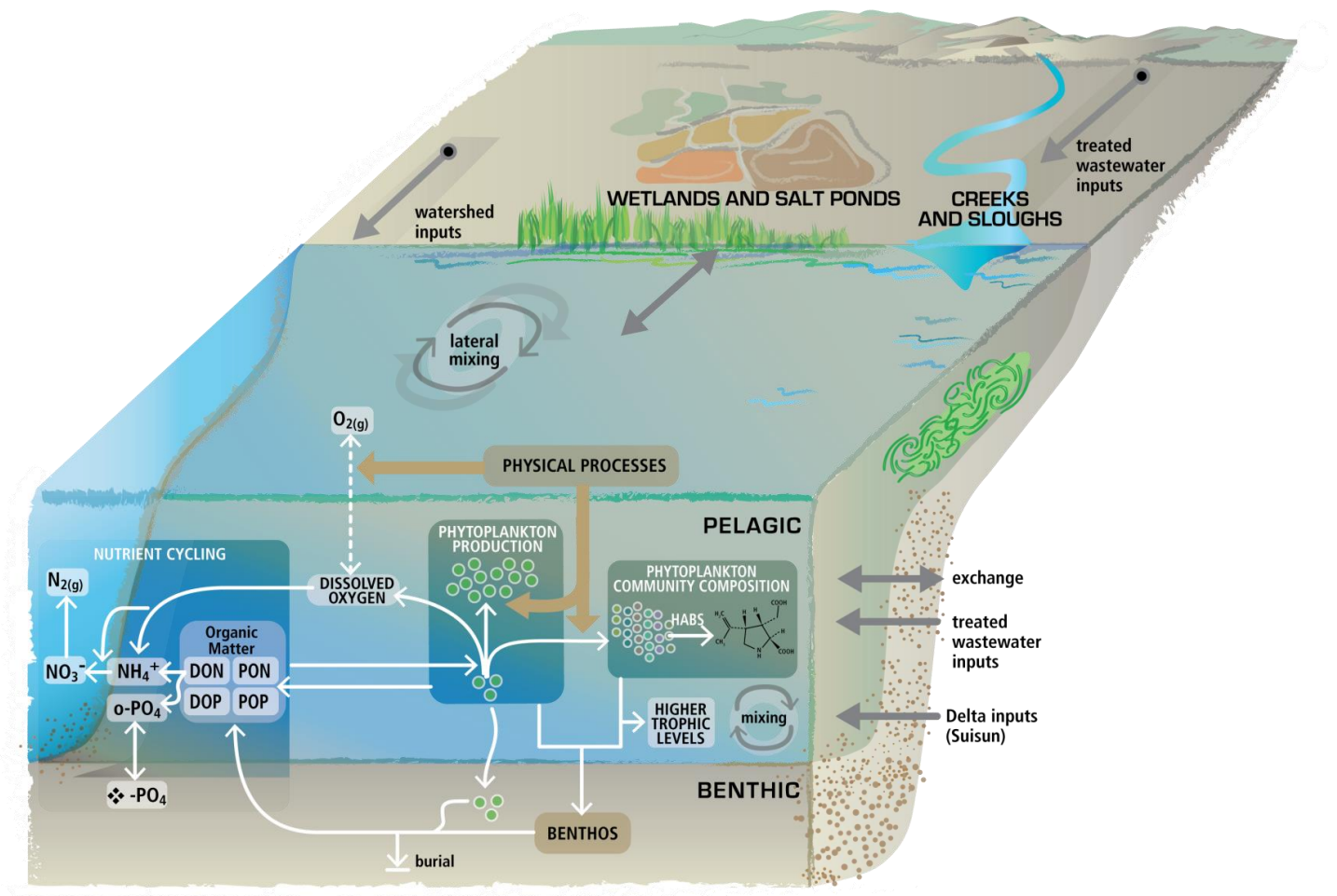# Scientific Foundation for the San Francisco Bay Nutrient Management Strategy

Draft FINAL – October 2014

David B Senn, Emily Novick, and additional co-authors to be determined

*Contact: davids@sfei.org

Summary

Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) are essential nutrients for primary production that supports estuarine food webs. However DIN and DIP concentrations in San Francisco Bay (SFB) greatly exceed those in other US estuaries where water quality has been impaired by nutrient pollution. SFB receives high nutrient loads from treated wastewater effluent, agricultural runoff, and stormwater.SFB has long been recognized as a nutrient-enriched estuary, but one that has exhibited resistance to some of the classic symptoms of nutrient overenrichment, such as high phytoplankton biomass and low dissolved oxygen. SFB receives high nutrient loads from treated wastewater effluent, agricultural runoff, and stormwater. Research and monitoring in SFB over the last 40 years have identified several factors that have historically imparted resistance to the adverse effects of high nutrient loads: high turbidity, strong tidal mixing, and abundant filter-feeding clam populations, all of which tend to limit the efficiency with which DIN and DIP are converted into phytoplankton biomass. While these factors have arguably had a protective effect in many areas of SFB with respect to nutrients, they havenegatively impacted the northern estuary by severely limiting food web productivity there.

However, recent observations indicate that SFB's resistance to high nutrient loads may be weakening. These observations include: a 3-fold increase in summer-fall phytoplankton biomass in South Bay since 1999; frequent detections of algal species that have been shown in other nutrient-rich estuaries to form harmful blooms; frequent detection of the toxins microcystin and domoic acid that are produced by some types of algae; an unprecedented red tide bloom in Fall 2004; low dissolved oxygen in some margin habitats, including sloughs and salt ponds; and studies suggesting that the chemical forms of nitrogen can decrease phytoplankton productivity or alter their community composition. To address growing concerns that SFB's response to nutrients is changing, the San Francisco Bay Regional Water Quality Control Board worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy (NMS), which lays out an overall approach for building the scientific understanding to support well-informed nutrient management decisions.

Among its early priorities, the NMS recognized the need for a conceptual model to lay the scientific foundation to guide the NMS' implementation. This report targets that need and aims to achieve four main goals:

  i.   Develop conceptual models connecting nutrient loads and cycling with ecosystem response in SFB;
 ii.   Apply those conceptual models to identify scenarios under which nutrient-related impairment may occur in SFB's subembayments; and
iii.   Identify knowledge and data gaps that need to be addressed in order for well-informed, science-based decisions to be made about how best to manage nutrient loads to mitigate or prevent adverse impacts.
 iv.   Develop an approach to prioritizing among data and knowledge gaps, and apply that approach to generate an initial recommended set of highest priority activities to inform the development of a science plan to guide NMS implementation.

This report was developed in collaboration with a team of regional scientists whose areas of expertise cover a range of relevant disciplines (see Table 1.1). Its main observations and recommendations are:

1. Changes in SFB's response to nutrient loads over the past decade, combined with the Bay's high nutrient loads and concentrations, justify growing concerns about elevated nutrients.

2. The future trajectory of SFB's response to nutrients is uncertain. One plausible trajectory is that SFB maintains its current level of resistance to the classic effects of high nutrient loads and no further degradation occurs. A second, equally plausible scenario is that SFB's resistance to nutrients continues to decline until adverse impacts become evident. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for future impairment. Any major reductions in loads to SFB will take years-to-decades to implement. Thus, if future problems are to be averted, potential impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset.

3. By considering current conditions in SFB, trends of changing ecosystem response, and a conceptual model for SFB's response to nutrients, we identified the following highest priority issues:
   a) Determine whether increasing biomass signals future impairment. This issue is most pertinent for Lower South Bay and South Bay.
   b) Characterize/quantify the extent to which excess nutrients contribute now, or may contribute in the future, to the occurrence of HABs/NABs and phycotoxins.
   c) Determine if low DO in shallow habitats causes adverse impacts, and quantify the contribution of excess nutrients to that condition.
   d) Further evaluate other hypotheses for nutrient-related adverse impacts to ecosystem health, including nutrient-induced changes in phytoplankton community composition and ammonium inhibition of primary production. That evaluation – to include data analysis, additional experimentation, or modeling – should assess their potential quantitative importance, and help to determine if they should be considered among the highest priority issues.
   e) Test future scenarios that may lead to worsening conditions through the use of numerical models.
   f) Quantify the contributions of nutrients by sources in different areas of the Bay, considering both their transport and in situ transformations and losses.
   g) Evaluate the potential effectiveness of various nutrient management strategies at mitigating or preventing adverse impacts.

4. Although concern related to changing ecosystem response in SFB is warranted, widespread and severe nutrient-related impacts do not currently appear to be occurring, based on existing sampling locations and parameters commonly measured. This apparent lack of current severe impacts translates into time for conducting investigations to improve understanding of SFB's response to nutrients and allows for sound, science-based management plans to be developed and implemented. That said, the considerable amount of time required to implement any management strategy raises the level of urgency such that work should move forward expeditiously.

5. Given the stakes of no action - and the time required for data collection, analysis, and modeling tools to reach a useable state - work needs to move forward in parallel on implementing multiple aspects of the Nutrient Strategy. A well-coordinated program is needed to maximize the

effectiveness and efficiency of this effort. That program needs to integrate seamlessly across what might otherwise be (or become) semi-independent program areas. Specifically, we recommend the following set of highly-integrated program areas:

a) Monitoring: Develop and implement a sustainably-funded and regionally administered monitoring program that continues routine monitoring, and fills newly-identified data gaps relevant to nutrients;

b) Modeling: Develop and apply linked hydrodynamic and water quality models to integrate observations, identify critical data gaps (to be addressed through monitoring or experimental studies), quantify processes at the ecosystem scale, and evaluate future scenarios (including management alternatives);

c) Observational and Experimental Studies: Undertake special studies (field investigations, controlled experiments) to address the highest priority knowledge and data gaps identified in #3; and

d) Data Synthesis and Interpretation: Analysis of existing and newly collected data (from monitoring and experimental studies), incorporatingmodels, to improve understanding of linkages between nutrients and ecosystem response and to inform the development of an assessment framework.

6. The Delta/Suisun boundary, while an important regulatory boundary, is not meaningful from ecological and loading standpoints. Nutrient loads to and transformations within the Delta exert considerable influence over nutrient loads to and ambient concentrations within Suisun, San Pablo, and Central Bays. Furthermore, the ecology and habitat quality of the Delta and Suisun Bay are tightly coupled. A unified approach – one that spans the Bay-Delta continuum - for evaluating the impacts of nutrients on beneficial uses will best serve both ecosystem health in the Bay-Delta and the information needs of environmental managers.

The report is lengthy, but the majority of its length comes from sections devoted to the development of a detailed conceptual model (Sections 5-9). For a higher-level read that still covers the key issues, main findings, and recommendations, we suggest reading the following sections:

- Sections 1-2: brief description of report goals and approach, and background on the NMS.
- Section 3: Overview of current conditions and a description of how nutrient-related problems would be expected to manifest in San Francisco Bay
- Section 4: Brief description of the conceptual model structure/approach
- Section 11: Identifying highest the priority scenarios, science questions, and data/knowledge gaps
- Section 12: Summary of main observations and recommendations

Acknowledgements

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1 Introduction

San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary, but one that has exhibited resistance to some of the classic symptoms of nutrient overenrichment, such as high phytoplankton biomass and low dissolved oxygen. However, recent observations suggest that SFB's resistance to high nutrient loads is weakening. The combination of high nutrient concentrations and changes in environmental factors that regulate SFB's response to nutrients has generated concern about whether SFB is trending toward, or may already be experiencing, adverse impacts due to elevated nutrient loads. In response to these concerns, the San Francisco Bay Regional Water Quality Control Board worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy (NMS),[1] which lays out an overall approach for building the scientific understanding to support well-informed nutrient management decisions. Among its early priorities, the NMS recognized the need for a conceptual model to lay the scientific foundation to guide the NMS' implementation. This report targets that need and aims to achieve four main goals:

    i.   Develop conceptual models connecting nutrient loads and cycling with ecosystem response in SFB;

    ii.   Apply those conceptual models to identify scenarios under which nutrient-related impairment may occur in SFB's subembayments; and

    iii.   Identify knowledge and data gaps that need to be addressed in order for well-informed, science-based decisions to be made about how to best manage nutrient loads to mitigate or prevent adverse impacts.

    iv.   Develop an approach to prioritizing among data and knowledge gaps, and apply that approach to generate an initial recommended set of highest priority activities to inform the development of a science plan to guide NMS implementation.

Audience, anticipated use, and approach

The report's approach and structure are summarized in Figure 1.1. Its primary intended audience includes technically-oriented regulators, decision makers, and other stakeholders. With that audience in mind, the report assumes a certain baseline familiarity with SFB as well as a basic understanding of the biology, nutrient cycling, biogeochemistry, and physical processes in estuaries. The report is an outgrowth of workshops and discussions over the past 2 years with a team of regional scientists whose areas of expertise cover a range of relevant disciplines and much of whose work has focused on San Francisco Bay (Table 1.1).

The report's main anticipated uses are to inform and help prioritize the types of special studies, monitoring, and modeling that are needed to inform management decisions by identifying major priority science issues and related knowledge and data gaps; and inform the development of criteria that will be used to assess ecosystem health and determine whether subembayments or specific habitats within SFB are experiencing nutrient-related impairment. Figure 1.1 summarizes the report's structure and the overall approach. The report begins by identifying what a nutrient-related problem would look like in SFB, and then summarizes recent observations that suggest SFB's response to nutrients is changing (Section 3). Focused by this problem statement, we present a the conceptual model, layed out as a series of linked modules, extending from nutrient loads and cycling to

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

ecosystem response (Sections 5-10). Each module ends with a table that summarizes data availability and state of knowledge about relevant processes. The conceptual models are then used to identify scenarios under which adverse impacts may occur, and scenarios under which those impacts may be mitigated or prevented (Section 11). The report closes with a summary of major observations and recommendations (Section 12). The report draws from several decades of research and monitoring in San Francisco Bay by USGS[2], multiple academic institutions, and the Interagency Ecological Program[3], and also builds upon other recent reports (e.g., McKee et al., 2011).
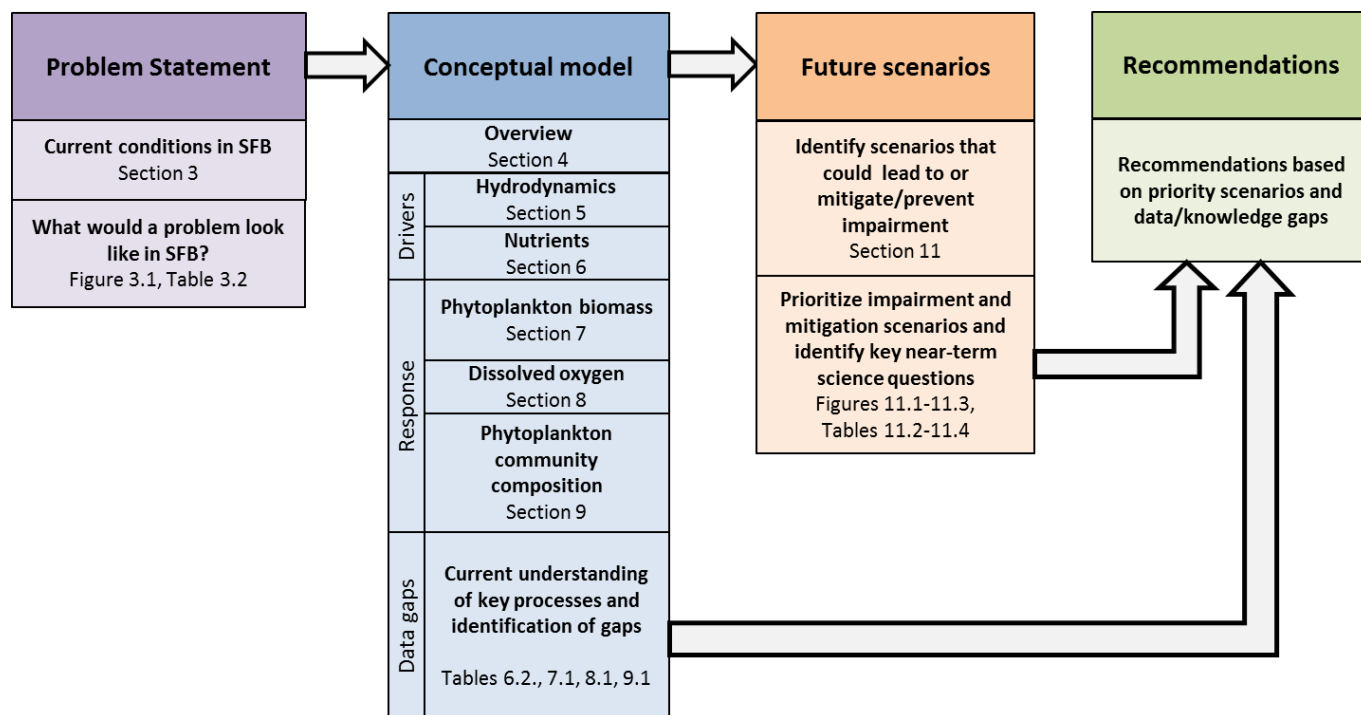
Figure 1.1 Report structure and approach

