxicity to aquatic invertebrates, and none of those studies used copepods as the test organism. In addition, Teh et al. (2011) observed an effect in the lowest dosed samples, and treatments at lower levels are needed to establish a no observed effect level (NOEL). Finally, studies at salinity and pH ranges relevant to Suisun Bay would be needed, in particular because toxicity is thought to be exerted through the Na^+/K^+ transporter and Na^+ and K^+ levels vary with salinity; therefore copepod sensitivity to NH_4^+ could vary with salinity.

Copepod ecology in Suisun Bay

Copepods are key links in the San Francisco Estuary (SFE) foodweb between microplankton and fish. As such, declines in the abundance and biomass of copepods and changes in the dominant copepod species over the past few decades in Suisun Bay, and the underlying causes of these changes, are of critical concern. Most of the copepods of the upper estuary are introduced species, some of which are not suitable as food for fish because of their small size. The biomass of the larger copepods is less than it was before the introduction of the clam *Corbula amurensis*, because of competition for food and grazing by clams on the early life stages of copepods. The resulting low abundance of copepods of suitable size, and the long food chain supporting them, may be contributing factors to the decline in abundance of several estuarine fish species.

Copepods live in a moving frame of reference and therefore are more closely tied to a particular salinity range than a geographic position. Some species use tidal vertical migration to maintain their position in the salinity field. Copepods have elaborate sensory, feeding, and swimming appendages that enable them to feed very selectively and to escape from predators. Some feed by scanning the water for particles and removing them with their feeding appendages (e.g., the calanoid copepod *Pseudodiaptomus forbesi*), while others attack individual motile prey (e.g., the tiny cyclopoid *Limnoithona tetraspina*). Most copepods will consume microzooplankton such as ciliate protozoans at higher rates than phytoplankton, but microzooplankton are not monitored in the estuary. Diatoms can be key primary producers in productive areas but copepods often feed on other particles even when diatoms are abundant, and there is some controversy about the suitability of diatoms as food. Common copepods in the upper SFE are severely food limited, which manifests as very low reproductive and growth rates. In the low-salinity zone (Suisun Bay and the western Delta) the combination of high grazing by clams and low food supply means that the *P. forbesi* population there must be subsidized through advection from their population center in freshwater.

Nutrient concentrations could have direct or indirect effects on copepods. As noted above, it has been hypothesized that ammonium could be exerting direct toxicity to copepods. Indirectly, elevated ammonium has also been hypothesized to slow diatom production, which could affect copepod growth and development and elevated NH_4^+ could also have a positive effect on growth of the toxic cyanobacteria *Microcystis*. However, so far there is no clear evidence documenting that these effects play an important role in regulating copepod populations in Suisun Bay and the Delta..

NH_4^+ loads, ambient concentrations, and fate

Over the period 1975-2011, NH_4^+ concentrations in Suisun Bay have increased 25-50% in some. months, and exhibited strong seasonal variability, with 2-4 fold lower concentrations in summer and fall months than in higher flow months.

The major anthropogenic NH_4^+ loads to Suisun Bay came from the Delta and from treated wastewater effluent discharged directly to Suisun Bay. Delta loads were estimated using an approach similar to Jassby and Cloern (2000), and, due to changes in data availability, we have the greatest confidence for the periods of 1975-1995 and 2006-2011, and describe those briefly here. Since 1975, NH_4^+ loads from the Delta to Suisun have increased substantially with most of the increase occurring after 1995. On an annual basis, the mean (± 1 s.d.) loads entering Suisun Bay from the Delta were 5800 ± 1800 kg N d^{-1} from 2006-2011, as compared to 4100 ± 2700 kg N d^{-1} from 1975-1995. NH_4^+ loads from the Delta varied seasonally, as did the magnitude in the increase between pre-1995 and post-1995. Estimated NH_4^+ loads to Suisun Bay from the Delta increased the most during spring months (April-May) increasing by 5000-6000 kg d^{-1} between over the entire period of 1975-2011, with most of this increase occurring after 1995. Most of the Delta-derived NH_4^+ load entering Suisun was estimated to have come from the Sacramento River, as opposed to the southern Delta (i.e., San Joaquin), and most of the NH_4^+ transported along the lower Sacramento River has been shown to originate at Sacramento Regional Wastewater Treatment Plant (SRWTP). SRWTP's NH_4^+ loads increased by nearly a factor of 2 between 1985 and 2005, with most of that increase occurring after 1995 (Jassby 2008) and were presumably responsible for most of the increase in estimated loads from the Delta to Suisun Bay during this time. Other studies have found that much of SRWTP's NH_4^+ load undergoes nitrification en route to Suisun Bay (Foe 2010; Parker et al., 2012). Our estimates are also consistent with substantial nitrification of effluent NH_4^+ during its transit to Suisun Bay: present day loads from SRWTP (annual average = 13200 kg N d^{-1} for 2006-2011) are much larger than the loads entering Suisun from the Delta (annual average = 5800 kg d^{-1}).