Table 1.1 Conceptual model technical team

	Affiliation	Expertise
James Cloern, PhD	U.S. Geological Survey	Estuarine biogeochemistry and ecology
Michael Connor, PhD	East Bay Dischargers Authority	Wastewater treatment and receiving water quality issues
Richard Dugdale, PhD	San Francisco State University, Romberg Tiburon Center	Nutrient fluxes and phytoplankton productivity
James T. Hollibaugh, PhD	University of Georgia	Estuarine microbial communities and their role in biogeochemical processes
Wim Kimmerer, PhD	San Francisco State University, Romberg Tiburon Center	Zooplankton ecology
Lisa Lucas, PhD	U.S. Geological Survey	Linked hydrodynamic and biological modeling
Raphael Kudela, PhD	University of California, Santa Cruz	Phytoplankton physiology and ecology
Emily Novick, MS	San Francisco Estuary Institute	Environmental engineering, nutrient biogeochemistry
Anke Mueller-Solger, PhD	U.S. Geological Survey	Estuarine and freshwater food webs
David Senn, PhD	San Francisco Estuary Institute	Contaminant fate and transport, nutrient biogeochemistry
Mark Stacey, PhD	University of California, Berkeley	Hydrodynamics, transport and mixing in estuaries and oceans
Martha Sutula, PhD	Southern California Coastal Water Research Project (SCCWRP)	Nutrient biogeochemistry and eutrophication

2. Background

2.1 San Francisco Bay and the Bay Area

San Francisco Bay (SFB) encompasses several subembayments of the San Francisco Estuary, the largest estuary in California (Figure 2.1). SFB is surrounded by remnant tidal marshes, intertidal and subtidal habitats, tributary rivers, the freshwater "Delta" portion of the estuary, and the large mixed-land-use area known as the San Francisco Bay Area (Figure 2.2.A). San Francisco Bay hosts an array of habitat types (Figure 2.1), many of which have undergone substantial changes in their size or quality due to human activities. Urban residential and commercial land uses comprise a large portion of Bay Area watersheds, in particular those adjacent to Central Bay, South Bay and Lower South Bay (Figure 2.2.A). Open space and agricultural land uses occupy larger proportions of the watersheds draining to Suisun Bay and San Pablo Bay. The San Joaquin and Sacramento Rivers drain 40% of California, including agricultural-intensive land use areas in the Central Valley. Flows from several urban centers also enter these rivers, most notably Sacramento which is ~100 km upstream of Suisun Bay along the Sacramento River.

SFB receives high nutrient loads from 42 public owned wastewater treatment works (POTWs) servicing the Bay Area's 7.2 million people (Figure 2.2.B). Several POTWs carry out nutrient removal before effluent discharge; however the majority perform only secondary treatment without additional N or P removal. Nutrients also enter SFB via stormwater runoff from the densely populated watersheds that surround SFB (Figure 2.2.A). Flows from the Sacramento and San Joaquin Rivers deliver large nutrient loads, and enter the northern estuary through the Sacramento/San Joaquin Delta (not shown, immediately east of the maps in Figure 2.1 and 2.2).

2.1 San Francisco Bay Nutrient Strategy

Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) are essential nutrients for primary production that supports SFB food webs. However DIN and DIP concentrations in SFB greatly exceed those in other US estuaries where water quality has been impaired by nutrient pollution (Cloern and Jassby, 2012). SFB has long been considered relatively immune to its high nutrient loads. For example, the original San Francisco Bay Regional Basin Plan from 1975 stated that only limited treatment for nutrients was necessary because the system was considered to be light limited (SFBRWQCB, 1975). Research and monitoring over the last 40 years have identified several factors that impart SFB with its resistance to high nutrient loads (e.g., see Cloern and Jassby 2012; Cloern et al., 2007; Kimmerer and Thompson, 2014): high turbidity (low light), strong tidal mixing (breaks down stratification and fully mixes the water column, resulting in low light availability), and abundant filter-feeding clam populations (remove phytoplankton from the water column).

However, recent studies indicate that the response to nutrients in SFB is changing, indicate that the system is poised to potentially experience future impacts, or suggest that current nutrient levels are already causing adverse impacts. These observations include: a 3-fold increase in summer-fall phytoplankton biomass in South Bay since the late 1990s; frequent detections in SFB of algal species that have been shown in other nutrient-rich estuaries to form harmful blooms; detection of algal toxins Bay-wide; an unprecedented red tide bloom in Fall 2004; and studies suggesting that the chemical forms of nitrogen can influence phytoplankton productivity and composition. To address

growing concerns that SFB's response to nutrients is changing and that conditions may be trending toward adverse impacts due to elevated nutrient loads, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) worked collaboratively with stakeholders to develop the San Francisco Bay Nutrient Management Strategy[4], which lays out an approach for gathering and applying information to inform management decisions. Overall, the Nutrient Management Strategy aims to answer four fundamental questions:

1. Is SFB experiencing nutrient-related impairment, or is it likely to in the future?
2. What are the major nutrient sources?
3. What nutrient loads or concentrations are protective of ecosystem health?
4. What are efficacious and cost-efficient nutrient management options for ensuring that Bay beneficial uses are protected?
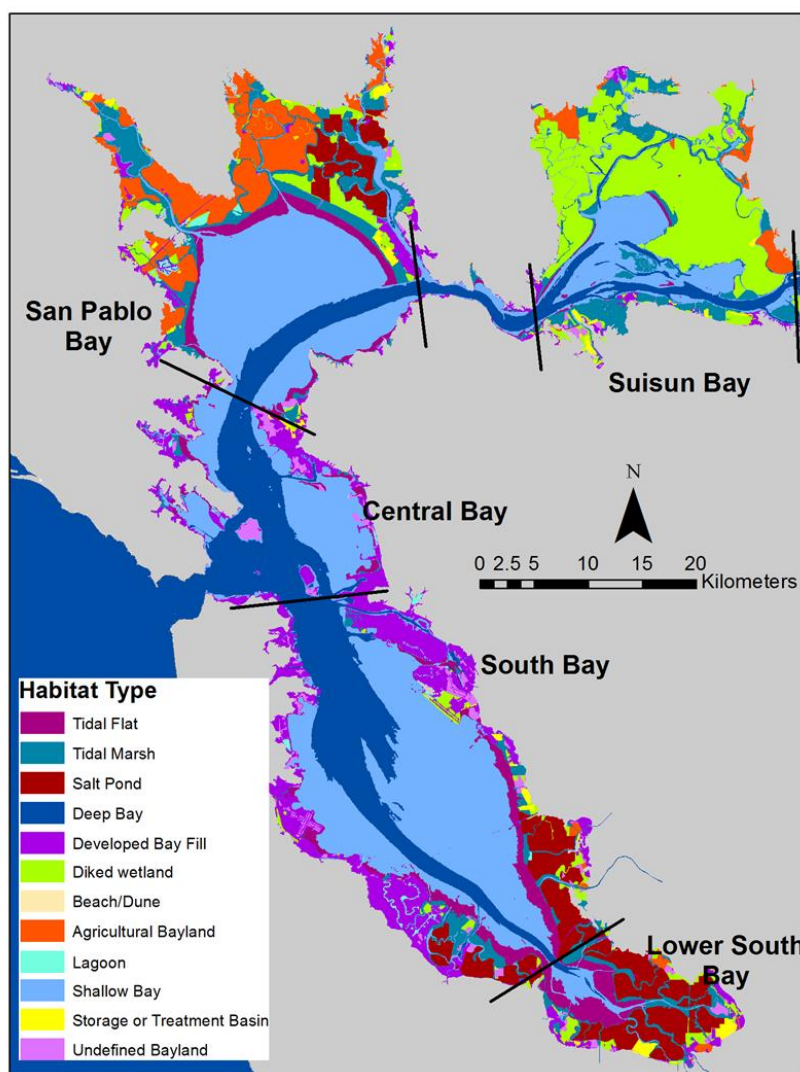
Figure 2.1 Habitat types of SFB and surrounding Baylands. Water Board subembayments boundaries are shown in black. Habitat data from CA State Lands Commission, USGS, UFWS, US NASA and local experts were compiled by SFEI.

The indications of changing SFB response to nutrients have come to the fore at a time when the availability of resources to continue assessing the Bay's condition is uncertain. Since 1969, a USGS research program has supported water-quality sampling in the San Francisco Bay. This USGS program collects monthly samples between the South Bay and the lower Sacramento River to measure salinity, temperature, turbidity, suspended sediments, nutrients, dissolved oxygen and chlorophyll a. The USGS data, along with sampling conducted by the Interagency Ecological Program (IEP), provide coverage for the entire Bay–Delta system (Figure 2.3). The San Francisco Bay Regional Monitoring Program (RMP) has no independent nutrient-related monitoring program, but instead contributes approximately 20% of the USGS data collection cost. The Nutrient Strategy

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

highlights the need for a regionally-supported, long-term monitoring program that provides the information that is most needed to support management decisions in the Bay.

The timing also coincides with a major state-wide initiative, led by the California State Water Resources Control Board (State Water Board), for developing nutrient water quality objectives for the State's surface waters, using an approach known as the Nutrient Numeric Endpoint (NNE) framework. The NNE framework establishes a suite of numeric endpoints based on the ecological response of a waterbody to nutrient over-enrichment and eutrophication (e.g. excessive algal blooms, decreased dissolved oxygen). In addition to numeric endpoints for response indicators, the NNE approach includes models that link the response indicators to nutrient loads and other management controls. The NNE framework is intended to serve as numeric guidance to translate narrative water quality objectives.

Since San Francisco Bay is California's largest estuary, it is a primary focus of the state-wide effort to develop NNEs for estuaries. Through the Nutrient Strategy, the SFBRWQCB is working with regional stakeholders and with the State Water Board to develop an

Figure 2.3 Location of DWR/IEP and USGS monthly sampling stations. Data from labeled USGS Stations (s6, s15, s18, s21, s27, s36) are used in Figures 5.7, 6.3-6.7 and 7.11.

NNE framework specific to SFB. That effort was initiated by a literature review and data gaps analysis that recommends indicators to assess eutrophication and other adverse effects of nutrient overenrichment in San Francisco Bay McKee et al., 2011)[5]. McKee et al. (2011) evaluated a number of potential indicators of ecological condition for several habitat types based on the following criteria:

- Indicators should have well-documented links to estuarine beneficial uses
- Indicators should have a predictive relationship with nutrient and hydrodynamic drivers that can be easily observed with empirical data or a model

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- Indicators should have a scientifically sound and practical measurement process that is reliable in a variety of habitats and at a variety of timescales
- Indicators must be able to show a trend towards increasing or/and decreasing benefical use impairment due to nutrients

The report recommended focusing on subtidal habitats initially, and proposed the following primary indicators of beneficial use impairment by nutrients: i. phytoplankton biomass; ii. phytoplankton composition; iii. dissolved oxygen; and; iv. algal toxin concentrations. In addition, 'supporting indicators' and 'co-factors' were identified, and are summarized in Table 2.1. Supporting indicators provide additional lines of evidence to complement observations based on primary indicators, and co-factors are essential information to help interpret and analyze trends in primary or supporting indicators.

Regions of SFB behave quite differently with respect to nutrient cycling and ecosystem response due to a combination physical, chemical, and biological factors (discussed in Sections 5-9). To facilitate discussion of spatial trends in this report, SFB was divided into 5 subembayments, as depicted in Figure 2.1: Suisun Bay, San Pablo Bay, Central Bay, South Bay and Lower South Bay (LSB). These subembayment boundaries were chosen based on geographic features and not necessarily hydrodynamic features, represent one of several sets of boundaries that could be used. The boundaries illustrated in Figure 2.1 are similar to those defined by the SFBRWQCB in the San Francisco Bay Basin Plan, although we use different names for the subembayments south of the Bay Bridge.

Table 2.1 Recommended indicators within the context of the SFB NNE. Excerpted from McKee et al 2011

Habitat	Primary Indicators	Supporting Indicators	Co-Factors
All Subtidal Habitat	Phytoplankton biomass, productivity and assemblage Cyanobacteria cell counts and toxin concentration Dissolved oxygen	Water column nutrient concentrations and forms[1] (C,N,P,Si) HAB species cell counts and toxin concentration	Water column turbidity, pH, conductivity, temperature, light attenuation Macrobenthos taxonomic composition, abundance and biomass Sediment oxygen demand Zooplankton
Seagrass Habitat	Phytoplankton biomass Macroalgal biomass & cover Dissolved oxygen	Light attenuation, suspended sediment concentration Seagrass areal distribution and cover Epiphyte load	Water column pH, temperature, conductivity Water column nutrients
Intertidal flats	Macroalgal biomass and cover	Sediment % OC, N, P and particle size Microphytobenthos biomass (benthic chl-a)	Microphytobenthos taxonomic composition
Muted Intertidal and Subtidal	Macroalgal biomass & cover Phytoplankton biomass Cyanobacteria toxin concentration	Sediment % OC, N, P and particle size Phytoplankton assemblage Harmful algal bloom toxin concentration	Water column pH, turbidity, temperature, conductivity Water column nutrients
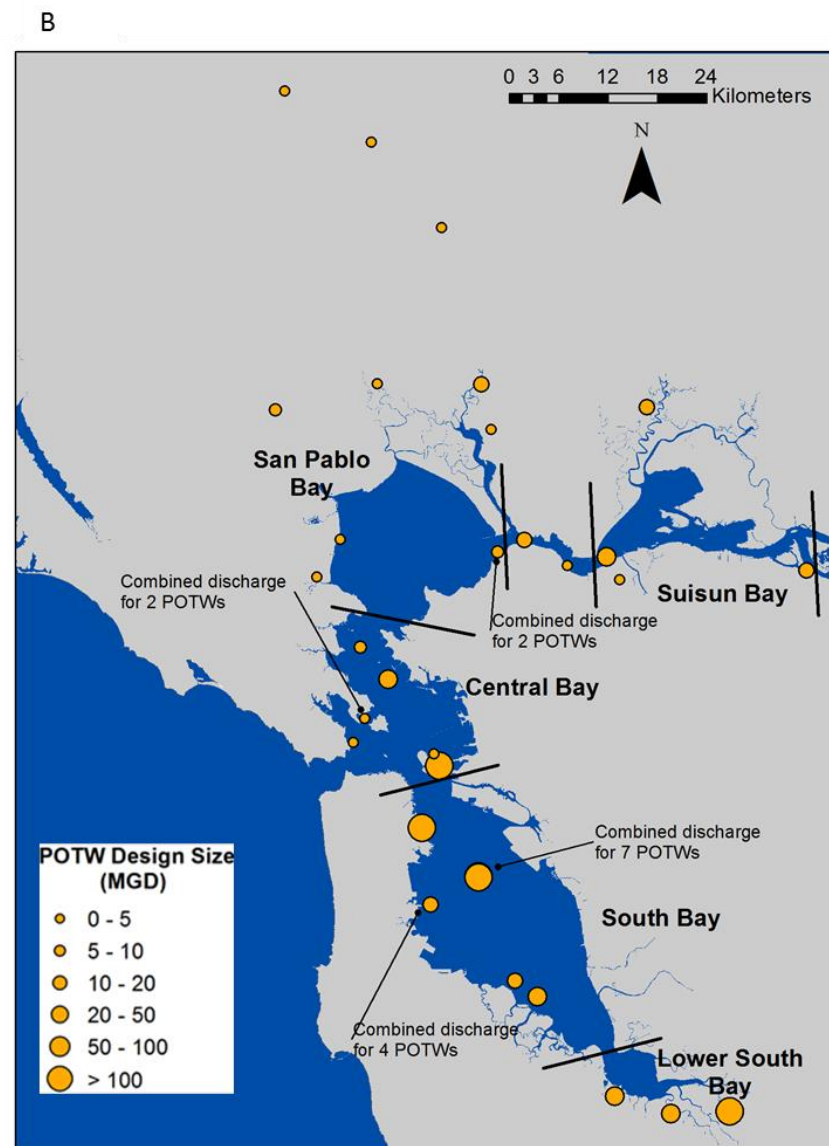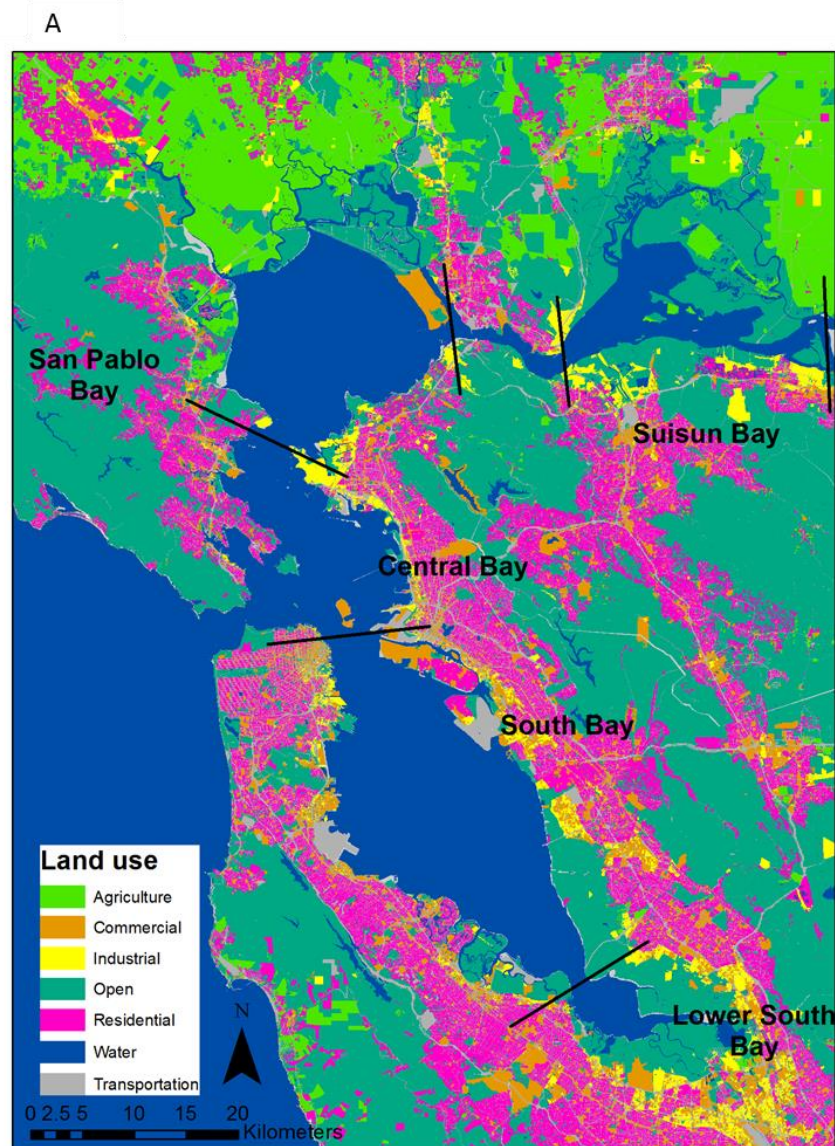
Figure 2.2 A. Land use in watersheds that drain to SFB (Data from Association of Bay Area Governments, 2000). **B.** Location and design size (in million gallons per day) for POTWs that discharge directly in SFB or in watersheds directly adjacent to subembayments. In both figures, Water Board subembayment boundaries are shown in black.

3 Problem Statement

3.1 Recent observations in SFB

In estuarine ecosystems in the US and worldwide, high nutrient loads and elevated nutrient concentrations are associated with multiple adverse impacts (Bricker et al. 2007). N and P are essential nutrients for the primary production that supports food webs in SFB and other estuaries. However, when nutrient loads reach excessive levels they can adversely impact ecosystem health. Individual estuaries vary in their response or sensitivity to nutrient loads, with physical and biological characteristics modulating estuarine response (e.g., Cloern 2001). As a result, some estuaries experience limited or no impairment at loads that have been shown to have substantial impacts elsewhere.

Figure 3.1 illustrates several potential pathways along which excessive nutrient loads could adversely impact ecosystem health in SFB. Each pathway is comprised of multiple linked physical, chemical, and biological processes. Some of those processes are well-understood and data are abundant data to interpret and assess condition; others are poorly understood or data are scarce. In Sections 5-9, we lay out a conceptual model describing the processes creating the pathways between loads and adverse response, and describe the current state of knowledge and data availability.
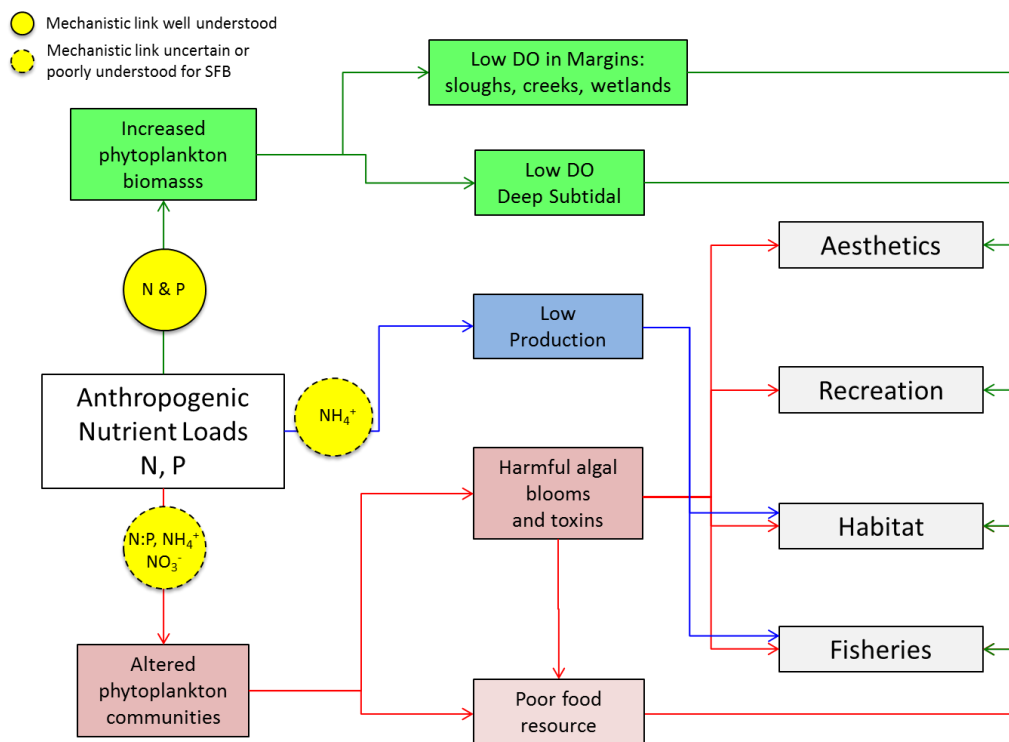
Figure 3.1 Potential adverse impact pathways: linkages between anthropogenic nutrient loads and adverse impacts on uses or attributes of SFB. The shaded rectangles represent indicators that could actual be measured along each pathway to assess condition. Grey rectangles to the right represent uses or attributes of SFB for which water quality is commonly managed. Yellow circles indicate the forms of nutrients that are relevant for each pathway

Current nutrient loads to some SFB subembayments are comparable to or much greater than those in a number of other major estuaries that experience impairment from nutrient overenrichment (Figure 3.2). Consistent with its high loads, SFB has elevated levels of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP) relative to other estuaries (Figure 3.3). Yet SFB does not commonly experience classic symptoms of nutrient overenrichment, such as massive and sustained phytoplankton blooms, or low dissolved oxygen over large areas in the subtidal zone. SFB has been spared the most obvious adverse impacts of high nutrient loads along these pathways due to a combination of factors that have imparted it with a degree of inherent resistance to these effects (Figure 3.4; discussed further in Sections 6 and 8). However, several recent sets of observations indicate that nutrient-related problems may already be occurring in some areas of SFB, or serve as early warnings of problems on the horizon.
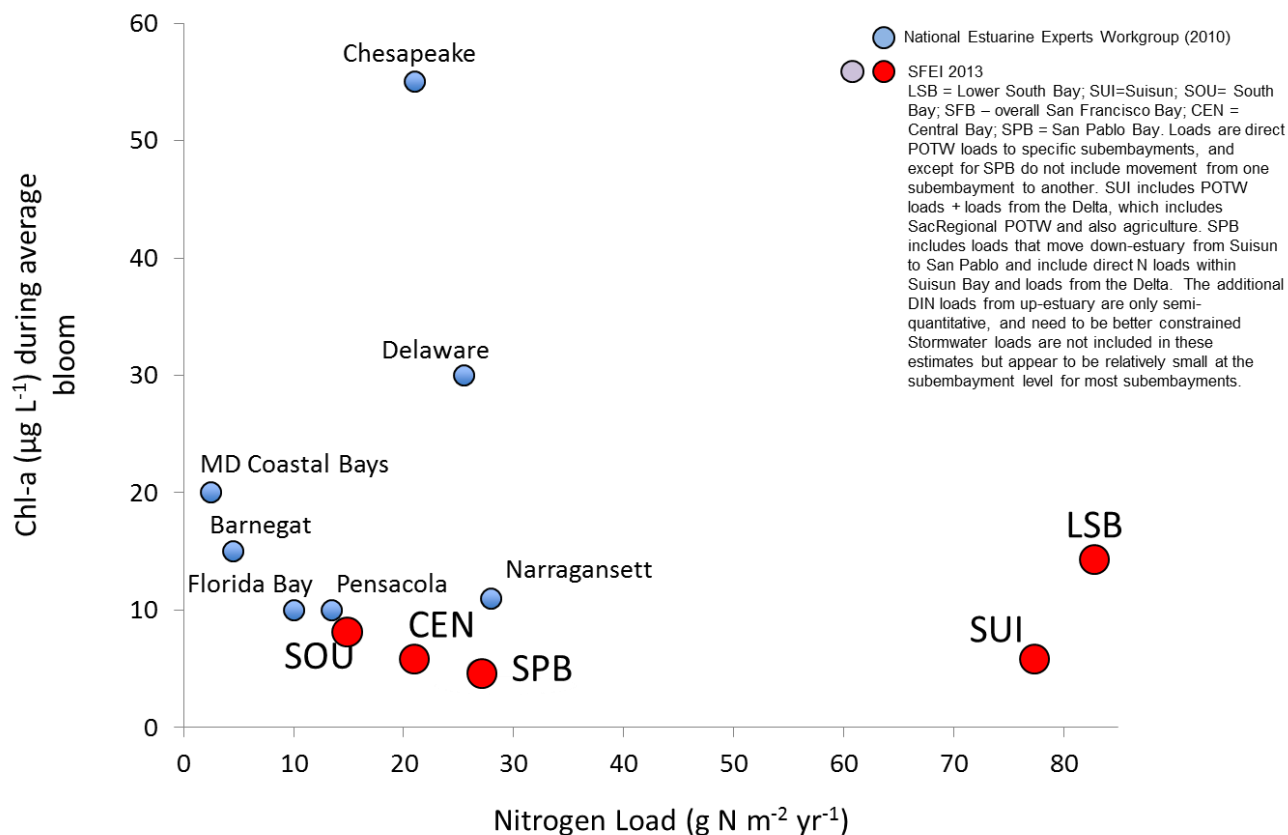
Figure 3.2 Chl-a concentration during an average bloom vs. nutrient loads to San Francisco Bay subembayments, compared to other estuaries that are considered to experience adverse impacts from nutrients. Loads considered include those from POTWs and loads entering from the Delta (which include N derived from upstream treated wastewater effluent and agriculture)
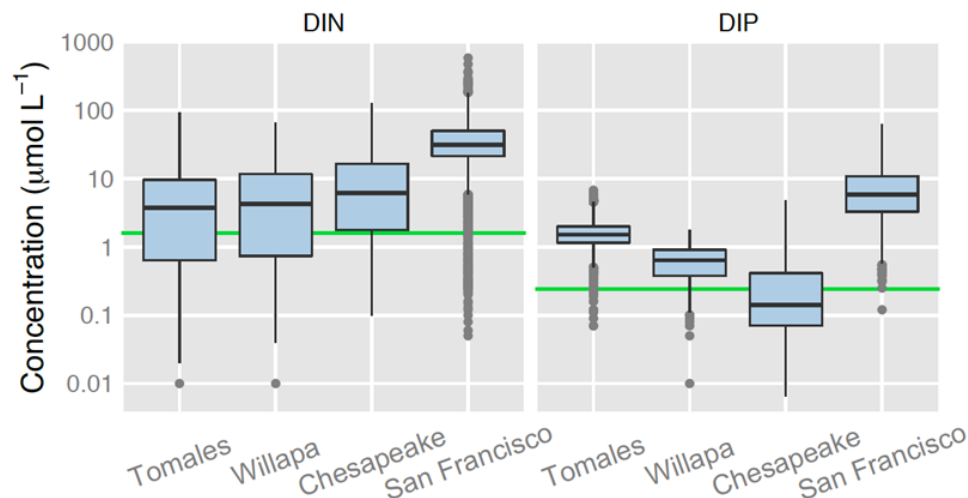
Figure 3.3 Nutrient concentrations in South Bay compared to other estuaries. Source: Cloern and Jassby (2012)

Over the past 15 years, statistically significant increases in phytoplankton biomass have been observed throughout SFB. Most notably summer/fall phytoplankton biomass tripled between the mid-1990s and the mid-2000s (Figure 3.5; Cloern et al., 2007) in South Bay and LSB, representing a shift in trophic status from oligo-mesotrophic (low to moderate productivity system) to meso-eutrophic (moderate to high productivity system) (Cloern and Jassby, 2012). More recent data from South Bay suggests that, at least presently, biomass concentrations have plateaued at a new level instead of continuing to rise (Figure 3.6; SFEI 2014a). Since the late 1990s, Fall blooms have begun occurring regularly in South Bay and LSB, areas where they seldom occurred previously (Figure 3.7 and Cloern and Jassby 2012). While the greatest magnitudes of biomass increase (i.e., in ug/L chl-a) have been observed in South Bay, other SFB subembayments have also experienced statistically significant increases in phytoplankton biomass (J Cloern, personal communication).
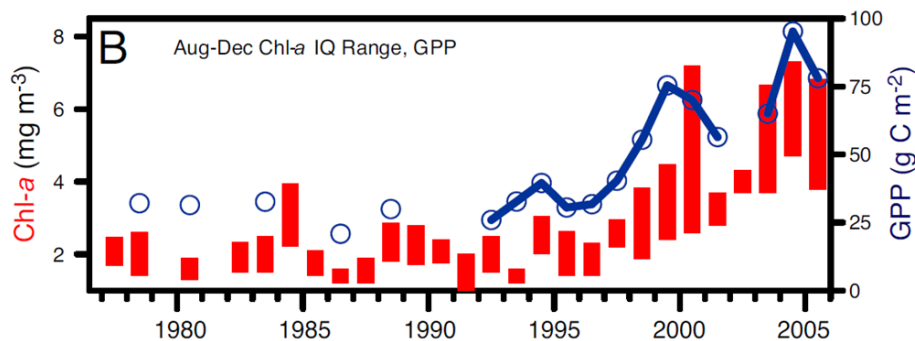
Figure 3.5 Interquartile range of Aug-Dec chl-a concentrations averaged across all USGS stations between Dumbarton Bridge and Bay Bridge, 1977-2005. Source: Cloern et al., 2007

Many other estuaries

1. Relatively high light levels over a substantial portion of the water column due limited light attenuation

2. Sustained periods of salinity- or temperature-stratification, during which phytoplankton residing in the surface layer grow rapidly on high light levels.

Nutrients are efficiently converted to phytoplankton biomass, and dissolved O_2 reaches low levels in the un-ventilated bottom waters where dead phytoplankton are respired by DO-consuming microorganisms. Discussed further in Sections 7 and 8.
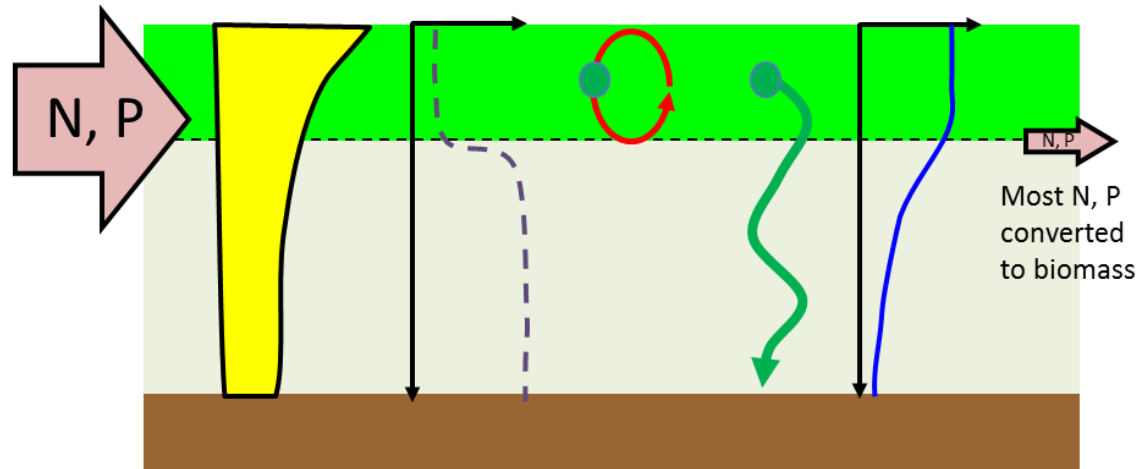
San Francisco Bay

1. High turbidity, and most light attenuated within 1-2m of the surface low light

2. Strong tidal mixing, well-mixed water column

3. High abundance of filter-feeding clams that consume phytoplankton biomass

A lower proportion of nutrients is converted into biomass, benthic grazers reduces standing stock of phytoplankton which overall results in lower productivity, and less DO demand bottom waters due to lower biomass, mixing ventilates bottom waters limiting and so biomass that is respired by DO-consuming microorganisms seldom reaches low levels, prevents development of low DO.