POTWs that discharge directly to Suisun Bay also contribute substantial NH_4^+ loads to the system. Next to loads entering from the Delta, Central Contra Costa Sanitation District was the second largest NH_4^+ source to Suisun Bay, with annual average loads that increased from 2600 kg d^{-1} in the early 1990s to current loads of 3400 kg d^{-1} (annual average for the years 2008-2011). Delta Diablo Sanitation District was the third largest NH_4^+ source to Suisun Bay (1100 kg d^{-1}), and its NH_4^+ loads have remained relatively constant since 1990. Initial estimates of stormwater loads suggest that they contribute less than 5% of NH_4^+ loads during wet periods, and little if any NH_4^+ during the dry season. The magnitude of internal NH_4^+sources (flux from the sediments) are poorly constrained but they could conceivably be as high as 1000s of kg d^{-1}, and thus may be a quantitatively-important unknown.

Box model mass balance estimates, calculated using data for the months of May-October over the period 2006-2011, suggest that NH_4^+ exhibits strong non-conservative behavior within Suisun Bay. If NH_4^+ behaved conservatively, concentrations would have been on the order of 20 µmol L^{-1} based on monthly-average load estimates. Instead, spring, summer, and fall concentrations typically fell in the range of 3-6 µmol L^{-1}. This large difference between predicted and measured concentration is especially relevant within this concentration range of 3-20 µmol L^{-1}, considering the levels at which NH_4^+ is hypothesized to inhibit primary production (>2-4 µmol L^{-1}) and have toxic effects on copepds (LOEL = 26 µmol L^{-1}). Based on box model estimates, on average only 25% of the NH_4^+ that was added to the system during these months was actually transported out of Suisun Bay through the Carquinez Straits. The remaining ~75% of the NH_4^+ must have been lost by transformation (e.g., nitrification) or uptake by phytoplankton. The first order rate constants required to explain the loss of NH_4^+ during low-flow periods was in the range of 0.1-0.3 d^{-1}, which is comparable in magnitude to nitrification rates typically used in water quality models. This mass balance analysis did not include NH_4^+ flux from the sediments, indicating that, if benthic fluxes were substantial, the calculated losses and rates are lower bound estimates.

Ambient NH_4^+ concentrations in Suisun Bay frequently exceeded the levels above which NH_4^+ inhibition of primary production has been hypothesized to occur. According to the conceptual model proposed by RTC researchers, at NH_4^+ concentrations of 2-4 µmol L^{-1} the uptake of NO_3^- by phytoplankton is substantially inhibited, resulting in lower primary production rates. RTC investigators note that 4 µmol L^{-1} is not a "bright-line" threshold, and that NO_3^- uptake and phytoplankton productivity are also inhibited at lower levels of NH_4^+ (down to ~1 µmol L^{-1}).The 4 µmol L^{-1} value is used here because it is the most commonly cited value. The 4 µmol L^{-1} threshold was compared to ambient concentrations in April-October, when high chlorophyll concentrations were most commonly observed prior to the mid-1980s. Between 1975-1986, NH_4^+ levels exceeded 4 µmol L^{-1} in 44% of the monthly observations. Between 1987-1997, the 4 µmol L^{-1} threshold was exceeded in 70% of monthly observations. Most recently, from 1998-2011, ambient NH_4^+ concentrations exceeded 4 µmol L^{-1} the vast majority of the time (87%). Thus, the frequency with which a 4 µmol L^{-1} threshold has been exceeded between April-October has approximately doubled over the past 35 years.