N, P

N, P

Most N, P converted to biomass

ρ

O_2

N, P

Most N, P unutilized
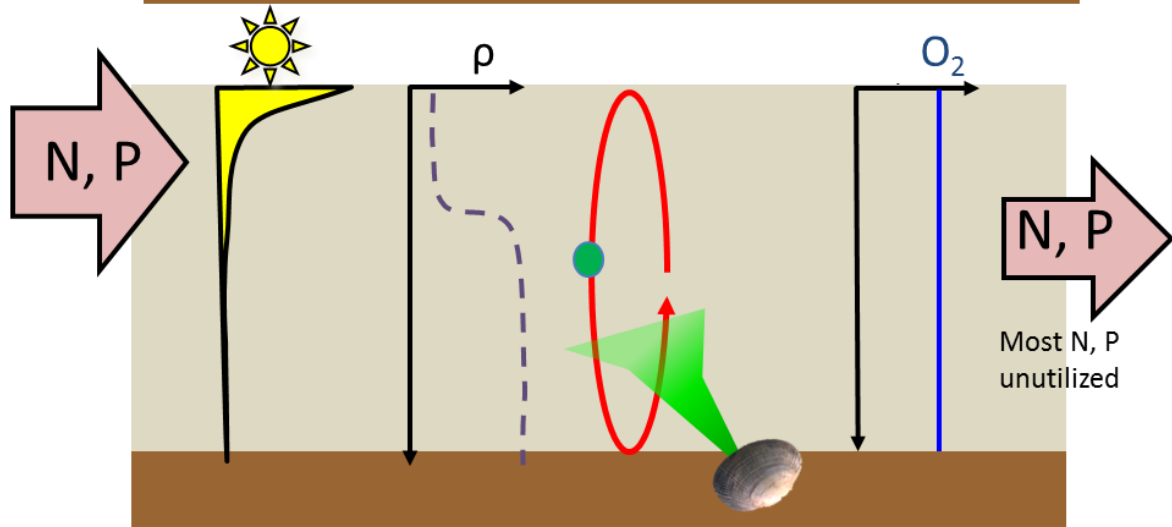
Figure 3.4 Simplified schematic illustrating key differences between SFB and many other estuaries that lead to SFB's attenuated response to nutrients in terms of phytoplankton biomass and dissolved oxygen.
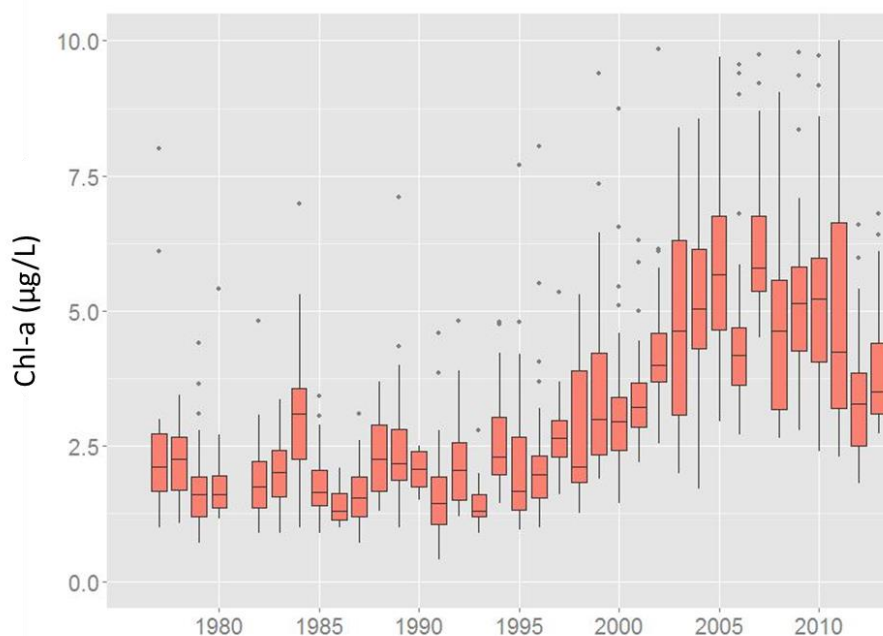
Figure 3.6 Same stations as and data as presented Figure 3.5, with data extended through 2013 (Interquartile range of Aug-Dec chl-a concentrations averaged across all USGS stations between Dumbarton Bridge and Bay Bridge, 1977-2013). Source: SFEI 2014c
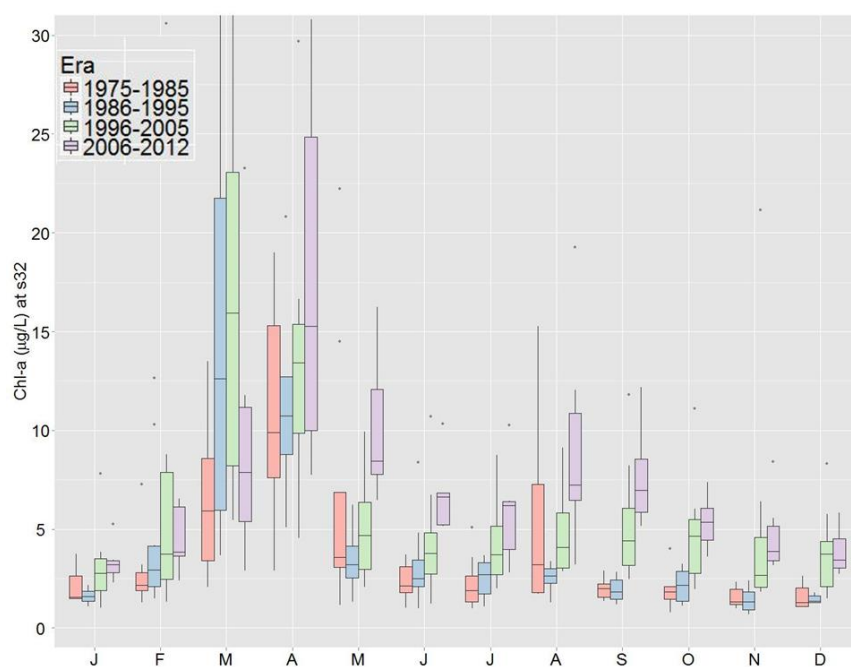
Figure 3.7 Seasonal box plot of chlorophyll-a concentrations near the Dumbarton Bridge (USGS s32), divided into ~10 year eras. Increases in summer baseline chl-a concentrations have been evident since 1996-2005. Fall blooms have also become a regular occurrence. The increases are statistically significant during all months except March and April.

In Suisun Bay, extremely low phytoplankton biomass has defined the system since 1987 (Figure 3.8), coincident in time with the invasive clam, *Potamocorubula amurensis,* becoming widely established. The extended period of low phytoplankton biomass and low rates of primary production are considered to be among the factors contributing to long-term declines in upper trophic level production in Suisun Bay and the Delta by limiting food supply (Baxter et al., 2010; NRC 2012). While the low phytoplankton biomass and productivity in Suisun Bay have generally been attributed to the impacts of *Potamocorbula* and low light levels due to high

suspended sediments (e.g., Kimmerer and Thompson, 2014), recent studies have argued that elevated ammonium (NH_4^+) concentrations in Suisun Bay also limit primary production rates and play an important role in both creating the low biomass conditions and exacerbating food limitation (Dugdale et al., 2007; Dugdale et al., 2012; Parker et al. 2012a,b). Other studies have proposed that high ambient concentrations of nitrate (NO_3^-) and NH_4^+, and altered ratios of N:P cause shifts phytoplankton community composition toward species having poor food quality, adversely impacting Delta food webs (Glibert 2010; Glibert et al., 2011).
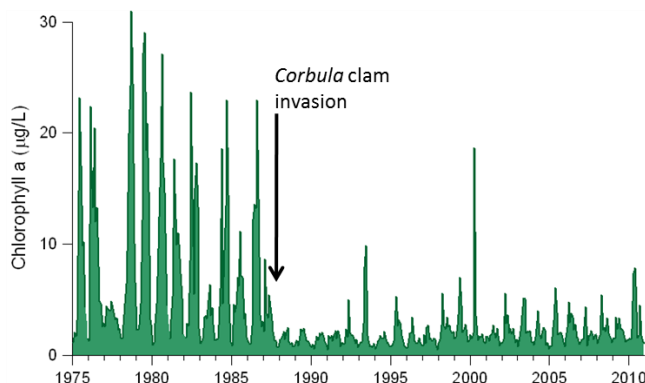
Figure 3.8 Phytoplankton biomass in Suisun Bay, 1975-2010. Source: J Cloern, USGS; Data: USGS, DWR-EMP

Harmful phytoplankton species also represent a growing concern. The harmful algae, *Microcystis spp.*, and the toxin they produce, microcystin, have been detected with increasing frequency in the Delta and Suisun Bay since ~2000 (Lehman et al., 2008). In addition, the HAB toxins microcystin and domoic acid have been detected Bay-wide (Figure 3.9). The ecological
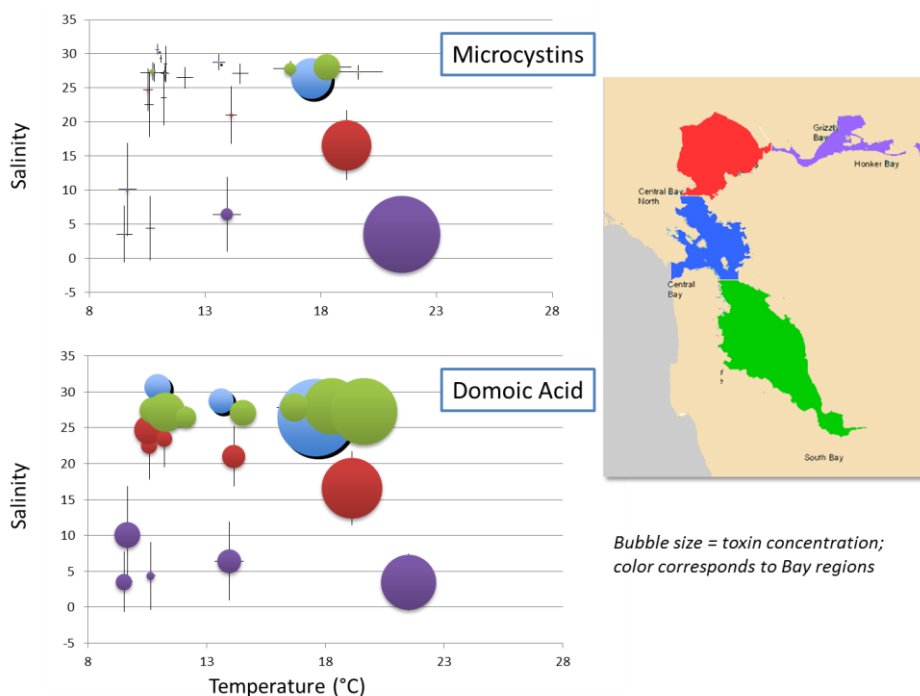
Figure 3.9 HAB toxins detected in SFB during 2011. Bars represent 1 SD for salinity and temperature Source: R. Kudela

Bubble size = toxin concentration; color corresponds to Bay regions

significance of observed toxin levels in the Bay are not yet known. A number of phytoplankton species that have formed harmful algal blooms (HABs) in other systems have been detected throughout SFB (Table 3.1 and Figure 3.10). Although the abundances of HAB-forming

organisms in SFB have not reached levels that would constitute a major bloom, they do periodically exceed thresholds established for other systems (Kudela et al., in prep), and major *Microcystis spp* blooms and elevated microcystin levels have been observed with some regularity in the Delta (Lehman et al., 2008). Moreover, since HAB-forming species are present in SFB and nutrients are abundant, HABs could readily develop should appropriate physical conditions create opportunities that HABs can exploit. In fact, an unprecedented large red tide bloom
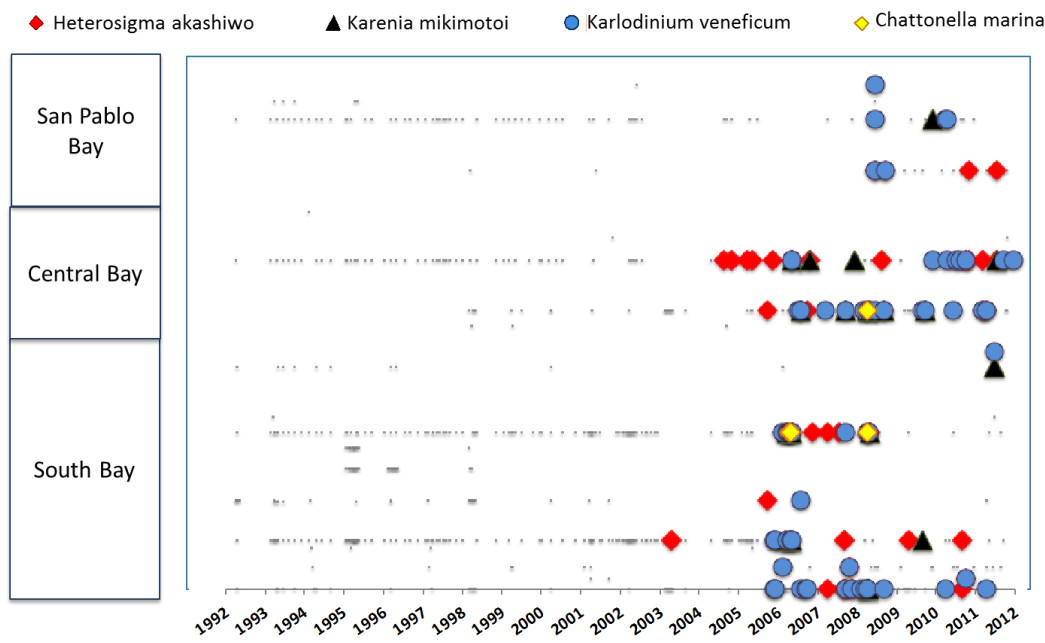
Figure 3.10 Several potentially harmful algal species detected in South Bay, Central Bay, and San Pablo Bay over the past 20 years. Y-axis represents distance to USGS stations from Lower South Bay. Grey dots represent sample collection/analysis, colored dots represent one of the 4 species detected in a collected sample. Source: T Schraga, USGS

occurred in Fall 2004 following a rare series of clear calm days during which the water column was able to stratify, and chl-a levels reached nearly 100 times their typical values (Figure 3.11; Cloern et al. 2005). In addition, harmful-bloom forming species have been detected at elevated abundances in salt ponds in LSB undergoing restoration (Thebault et al., 2008), raising concerns that salt ponds could serve as incubators for harmful species that could then proliferate when introduced into the open bay.
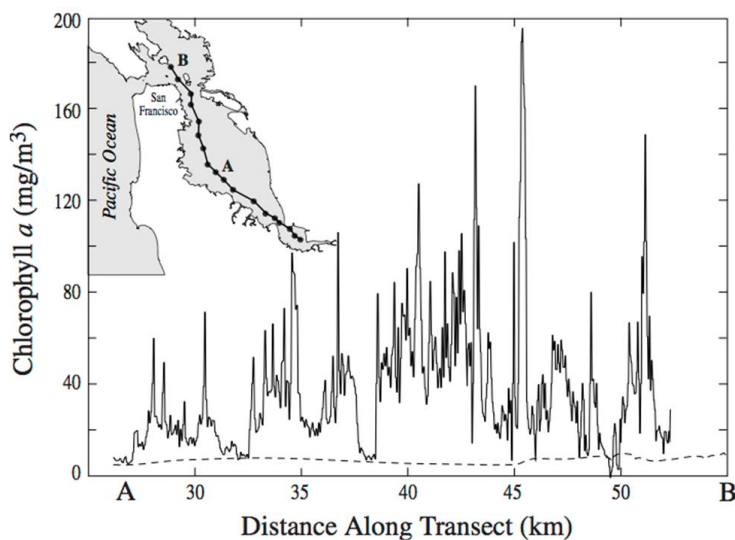
Figure 3.11 Phytoplankton biomass South and Central Bays. Measurements taken during a red tide on 8 September 2004 (solid curve). Phytoplankton biomass returned to typical seasonal levels on 14 September (dashed curve). Inset map shows location of the sampling transect A-B. Source: Cloern et al. 2005

Table 3.1 Potentially harmful algal species detected through USGS science program in SFB: 1992-2012. Source: T Schraga, USGS

Genus/Species	Division/ Phyla	1st observed	Most recent observed	# of times observed	Toxin**	Impact	Location and timing of observations
Alexandrium	Dinoflagellate	1992	2011	247	saxitoxin	neurotoxin, fish kills	South, Central, and San Pablo Bays - Spring and Fall
Amphidinium	Dinoflagellate	1996	2008	36	compounds with haemolytic and antifungal properties	fish kills	South Bay - spring bloom (March-April) and occasionally fall bloom (September-October).
Dinophysis	Dinoflagellate	1993	2011	51	okadaic acid		Central bay
Heterocapsa	Dinoflagellate	1992	2012	394		food web hab, kills shellfish	Found throughout year, but mostly seen in spring and summer, South and Central Bay, occasionally up to San Pablo Bay
Karenia mikimotoi *	Dinoflagellate	2006	2011	22	gymnocins, compounds similar to brevetoxin	kills benthic organisms, fish, birds, + mammals	South bay + Central Bay
Karlodinium veneficum *	Dinoflagellate	2005	2012	63	compounds with hemolytic, ichthyotoxic, and cytotoxic effects	kills fish, birds + mammals	South bay + Central Bay
Heterosigma akashiwo *	Raphidophyte	2003	2011	39	neurotoxin	fish kills	South bay + Central Bay
Pseudo-nitzschia	Diatom	1992	2011	132	domoic acid		Large blooms occurred in central and south Bay (stn 27) in 1990s
Anabaena	Cyanobacteria	1993	2011	24	PSTs		Sacramento River and confluence.
Aphanizomenon flos-aquae	Cyanobacteria	1995	2011	13	PSTs		Sacramento River and confluence. Low #s in South Bay

Table 3.1 continued

Genus/Species	Division/Phyla	1st observed	Most recent observed	# of times observed	Toxin**	Impact	Location and timing of observations
Aphanocapsa	Cyanobacteria	1993	2011	22			South Bay 2005+6, 2011 Delta confluence (San Joaquin source most likely)
Aphanothece sp.	Cyanobacteria	1992	2011	32			South Bay 2005+6, 1990s and 2010-11 Suisun and Sac River
Cyanobium sp.	Cyanobacteria	1999	2008	79	microcystin		South and Central Bay
Lyngbya aestuarii	Cyanobacteria	2011	2011	1	saxitoxin	human health impacts (skin, digestion, respiratory, tumors) and paralytic shellfish poisoning	September 2011 - large bloom in Suisuin area (stn 3)
Planktothrix	Cyanobacteria	1992	2011	23	PSTs		South Bay 2005-2007, 1990s, 2010-11 Suisun and Sac River
Synechococcus sp.	Cyanobacteria	1992	2011	66			South Bay spring (March/April)
Synechocystis	Cyanobacteria	1997	2011	224	microcystin		South Bay and San Pablo Bay, mostly in fall

All of these species have had high biomass in SFBAY. Multiple species are grouped within a genera. If it's a single species, it is listed as such
*Known as exceptionally harmful in temperate estuaries such as in Japan and Atlantic coast estuaries. All were detected for the first time in SFb in the past 10 years and have persisted
** Not all toxins are known. Genera with PST have two or more Paralytic Shellfish Toxins = microsystin, cylindrospermopsin, anatoxin, saxitoxin. All cause Paralytic Shellfish Poisoning. PSTs microcystin and cylindrospermopsin cause liver damage in mammals, anatoxin and saxitoxin damage nerve tissues in mammals (humans, dogs, etc.)
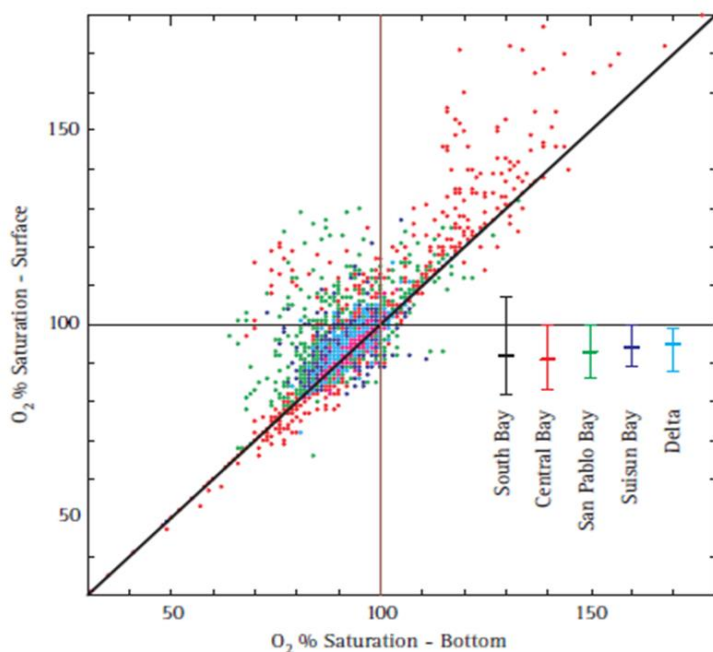
Figure 32. Oxygen concentration as percent saturation in near-surface and near-bottom samples. Color indicates region, and error bars give medians and 10th and 90th percentiles of the data. Data from USGS monitoring program, which focuses on channel stations and the portion of the Delta in the lower Sacramento River.

DO concentrations in deep subtidal habitats throughout the Bay typically remain at levels above 5 mg L^{-1}, (Figure 3.12), the San Francisco Bay Basin Plan standard. However, in LSB, sampling has most frequently occurred at slack high tide. Recent continuous measurements at the Dumbarton Bridge indicate that DO levels at low tide are commonly 1-2 mg/L lower than at high tide during summer months (e.g., Figure 3.13.A; SFEI, 2014c), and can occasionally dip below, 5 mg L^{-1} (SFEI, unpublished data). During Summer 2014, USGS sampling cruises detected DO < 5 mg/L at other deep subtidal stations south of the Dumbarton Bridge during two cruises[6].

Low DO commonly occurs in some shallower margin habitats (Figure 3.14). For example, studies of salt ponds undergoing restoration in LSB show that they experience large diurnal DO fluctuations (Figure 3.15.A; Topping et al., 2009) and occasionally experience sustained periods of anoxia (Figure 3.15.B; Thebault et al., 2008). In some slough habitats of LSB, DO regularly dips below 5 mg L^{-1}, frequently approaches 2 mg L^{-1} (Shellenberger et al., 2008), and at a site in Alviso Slough, DO remained near or below 2 mg L^{-1} for sustained periods (up to 10-12 hours) during Summer 2012 (Figure 3.13.B) and Summer 2014 (SFEI,2014c). Low DO has also been observed in Suisun Marsh, although whether that low DO is linked to nutrient issues in SFB is still being investigated (effluent from managed duck ponds is presumed to be a major cause; Tetra Tech 2013). Under natural conditions, shallow subtidal and tidal wetland habitats commonly experience low DO, and plants and animals native to these habitats are often well-adapted to these DO swings. However, there is a paucity of DO data in margin habitats, and the severity of low DO (frequency, duration, spatial extent, concentration), whether it is impacting biota, and the extent to which excess nutrients cause or contribute to the low DO conditions are all poorly known.

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[6] http://sfbay.wr.usgs.gov/access/wqdata/query/easy.html

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A. Dumbarton   B. Alviso
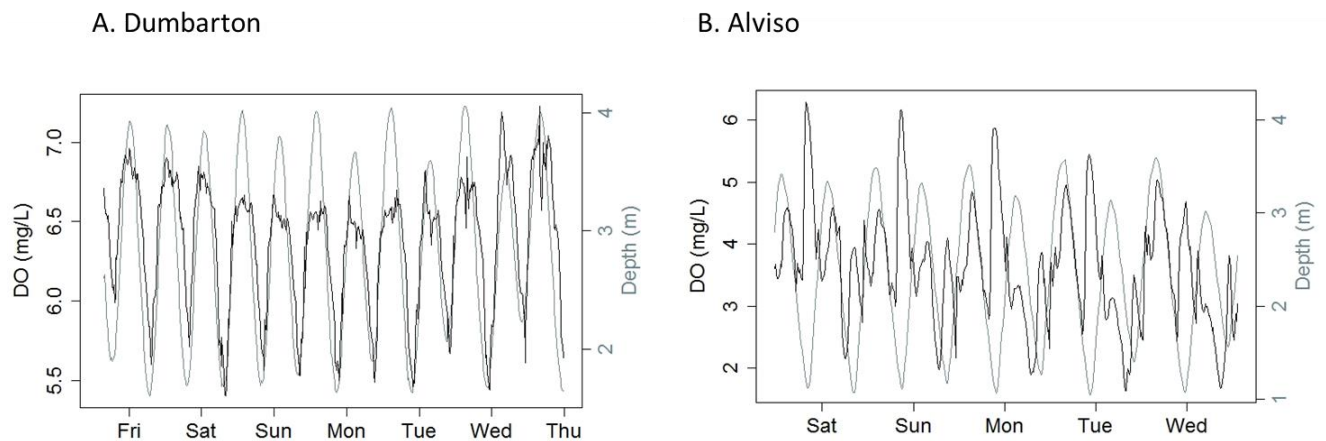
Figure 3.13 Time series of DO (mg/L) and depth at **A.** Dumbarton Bridge and **B.** Alviso Slough, Sep 5-12 2013.

In addition to characterizing and addressing any current nutrient-related problems in SFB, there is a need to anticipate potential future adverse impacts. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for future impairment to develop. Any major reductions in loads to SFB will take years-to-decades to implement. Thus, if future problems are to be averted, potential impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset. A proactive approach to characterizing and managing potential problems – while they are on the somewhat-distant horizon, as opposed to imminent – will allow greater flexibility in the management options that can be pursued.
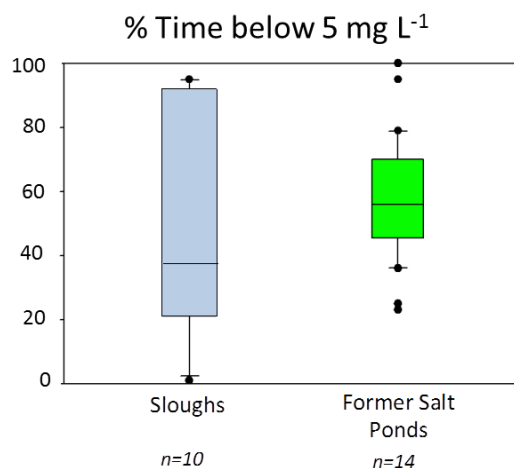
Figure 3.14 Percentage of time DO less than 5 mg/L in sloughs and salt ponds rimming Lower South Bay, based on a review of all available multi-program continuous sensor measurements. Source: SFEI 2014c

A.

B.

Figure 5. Plot of dissolved oxygen data in the water-column as monitored
by dataloggers (Pond A3W)
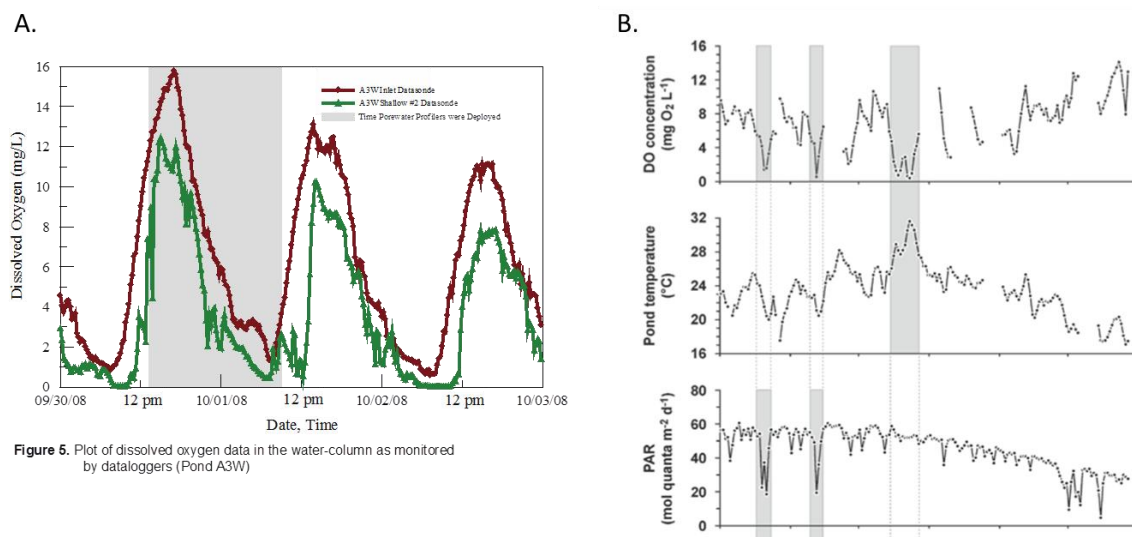
Figure 3.15 A. Dissolved oxygen concentrations in LSB salt pond A3W undergoing restoration Source: Topping et al. 2008 **B.** Dissolved oxygen concentration in LSB salt pond A18. Grey bars indicate time periods when incident light was low (clouds) or temperatures were high enough to inhibit primary production. These factors lead to sustained periods of low DO. Source: Thebault et al. 2008

3.2 What would a problem look like in SFB?

At the outset of the SFB conceptual model development, we asked the question:
What would a nutrient-related problem look like in SFB subembayments, if a problem were currently occurring, or if one was to occur in the future?
This report does not aim to answer the question of whether SFB subembayments are currently impaired or will be in the future. Instead, we used the answers to this question to help focus the conceptual model on issues most relevant for detecting impairment and anticipating potential future impairments, and to identify meaningful and measurable indicators of ecosystem response to nutrients and ecosystem health.

Table 3.2 summarizes nutrient-related adverse impacts (AI) that were identified as plausible in San Francisco Bay, divided into eight categories. The problem categories are specific examples that extend from the more general paths depicted in Figure 3.1.

High phytoplankton biomass can have direct adverse impacts (AI.1) in SFB, through acting as a nuisance (aesthetics, odor) or through direct impacts on biota (e.g., smothering or shading aquatic macrophytes, coatings on bird wings). However, among the most common and problematic impairments due to high phytoplankton biomass is low dissolved oxygen in deep subtidal areas that develops due to degradation of phytoplankton-derived organic matter by oxygen-consuming microorganisms (AI.2). In the case of both high phytoplankton biomass and low DO, the magnitude, duration, and spatial extent are important to consider. Extremely low DO (e.g., <2 mg L^{-1}), and the high phytoplankton biomass that causes it, over large areas for extended periods of time could lead to considerable impairment, whereas moderate DO deficits, or spatially-limited or short-duration events may be less problematic. In addition, low DO occurs

naturally in shallow margin habitats (e.g., sloughs, salt marshes), and native organisms are adapted to these conditions. However, elevated anthropogenic nutrient loads could exacerbate these issues by increasing the intensity of these events (i.e., even lower DO), or increasing the spatial extent, temporal frequency, or duration (AI.3). Thus, both the severity of events and whether they are entirely natural or caused or exacerbated by anthropogenic nutrients need to be considered.

Elevated nutrient concentrations, or changes in relative abundance of nutrient forms, could increase the frequency with which HABs occur, the severity of a HAB event (abundance, duration, spatial extent), and the levels of HAB-related toxins (AI.4). Phycotoxins, i.e., toxins produced by phytoplankton, bioaccumulate and can exert toxicity to consumers at all levels of the food web, including humans. Some phycotoxins also exert direct toxicity (e.g., skin contact). High nutrient loads may also increase the frequency of so-called nuisance algal blooms (NABs), which are not toxic but may degrade aesthetics due to surface scums or odors.

Several recent studies, focused in the northern Bay-Delta, have hypothesized that high NH_4^+ levels contribute to the low biomass and infrequent phytoplankton blooms in Suisun Bay by inhibiting primary production (AI.5), in particular the growth of diatoms (Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al., 2012). Low phytoplankton biomass stands among the factors thought to contribute to ecosystem decline in Suisun Bay and the Delta. To the extent that elevated NH_4^+ contributes to lower productivity, elevated nutrient loads – and in particular NH_4^+ loads – would adversely impact ecosystem health along this pathway (Figure 3.1).