Teh et al (2011) found that the LOEL for chronic toxicity to copepods was 26 µmol L^{-1}. Year-round ambient NH_4^+concentrations at D6, D7, and D8 were compared to this value and found to exceed the LOEL only two times, once at each D6 and D7, and both times in 1977.

While considering the above comparisons of ambient concentrations with proposed effect concentrations, one should keep in mind the remaining uncertainties about the underlying mechanisms and in the concentrations at which effects may be observed. The underlying mechanisms of the NH_4^+-inhibition hypothesis still require further testing; in addition, if it is found to be an important mechanism, the lowest level at which ecologically-meaningful effects occur needs to be determined. The copepod toxicity study by Teh et al. (2011) has not been replicated. In addition, Teh et al. (2011) observed adverse effects in the lowest dosed samples, and treatments at lower NH_4^+ concentrations are needed to establish a no observed effect level (NOEL).

Recommended Next Steps

The recommendations identified here are not intended to be comprehensive, but rather communicate some broad suggestions that became clear during this report's writing.

1. General: A coordinated nutrient science plan should be established for Suisun Bay and the Delta, with clearly articulated scientific questions, recommended experiments or monitoring, and a prioritization of work. There are currently numerous nutrient-related studies being conducted in Suisun and the Delta. However, the work is being carried out in more of a patchwork fashion, funded or directed by different organizations, and with limited overarching prioritization and coordination. This does not necessarily require a new entity. Instead, the development of a Delta-Suisun nutrient science plan could be coordinated among the Bay-wide nutrient strategy participants, the IEP, and other entitites. Developing such a coordinated nutrient science program is consistent with recent recommendations in the Delta Plan V6.0.

2. NH_4^+ inhibition hypothesis*:*

2.a To identify the specific science questions and the types of studies needed to better understand the hypothesized mechanisms of the NH_4^+-inhibition conceptual model, it would be both helpful and efficient to convene a science panel. This panel should consist of regional scientists working on phytoplankton ecology and nutrient issues in the Bay, as well as outside experts. The panel would explore the detailed evidence from studies in San Francisco Bay and literature from other systems and identify: science issues on which there is consensus among the panelists; outstanding scientific questions; and studies that need to be carried out to address the outstanding questions. It is recommended that the panel develop a brief consensus document summarizing their observations and recommendations. Such a document could be a key component of the Suisun nutrient science plan mentioned above..

2.b. In parallel with any field or experimental studies, modeling work should be carried out to evaluate the potential quantitative importance of NH_4^+-inhibition at the ecosystem scale, relative to other factors known to play important roles in limiting primary production rates (e.g., light limitiation) or biomass accumulation (clam grazing, residence time) in Suisun Bay. Thus far this issue has not been adequately investigated. Such an analysis could be carried with relatively basic biogeochemical models and existing data, and using current parameterizations of the proposed mechanisms. These modeling efforts have benefits well beyond testing the NH_4^+ hypothesis, in that they will simultaneously yield tools for quantitatively synthesizing existing nutrient and phytoplankton data in Suisun Bay and other embayments, identifying data and monitoring needs, and informing the broader modeling strategy for the Bay.

3. NH_4^+ toxicity to copepods: If toxicity to copepods from NH_4^+ will be among the issues that will inform nutrient management decisions in Suisun Bay, it would worthwhile to conduct further investigations. While the copepod toxicity study by Teh et al. (2011) was carefully executed, it has not yet been replicated. Furthermore, although there is some support for the proposed toxicity mechanism in the literature, only a handful of studies have been published on NH_4^+ toxicity to aquatic invertebrates, and none of those studies used copepods as the test organism. Prior to beginning work it would be valuable to have the study design peer reviewed, and to have broad buy-in among regulators and stakeholders (see recommendation #1). Teh et al. (2011) observed an effect in the lowest dosed samples, and treatments at lower NH_4^+ concentrations would be needed to establish a no observed effect level (NOEL). In addition, treatments using salinity and pH ranges relevant to Suisun Bay would be needed, since copepod sensitivity to NH_4^+ could vary with salinity. While other more nuanced questions and complex study designs may eventually be warranted (e.g., effect of food limitation plus NH_4^+), replicating the chronic toxicity experiment first, and determining if similar or different thresholds are observed, is a logical next step.