Other recent studies have hypothesized that high nutrient concentrations, elevated NH_4^+, or altered N:P in SFB adversely impacts food webs by shifting phytoplankton community composition away from healthy assemblages and toward suboptimal compositions that do not adequately sustain organisms at higher trophic levels (AI.6; Glibert et al., 2012). Another recent study observed that high NH_4^+ concentrations can exert chronic toxicity on an important Delta/Suisun copepod at concentrations (25 µM) that approach ambient concentrations in some areas along the Sacramento River and in the Delta (Teh et al, 2011). Other studies have argued that high nutrient concentrations or altered N:P can alter individual cell composition in ways that adversely impact primary consumers (Glibert et al., 2013). The latter two examples are included under "Other nutrient-related impacts" (AI.7), along with other potential adverse impact pathways not explicitly noted.

Table 3.2 What would a problem look like in SFB? Plausible adverse impacts (AI).

	Impacted State	Rationale or Link to Beneficial Uses
AI.1	**High Phytoplankton Biomass** High phytoplankton biomass of sufficient magnitude (concentration), duration, and spatial extent that it impairs beneficial uses due to direct or indirect effects (IS.2). This could occur in deep subtidal or in shallow subtidal areas.	Direct impairment due to aesthetics (odors, surface scum) and potentially directly impairing biota (at very high levels, e.g., coating birds wings). Other main concern is through causing low dissolved oxygen (IS.2, IS.3)
AI.2	**Dissolved Oxygen – Deep subtidal** Low DO in deep subtidal areas of the Bay, over a large enough area and below some threshold for a long enough period of time that beneficial uses are impaired.	Fish kills, die-off of beneficial benthos, loss of critical habitat that result in lowered survival or spawning/reproductive success or recruitment success of fish and beneficial benthos.
AI.3	**Low DO – Shallow/margin habitats**: DO in shallow/margin habitats below some threshold, and beyond what would be considered "natural" for that habitat, for a period of time that it impairs beneficial uses	Fish kills, die-off of beneficial benthos, loss of critical habitat that result in lowered survival or spawning/reproductive success or recruitment success of fish and beneficial benthos
AI.4	**HABs/NABs and phycotoxins** Occurrence of HABs/NABs and/or related toxins at sufficient frequency or magnitude of events that habitats reach an impaired state, either in the source areas or in areas to which toxins are transported.	*HABs and phycotoxinx*: Passive or active uptake of toxins, or ingestion of HAB-forming species and accumulation of toxins. Ingestion of bioaccumulated toxins by is harmful to both wildlife and humans through consumption of tainted shellfish or fish. Skin contact and inhalation can also be problematic. *NABs*: Some species are considered nuisance for reasons other than toxins (e.g., rapid biomass production leading to low DO). Impaired aesthetics, surface scums, discoloration, odors
AI.5	**Low Phytoplankton Biomass** Low phytoplankton biomass in Suisun Bay or other habitats due to elevated NH_4^+, which would exacerbate food supply issues.	Suisun Bay is considered a food limited system, and low levels of phytoplankton may contribute to impairment in this highly altered system.
AI.6	**Suboptimal phytoplankton assemblages** Nutrient-related shifts in phytoplankton community composition, or changes in the composition of individual cells (N:P), that result in decreased food quality, and have cascading effects up the food web.	Phytoplankton primary production is the primary food resource supporting food webs in SFB. Changes in the dominant assemblages would impact food quality.
AI.7	**Other nutrient-related impacts.** Other direct or indirect nutrient-related effects that alter habitat or food web structure at higher trophic levels by other pathways.	Several additional nutrient-related impacts on food webs in the northern estuary have been proposed that are not captured by IS.1-IS.6, and that are not explored in detail in this report.

4. Conceptual Model Overview

The conceptual model is described as a set of modules (Sections 5-9) that establish the mechanistic framework connecting nutrient loads with ecosystem response. Major components of the conceptual model are illustrated generally in Figure 4.1.A. The goal in developing this conceptual model was to make explicitly the multiple steps and mechanisms that fall along the path between nutrient loads and ecosystem response, and therefore views biogeochemistry, ecology, and beneficial uses in SFB through a nutrient-centric lens. In particular the conceptual model explores the pathways and mechanisms along the adverse impact pathways illustrated in Figure 3.1 and summarized in Table 3.2, and ties back to the proposed NNE indicators for assessing condition in SFB (Table 2.1).

The conceptual model is organized into five main modules:
- Section 5: Physical processes (hydrodynamics and sediments)
- Section 6: Nutrients
- Section 7: Primary production, with a major focus on phytoplankton biomass
- Section 8: Dissolved Oxygen; and
- Section 9: Phytoplankton Community Composition, HABs, and HAB toxins

The modules considered in this report extend only as far along the food web as phytoplankton biomass and community composition. Zooplankton, benthos, and fish played a central role in shaping the other modules: their habitat and food requirements were used to focus the modules for phytoplankton biomass, phytoplankton community composition, and dissolved oxygen on the most relevant processes and information needs; and the roles of primary consumers (benthic and pelagic grazers) were explicitly considered in as much as they influence phytoplankton biomass, phytoplankton community composition, and carbon flow in the system and are themselves influenced by food quality. Figure 4.1.B depicts the detailed conceptual model, with all components combined. The subsequent sections of this report focus on specific parts of this overall conceptual model. Physical processes play an important role in dictating ecosystem response to nutrients in SFB. Section 5 provides an introduction to hydrodynamic considerations, and hydrodynamic controls are woven throughout the discussions in Sections 6-9. Section 10 briefly summarizes pathways or indicators not included in the conceptual model at this time.

Although SFB's 5 subembayments have very different physical, biogeochemical, and biological characteristics that shape their individual responses to nutrients, a single set of modules was developed for all of SFB. This is appropriate since the same fundamental processes operate in each subembayment. Inter-subembayment differences in nutrient concentrations or forms and ecosystem response arise from differences in the relative importance of major drivers among subembayments, and these differences are discussed within each module.
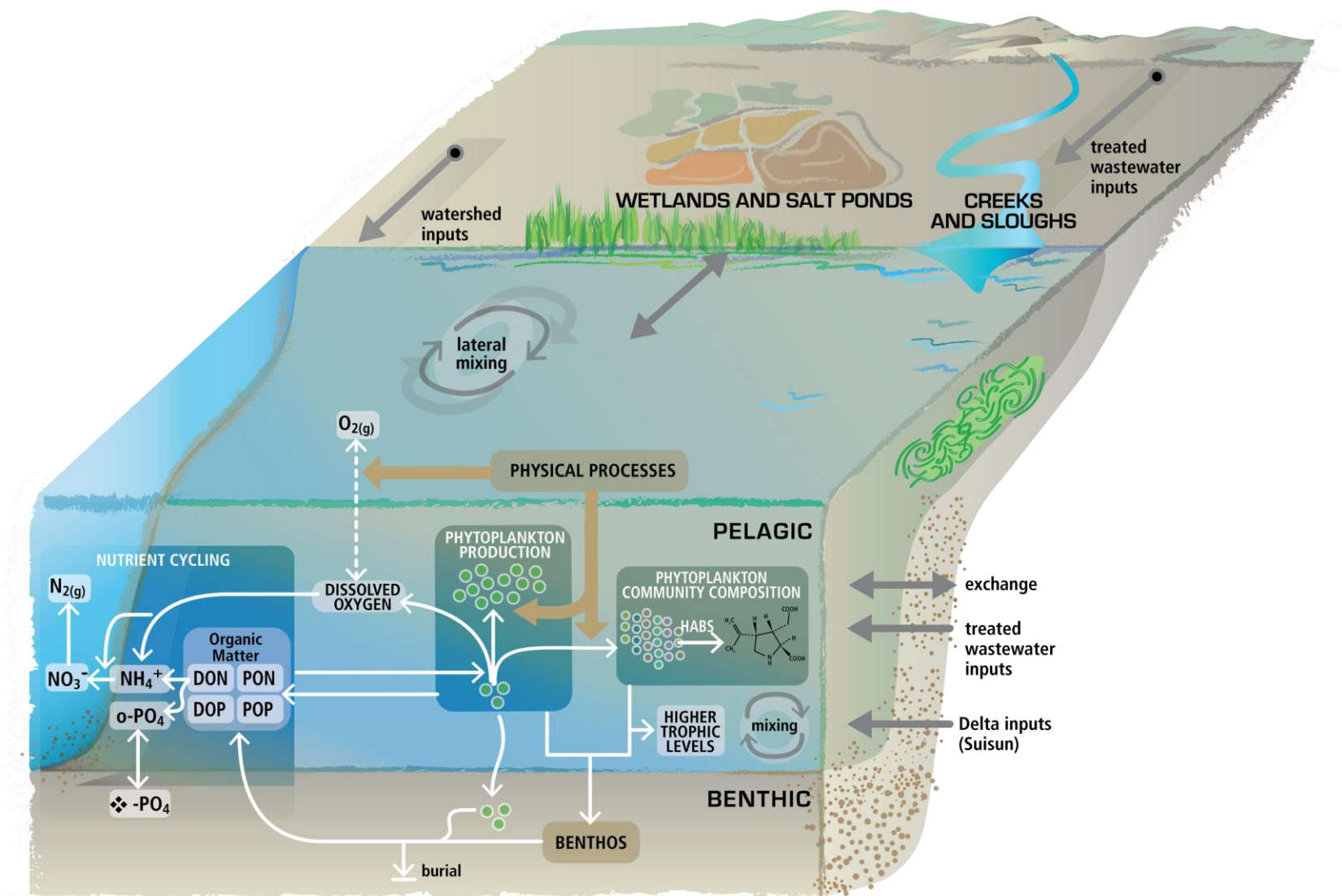
Figure 4.1.A Simplified nutrient conceptual model, showing major components. Those discussed in more detail include physical processes, nutrient cycling, phytoplankton production, dissolved oxygen, and phytoplankton community composition

Figure 4.1.B Detailed conceptual model, all modules

5 Physical Processes: Hydrodynamics and Sediment dynamics

5.1 Introduction

Characteristics of the 5 SFB subembayments considered in this report are presented in Table 5.1. San Francisco Bay has an open water surface area of approximately 1100 km^2 and an average depth of approximately 7 m, resulting in a total volume of approximately 7400 km^3 (Smith and Hollibaugh, 2006). Shallow shoals comprise large areas of LSB, South Bay, San Pablo Bay, and Suisun Bay (Figure 5.1; see also Figure A.1 in Appendix for higher resolution bathymetry).

The physical dynamics of San Francisco Bay are driven by the interplay of tidal, freshwater, and wind forcing with the complex topography of the Bay. In general terms, the Bay is made up of a series of subembayments: Central Bay is the deepest basin and is most strongly coupled to the Pacific. Landward from Central Bay, South Bay, Lower South Bay, and San Pablo Bay are each characterized by a single deep channel that bisects broad subtidal shoals. Upestuary from San Pablo Bay, on the landward side of Carquinez Strait, lies Suisun Bay, which is distinguished from the other embayments by its braided channels and the presence of two distinct shallow subtidal embayments: Grizzly Bay and Honker Bay. Finally, the Sacramento-San Joaquin Delta is not so much an embayment but a network of channels connecting the landward estuaries with the Bay. This complex topography sets the environment for tidal forcing, wind forcing and freshwater flows, which define the variability of tidal stage (inundation regime), salt and nutrient transport, stratification, turbulent mixing and sediment dynamics.

Freshwater inputs vary greatly among the subembayments. Suisun Bay and San Pablo Bay are river-dominated estuaries. The Sacramento and San Joaquin Rivers, enter SFB through Sacramento/San Joaquin Delta east of Suisun Bay, and 90% of the annual freshwater to SFB enters through the Delta. Additional freshwater inputs to SFB come from smaller perennial tributaries that drain the immediate surrounding watersheds, and stormwater runoff. Suisun Bay hydraulic residence times range from less than 1 day during high-flow periods to ~1 month during dry periods. Low salinity conditions generally define Suisun Bay, while San Pablo Bay is considerably more saline due to exchange with Central Bay. Compared to the northern estuary, freshwater inputs to Lower South Bay and South Bay are quite limited and consist mainly of wastewater treatment plant effluent and stormwater during the rainy season. LSB and South Bay behave more like tidal lagoons, and residence times can range from weeks to months.

Hydrodynamics and sediment dynamics play a critical role in determining San Francisco Bay's direct and indirect responses to nutrients. The intensity of vertical mixing and the length of time that a stratified water column (i.e., a surface layer and bottom layer) can be maintained strongly regulate the timing, magnitude, and duration of phytoplankton blooms in deeper sections of this turbid (light-limited) yet nutrient-rich estuary. Suspended sediment loads, tidal mixing, and wind-driven mixing maintain high levels of particles in the water column resulting in light-limiting conditions for phytoplankton growth. Exchange between the Bay's channels and broad shallow shoals – where higher average light availability allows for faster phytoplankton growth – can influence the degree to which blooms develop in the shoals and propagate to the channels. Vertical mixing rates, duration of stratification, and rates of exchange or flushing between subembayments and habitats determine the extent to which low oxygen levels can develop. A

comprehensive review of the hydrodynamics of San Francisco Bay is beyond the scope of this document. Instead, this section first describes four major physical forcings (tides, wind, freshwater flow, and coastal ocean exchange). We then focus on three issues that are particularly relevant to consideration of ecological change in response to shifting nutrient regimes: flushing times, density stratification and suspended sediment.
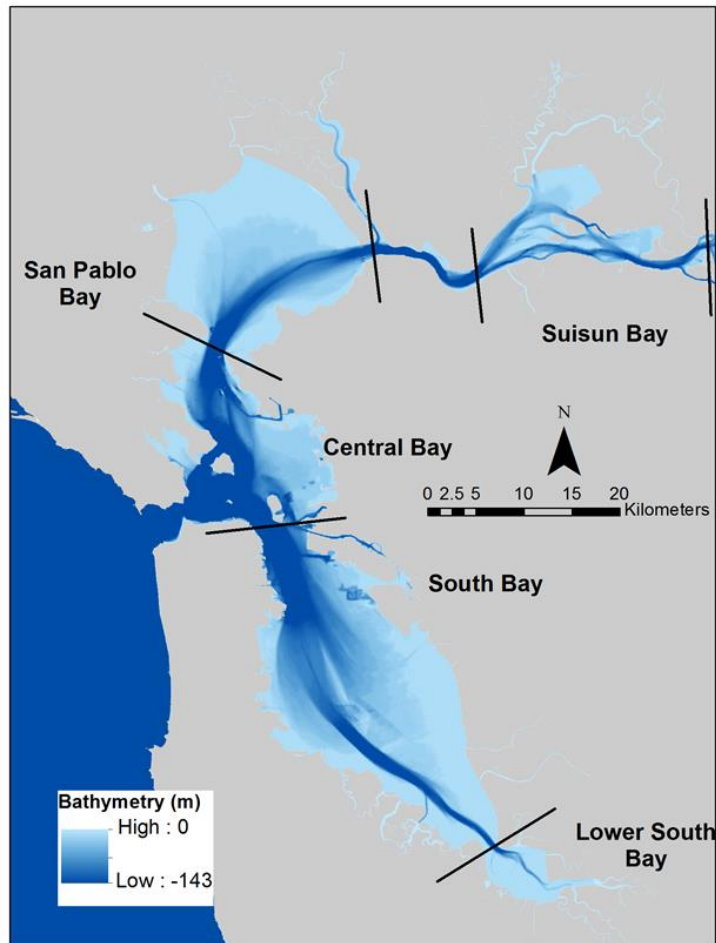
Figure 5.1 Bathymetry in SFB, shown as distance below surface (m). Water Board subembayment boundaries are shown in black. Source: NOAA bathymetry soundings

5.3 Major drivers

5.3.1 Tidal forcings

The spring-neap (~14 day) cycle in San Francisco Bay produces large diurnal asymmetries in the tides during the springs, which are characterized by one large tide and one small tide in each 24 hour cycle. The neaps, on the other hand, have more symmetric tides, which are intermediate in magnitude to the two tides seen each day during the springs. Tidal mixing energy also varies over the course of the year, with sustained highest-energy periods around the solstices (June, December), and sustained minimum energy periods around the equinoxes (March, September) (Figure 5.2)

Table 5.1 Subembayment area and volume, and watershed area and land-use

	Boundary	Bay area[1] (10⁶ m²)	Bay volume[1] (10⁶ m³)	Watershed area (10⁶ m²)	% surface water[2]	% open[2]	% agriculture[2]	% commercial[2]	% industrial[2]	% residential[2]	% transportation[2]
Lower South Bay	South of Dumbarton Bridge	30	90	1320	1%	37%	2%	11%	5%	30%	14%
South Bay	Dumbarton to Bay Bridge	460	2530	1685	1%	55%	2%	8%	3%	21%	10%
Central Bay	Bay Bridge to Richmond Bridge	200	2620	255	1%	33%	0%	10%	4%	36%	16%
San Pablo Bay + Carquinez	Richmond Bridge to Benicia Bridge	310	1690	2180	3%	42%	33%	3%	2%	13%	4%
Suisun Bay	Benicia Bridge to Mallard Island	100	500	1465	4%	51%	18%	4%	2%	14%	7%

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Spatially, there is an important distinction to be made between North Bay and South Bay in their response to tidal forcing. North Bay features a progressive tide, with the amplitude gradually dissipating as the tide propagates through each of the subembayments, eventually being completely dissipated upstream of the Delta. South Bay, by contrast, amplifies the tides by about 50% from the Golden Gate. This amplification is due to the specific geometry of South Bay and the nature of and position of the South Bay shorelines through a combination of reflection and funneling of the incoming tide. As a result, shoreline changes, whether development or wetland restoration, will have very different effects between North and South Bay. For example, wetland restoration in North Bay will reduce tidal energy primarily through increases in tidal dissipation due to friction. In South Bay, wetland restoration could alter the fundamental tidal dynamics in the basin, potentially reducing the tidal amplification significantly (with potential benefits for inundation, but negative effects on marsh habitat). The large areas of salt ponds slated for restoration in Lower South Bay and southern South Bay make changes in tidal dissipation a major consideration there (Figure 2.1).

5.3.2 Wind
Wind forcing is strongly diurnal during the summer months due to the afternoon sea breezes, which are from the west but modified by local topography. During the winter months, the dominant wind events are tied to storms, and they frequently are characterized by wind out of the south (on the leading edge of low pressure systems moving off of the Pacific). Winds during the fall and spring are more variable, but tend to be smaller in magnitude (Figure 5.2). The effects of the winds on transport include both direct effects on mixing and sediment resuspension and indirect effects on circulation, through the development of a surface tilt in response to sustained wind forcing.

5.3.3 Freshwater flow
Freshwater flow enters the Bay primarily through the Sacramento-San Joaquin Delta (Delta). Daily net outflow estimates from the Delta to Suisun Bay are provided in the CA Department of Water Resources "DAYFLOW" [7] database. Daily net Delta outflow in DAYFLOW is calculated based on a combination of daily averaged inflows into the Delta, in-Delta consumptive water use, and water exports from the Delta. Other sources of freshwater flow around the perimeter of the Bay include several moderate rivers (Napa, Petaluma, Guadalupe, Alameda and Coyote Creek), small inflows from local watersheds and water treatment returns. Each of these categories of sources has its own distinct seasonal variability. The flows in the small and moderate rivers and streams entering directly into the Bay are tied to local precipitation events and peak during the winter (rainy) months. The larger inflows from the Delta are tied to Sierra snowmelt and the management of reservoirs, leading to a peak in the spring and moderate flows during the summer, decreasing into the fall (Figure 5.2). Finally, wastewater returns are much more uniform throughout the year. Spatially, the North Bay is dominated by the Delta flows, while the South Bay is influenced by a mix of local freshwater flows, wastewater returns and even Delta flows in the late Spring and early Summer months.

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[7] http://www.water.ca.gov/dayflow/
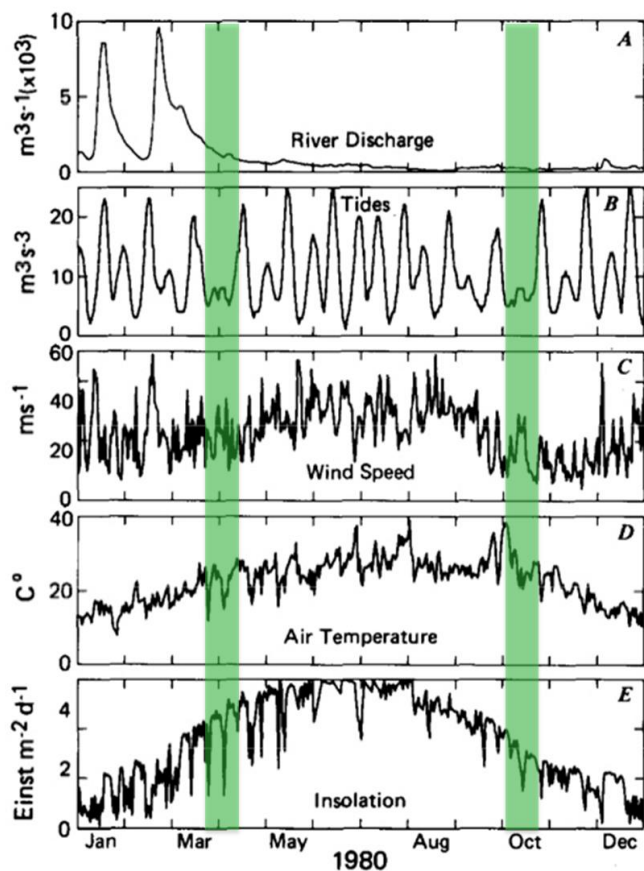
Figure 5.2 Physical drivers in San Francisco Bay. The green vertical bars illustrate the periods of minimum tidal mixing energy. In March/April, freshwater inputs and relatively low mixing energy allow the water column to stratify for ~10-14 days. In September/October, lower freshwater inputs limit the potential for salinity stratification. However, since winds are typically calm during this period, if sufficient insolation occurs (requires clear skies), surface layers will warm and the water column can be thermally stratified. Source: Cloern and Nichols, 1985

5.3.4 Coastal ocean exchange

In addition to providing tidal forcing, the oceanic boundary is also the source of salt water for the Bay. The interplay of freshwater flows and the tides leads to the intrusion of salt into the Bay, with the extent of salt intrusion, which is frequently characterized by X2[8] in the North Bay, being highly seasonally variable. Briefly, during high flow periods, the salt field is compressed down-estuary (Figure 5.3); when the flows relax, the salt field disperses back up-estuary. There is an asymmetry in the process for down-estuary and up-estuary movement of the salt field that is important to characterize. The down-estuary movement is advective and relatively rapid, whereas the up-estuary movement is primarily dispersive and more gradual. In South Bay, the seasonal variation of salinity is more complex: during winter, runoff events reduce the salinity locally, but it is not until late spring or early summer that the effects of Delta flows are felt south of the Bay Bridge. During winter and spring, it is possible for South Bay to have low salinities at both ends: reduced salinity in both Central Bay due to Delta flows and Lower South Bay and southern South Bay due to local flows. Finally, in the late summer and fall, evaporation in Lower South Bay can lead to hypersaline conditions and a reversed estuarine density gradient.

5.4 Estuarine circulation, flushing and residence times

The flushing (or, inversely, the residence time; see Monsen et al. 2002 for detailed discussion) of an estuary, or an embayment within an estuary, is driven by a combination of factors, including tidal forcing, density-driven circulation and, potentially, wind forcing. The combination of these influences define the "estuarine circulation". Typical estuarine circulation has up-estuary flow in the subsurface waters due to denser saltier waters moving underneath freshwater. Less-dense

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[8] X2 is the distance in kilometers measured from the Golden Gate to the position along the North Bay's axis where near-bottom salinity equals 2 psu. The position of X2 is strongly related to flow from the Delta, with a time lag.
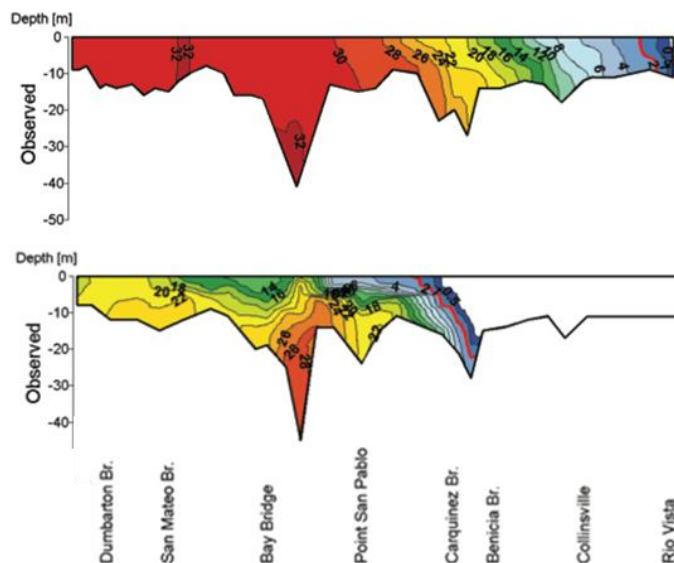
Figure 5.3 Observed salinity along main channel surveys of SFB. Top panel: Low flow period, October 26 1994. Bottom Panel: High flow period, January 18 1995. Source: Gross et al., 2009

fresher waters move down-estuary along the surface. These up-estuary salty and down-estuary exchanges occur along the axis of an estuary as well as laterally between deeper and shallower water regions. This circulation is defined both by direct forcing by the density gradient (gravitational circulation; Hansen and Ratray, 1965; Officer and Kester, 1991) and asymmetries in the tidal flows (Stacey et al., 2001; Stacey et al., 2008). The influence of wind is less established, and is likely to depend on the specific details of an estuary's geometry and a particular wind event. Supplementing the estuarine circulation, tidal dispersion processes, including tidal pumping (Fischer et al., 1979), tidal trapping (Okubo, 1973; MacVean et al., 2011) and shear dispersion (Fischer et al., 1979) will create exchanges between regions of an estuary. In many cases, these tidal processes will overwhelm the estuarine circulation and dominate flushing (Fram et al., 2007; Stacey et al., 2001; Monismith et al., 2002).

At the transition between embayments, or between the ocean and the estuary, the interplay of the tides, density-driven exchange and the topography determines the exchange. In one limiting case, pure density-driven (or gravitational) exchange determines transport between basins. In this hydraulic limit, there is no mixing in the strait and the waters of the two adjoining basins exchange under the influence of their density difference. The maximum exchange has been analyzed by Farmer and Armi (1986), and is set by the geometry of the strait and the density difference. The other limiting case is pure diffusive exchange, which results from tidal forcing interacting with the topography (see Hogg et al., 2001 for detailed discussion). The distinction between these two cases is important to the net transport: In hydraulic exchange, waters from each embayment are transported into the other in distinct layers; in diffusive exchange, net transport is directed down gradient.

At the mouth of San Francisco Bay, evidence suggests that tidal (diffusive) processes dominate the exchange, with density-driven circulation providing only about 10-15% of the total exchange (Fram et al. 2007). The implication is that the magnitude of flushing will primarily vary with the strength of the tides, which vary on the spring-neap and seasonal cycle. The Fram et al. estimate that approximately 80% of the exchange at the Bay's mouth is tidal is based on data spanning a spring-neap cycle, so spring-neap variability is aggregated in this estimate. Seasonal variability

of this result, however, is expected, with minima occurring during the spring and fall (just after the equinoxes) and maxima in the summer and winter (around the solstices). This variability was evident in the Fram et al. (2007) results, with fall dispersion coefficients reduced by about 45% relative to summer conditions. The dispersive nature of this exchange means that flushing is driven by the interaction of the tidal motions with the ocean-estuary gradient of the quantity being analyzed. In fact, the bi-directional nature of dispersive exchange means that net fluxes of individual species may be completely different from aggregate fluxes or exchanges, if their gradients are reversed (Martin et al., 2007). Similar results are to be expected at other narrow straits connecting embayments throughout San Francisco Bay.

Within individual subembayments, the residence time of subhabitats will be determined by the flushing and exchange flows along the perimeter of the subhabitat. An important distinction in much of San Francisco Bay is separating the deep channels from the broad shoals that characterize much of the Bay. In the channel, tidal and freshwater flows dominate along-channel transport, but the shoals are more strongly influenced by the interplay of tides and winds. The residence time of the shoals will be determined by the net exchange between the shoal and the adjoining channel, which has been recently examined in South Bay in a series of papers (Collignon and Stacey, 2012; Collignon and Stacey, 2013). In this work, the authors found that shoal waters were exchanged into the channel late in each ebb tide, but the nature of the exchange was a strong function of the local density gradients. Frequently, at the end of ebb the shoals are more saline than the channel (due to differential advection of the salinity gradient during the ebb), so the shoal waters that are pulled towards the channel by the tides late in the ebb tend to plunge down the slope and intrude into the channel at an intermediate depth. Although the net exchange from this transport process is not yet determined, the fact that shoal waters enter the channel at variable depths is likely to have important implications for the ecosystem through the effects on productivity. Although reversed salinity gradients were not analyzed at this site, they could develop in the early summer (due to the influence of Delta flows in northern South bay) or in the fall (due to evaporation in the Far South Bay). If the salinity gradient were reversed, then the late ebb flow of shoal waters towards the channel would lead to a surface flow in the channel, due to the shoal waters, in this case, being less saline than the channel.

At a much smaller scale, and considering local effects, recent analyses have looked at flushing of small perimeter habitats around the edge of the estuary (Hsu and Stacey, 2013). Using a combination of numerical and observational analyses, the authors found that tidal exchanges dominate the flushing of small slough-marsh complexes, but the net exchange is likely to be strongly affected by wind forcing, which is currently being analyzed. In the absence of wind, the Hsu and Stacey (2013) found that approximately half of the waters in a small slough-marsh complex in South San Francisco Bay was exchanged each tidal cycle.

Finally, small-scale features can result from local retention or convergence. The presence and maintenance of convergent fronts can lead to locally high residence times in relatively small regions. Simplified analyses of convergences and mixing (which must be in balance for the front to be maintained) can define representative timescales for retention and exchange (O'Donnell 1993; Stacey et al., 2007). Examples of these convergences are frequently associated with the

channel-shoal transition (Collignon and Stacey, 2012) or other lateral density-driven flows (Lacy et al. 2003).

5.5 Stratification

As outlined in the introduction, the Bay is characterized by large-scale salinity gradients along the Bay axes (Figure 5.3). At a large scale, the North Bay gradient is the most prominent in the estuary, defined by a transition from fresh to oceanic conditions over the length of the Bay; the gradient in South Bay is more variable and tends to be weaker than its North Bay counterpart. Moving away from the primary axis of the estuary, in other parts of the Bay salinity gradients may be comparable to or stronger than those along the North Bay axis. Specifically, the gradient along North Bay is approximately 0.5 psu/km, but salinity gradients in perimeter habitats may be 10 times that (Ralson and Stacey, 2005a,b). The presence of a horizontal salinity gradient makes the estuary susceptible to vertical stratification due to the tendency of the horizontal gradient to relax, or "lay down", into a vertical gradient. The interaction of horizontal salinity gradients and tidal forcing, which can both create and destroy vertical stratification, leads to dynamic density stratification with important implications for vertical mixing.

In the estuarine water column, velocity shear (or vertical mixing energy) and density stratification are in competition in defining the state of the turbulence. Sheared velocity profiles act to increase the turbulent energy (and mixing), while stable density stratification acts to reduce the same (Fischer et al. 1979; Turner, 1980). The competition between shear and stratification plays a critical role in determining whether phytoplankton blooms develop (see Section 7).

The potential for stratification to develop depends on both longitudinal and lateral salinity gradients, related to the concepts of the Richardson number and Strain Induced Periodic Stratification (SIPS), whose discussion is beyond the scope of this overview. The magnitudes of these salinity gradients vary seasonally (Figure 5.3).

More recent studies of San Francisco Bay stratification dynamics (as well as other estuaries) have demonstrated the importance of lateral dynamics. If there is a lateral density gradient, as develops at the channel-shoal transition, and a lateral velocity, then lateral straining can contribute to the vertical stratification in the same way as the longitudinal does in the SIPS equation above. Examples of lateral straining's influence on stratification come from South Bay (Collignon and Stacey, 2012); Suisun Bay (Lacy et al. 2003) as well as other estuaries.

Taken together, we expect an estuarine water column to stratify and destratify on a wide range of timescales that represent the variation of the density and tidal forcing as captured in the Simpson number. At seasonal timescales, the strength of the longitudinal density gradient varies; but just as importantly, its position changes so that the strongest density gradients may move between deep and shallow portions of the Bay (e.g., between Suisun Bay and Carquinez Strait, e.g.). As the density gradient strengthens, or moves into deeper regions, its effectiveness at creating stratification is increased and a stratified water column becomes more likely. Variations in tidal energy at the seasonal and spring-neap timescales can cause density stratification to adjust, and the strongest salinity stratification should occur during neap tides when the salinity gradient is compressed (following large freshwater flow events, e.g.). The ability of stratification to persist varies on multiple time scales due to changes in the vertical mixing energy of the tides with the spring-neap cycle: during neap tides, stratification is more persistent, but becomes periodic

during the springs (Stacey et al., 2001). The straining effects of the tidal flows lead to stratification that strengthens and weakens within the tidal cycle.

Beyond the spring-neap cycle, SFB experiences two annual minima periods in tidal energy (March/April, September/October). The green vertical bars in Figure 5.2 illustrate the periods of minimum tidal mixing energy. In March/April, freshwater inputs and relatively low mixing energy allow the water column to stratify for ~10-14 days. In September/October, lower freshwater inputs limit the potential for salinity stratification. However, it is also possible to have density stratification induced by temperature variations, although temperature induced stratification is not as commonly analyzed in estuaries (because of the dominance of salinity stratification) as in lakes or the deep ocean where it is an important factor. There are times, however, when temperature stratification may be an important factor for estuarine mixing: they result from a confluence of events involving warm, sunny days, neap (low energy) tides and low wind energy. Throughout much of the year in San Francisco Bay, this combination is unlikely, except perhaps during the fall, when the diurnal sea breeze is reduced, fog is less present, and tidal energy is at its annual minimum (Figure 5.2).

5.6 Suspended Sediment

The common paradigm for San Francisco Bay is that it is quite turbid due to high suspended sediment concentrations, or suspended particulate matter (SPM). Recent analyses (Schoellhamer 2011) have indicated that the Bay may be clearing, with Bay-wide SPM decreases of ~35% since 1998 (Figure 5.4.A), and up to 50% since 1975 in Suisun Bay (Figure 5.5). Within the Bay itself, the dynamics of the inorganic fraction of turbidity, suspended sediment concentration, is governed by its upstream supply, resuspension and deposition in the Bay, and transport throughout the Bay. The explanation for the decreased concentrations is that both external loads of suspended sediment and resuspension of material from the bed have decreased (because of a depleted erodible sediment pool; see Figure 5.4.B).
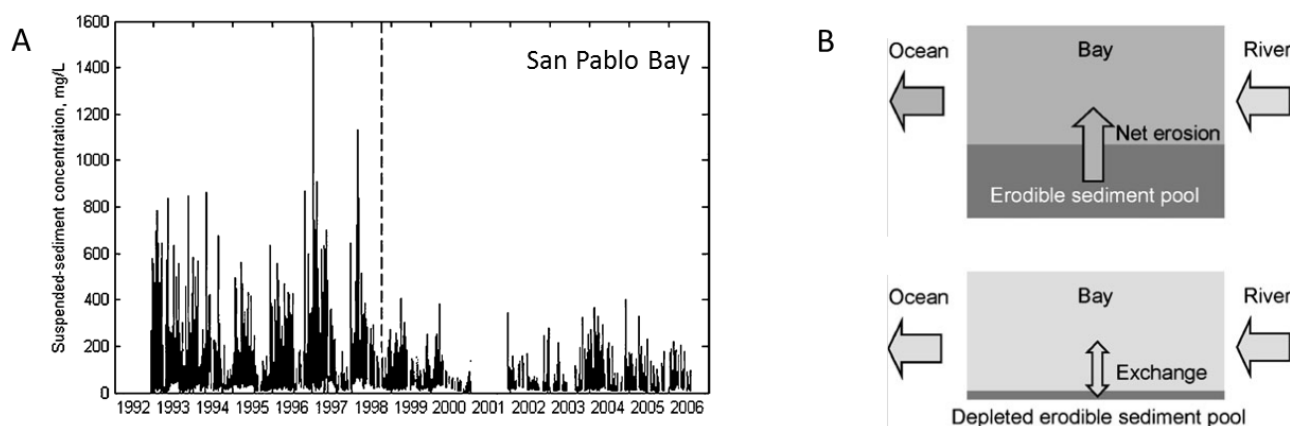
Figure 5.4 A. Time series of suspended particulate matter concentrations in San Pablo Bay measured by a continuous monitoring. **B.** Conceptualization of cause of declining sediment concentrations. Sediment inputs to SFB have declined substantially in recent years. Due to the lack of replenishment, the erodible sediment pool in the bed has been gradually depleted. As a result, less material is resuspended, resulting in lower concentrations.
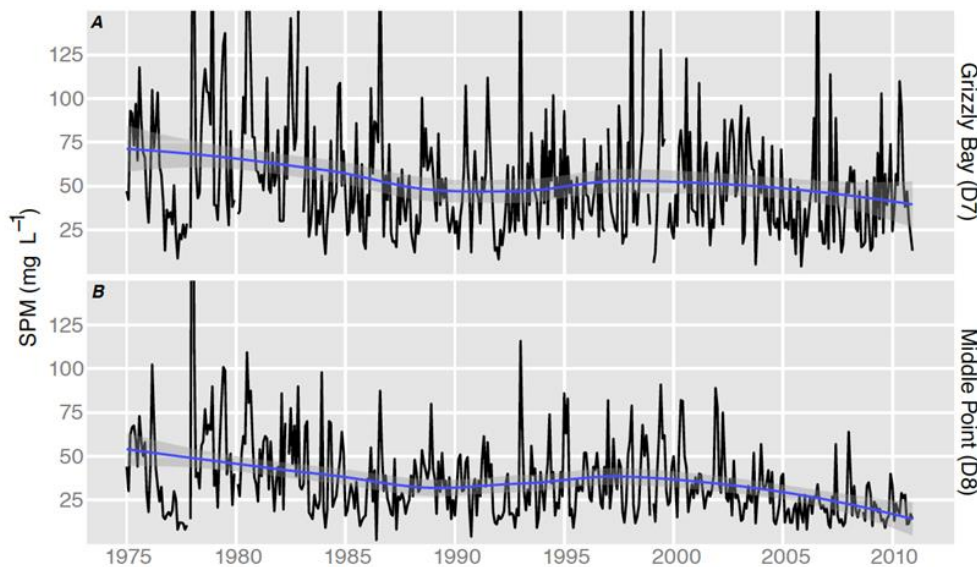
Figure 5.5 Suspended sediment concentrations in Suisun Bay: shallow Grizzly Bay (top) and in the channel (bottom). Source: Cloern and Jassby 2012

The circulation that governs sediment transport is largely the same as what governs salinity, flushing times and even stratification. The effects of supply have been considered elsewhere (Schoellhamer 2011), and we will focus here on resuspension and deposition and vertical transport. For sediment to be resuspended from the bed, the flow-induced bed stress, i.e., the frictional force at the sediment:water interface, must exceed a critical threshold (Sanford 2008; Wiberg et al. 1994). The magnitude of the critical stress will vary with the type of sediment and the degree of consolidation of the bed (Sanford 2008; Wiberg et al. 1994). Newly deposited sediments are more readily resuspended; after some time (approximately 3 days, Wiberg et al. 1994), the bed consolidates considerably and becomes more resistant to resuspension.

Both wind waves and tidal flows create stresses at the estuary bed that can act to resuspend sediments. In the deep channels, the effects of wind waves do not extend to the bed (Kundu et al. 2011), so only tidal forcing needs to be considered when analyzing resuspension. Although the tides are nearly symmetric, because of the threshold nature of sediment resuspension, even subtle asymmetries could have large impacts on the timing of sediment resuspension and net transport. The superposition of density forcing (flow in at the bed, out at the surface) with tidal flows adds to the bed stress on flood tides and reduces it on ebbs. If this asymmetry crosses the resuspension threshold, then sediment concentrations may be higher on floods than ebbs, leading to a net upstream transport of sediment. This effect is counteracted by large freshwater flow events, which add to the bed stress on ebbs and reduce it on floods. The net effect is expected to be a downstream push of sediments due to large freshwater flows events followed by tidally-driven up-estuary sediment transport once the flows reduce (Ralston and Geyer, 2009).

In the shallows, windwaves are able to reach the bed and create large oscillatory bed stresses that can resuspend sediments. The resuspended sediment from windwaves is largely contained in the wave boundary layer, which may only be a few centimeters thick, but if tidal flows coincide with this resuspension, then they can mix sediments further up into the water column. This combination of factors was found to be important to the sediment dynamics on South Bay shoals by Brand et al. (2010), who found that the highest sediment fluxes into the water column occurred on flood tides that followed wavy low water periods. The explanation was that wind

waves were able to resuspend sediments into the wave boundary layer, and then the following flood tide mixed the sediments into the water column. The importance of windwaves to resuspension mean that summer months, characterized by strong diurnal sea breezes, are likely to have the highest sediment concentrations in the shallows, even though the watershed supply is at its lowest during that period.

In the water column, settling and turbulent mixing define the evolution of the suspended sediment concentration profile. The settling velocity for the sediment depends on the particle size and density, which may be poorly defined for fine particles that form flocs. For large, dense particles, or during low energy periods, the suspended sediment is largely constrained to the near-bed region; for smaller particles, or less dense flocs, or during high energy periods, the suspended sediment is more widely distributed throughout the water column.

Figure 5.6 presents monthly-average SPM concentrations in SFB's five main subembayments. The suspended sediment concentrations in the waters of San Francisco Bay will vary tidally and diurnally (or in response to wind events), will vary between subembayments due to supply (Figure 5.6), and will vary within embayments due to spatially variable resuspension in response to the local depth. Seasonally, supply has a strong variation, with more turbid waters being brought into the Bay with winter rains, but the shoals may actually be more turbid during summer months due to resuspension of sediments from the bed.

5.7 Summary
This review is not meant as a comprehensive description of the hydrodynamics of San Francisco Bay, but is instead focused on the basics of flushing, stratification and suspended sediment. The key factors driving all three of these processes are tidal, wind and freshwater forcing. The variability of those factors, and their interactions, define the dynamics of the processes. Looking ahead several decades, the prospects for change in the Bay are extensive. Climate change and variability will bring with it warmer air temperatures and more frequent heat waves, creating the risk of more anomalous temperature stratification events. Precipitation may shift towards rain from snow, altering the timing of freshwater flows entering the Bay and the associated response in the salt field. Sea level rise will alter the tidal dynamics of the Bay, perhaps increasing the dissipation of energy due to extra inundation, or decreasing it if the Bay is made deeper (i.e. sediment accumulation does not keep pace with sea level rise). The changes the Bay faces are not limited to climate forcing, however, and anthropogenic changes may be just as pronounced. Along the Bay's shorelines, marsh restoration will alter the tidal dynamics by increasing tidal dissipation locally and, for large restoration projections, could potentially alter the tidal dynamics more broadly. The management of California's water resources through reservoir operations alters the timing and amount of freshwater flows that enter the Bay, perhaps in a more profound way than a shift in the type of precipitation would. Finally, land use practices, as well as the operation of reservoirs, alter the sediment supply that watersheds provide to the Bay. While these scenarios are all plausible, the potential magnitudes of their effects on nutrient cycling and ecosystem response remain highly uncertain.
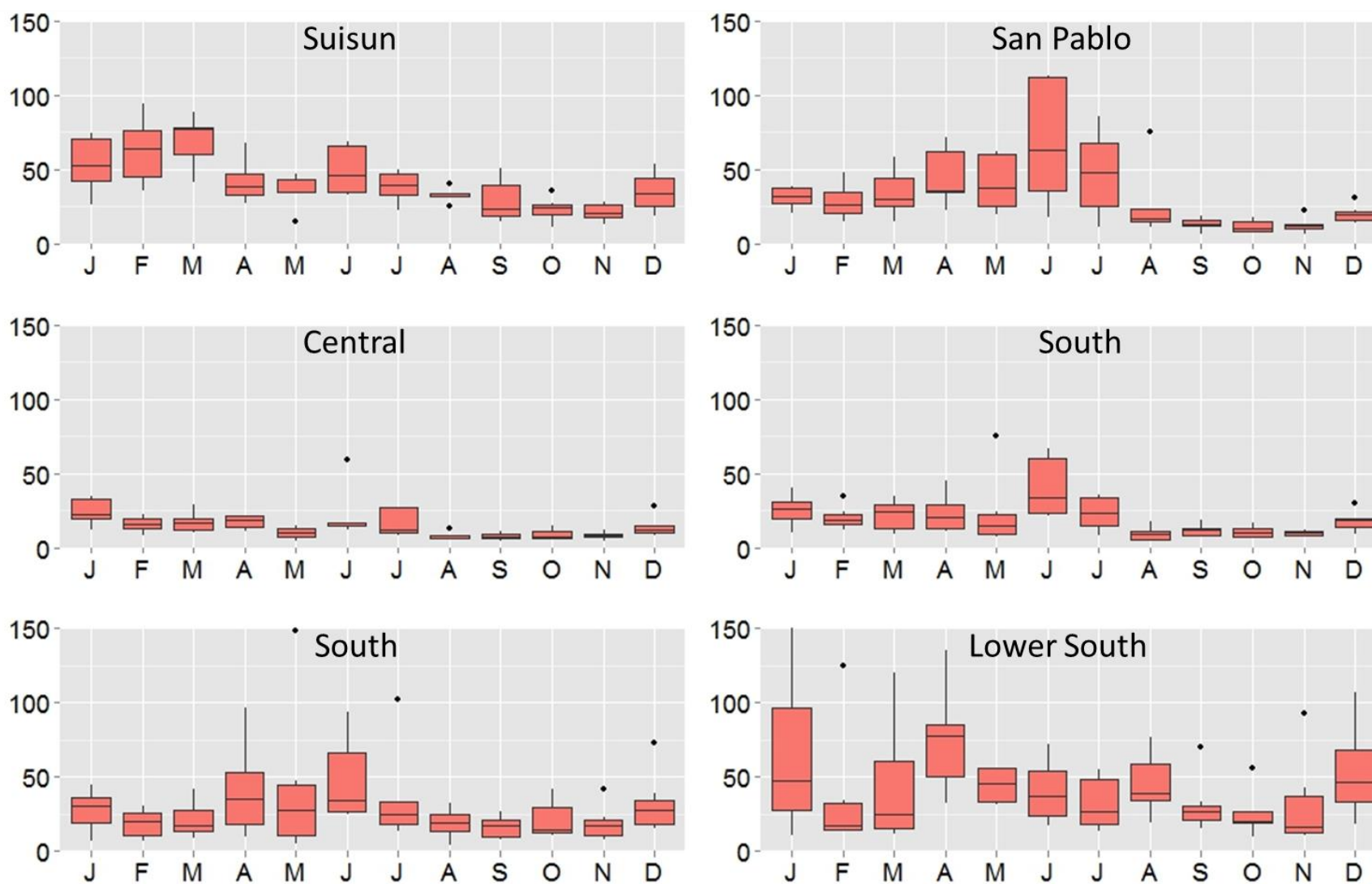
Figure 5.6 Monthly average SPM (mg/L) – 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: http://sfbay.wr.usgs.gov/access/wqdata/

6 Nutrients

6.1 Introduction

The nutrient module focuses on the macro-nutrients N, P, and Si, with a greater emphasis on N and P because their loads and concentrations have been the most altered by anthropogenic activities. N, P, and Si are essential for primary production in all aquatic environments, including SFB. Cellular requirements for N, P, and Si differ among phytoplankton species, as do uptake rates. In addition, some species show a relative preference for certain forms of N. These requirements and preferences, along with the relative nutrient abundances, can influence the growth rate of phytoplankton and the magnitude (concentration) of phytoplankton blooms (Section 7). They may also influence the types of phytoplankton species that prosper under different conditions and influence the seasonal succession of the overall phytoplankton assemblage (Section 9).

The observed nutrient concentration at any given point in space and time in SFB represents a balance of multiple processes, including: input, export, mixing (vertical, lateral, longitudinal), uptake by phytoplankton, transformations, and losses. The discussion below covers the major processes that regulate nutrient cycling, with a focus on those that are important enough in SFB to be considered within a management-driven discussion, and only minimally treats some topics.

6.2 N, P, and Si cycling

6.2.1 N cycling

Nitrogen exists in several forms in aquatic systems and undergoes numerous biologically-mediated transformations between these forms (Figure 6.1). The major dissolved inorganic forms of N are the ions nitrate (NO_3^-), ammonium (NH_4^+), and nitrite (NO_2^-). Dissolved and particulate organic nitrogen (DON and PON) can comprise important fractions of N in some aquatic systems, and tend to represent lower portions of total N in systems that receive large nutrient anthropogenic inputs. Dissolved gaseous forms of N include di-nitrogen (N_2) and nitrous oxide (N_2O). N_2 is both an end-product of denitrification (discussed below) and a potential N source for a limited set of phytoplankton that perform nitrogen fixation, an energy-intensive process through which they convert N_2 into an usable organic form. Both NO_2^- and N_2O are important intermediaries in some N reactions, but typically present only at relatively low concentrations in estuarine water columns. The "bio-accessible" forms of N include NO_3^-, NH_4^+, NO_2^-, DON, PON, and N_2O. The remainder of the N cycling description focuses primarily on NO_3^- and NH_4^+, since they are the dominant bioaccessible N forms.

Figure 6.1 illustrates the major processes that will influence the forms and concentrations of N in SFB. Nitrogen inputs include: point-sources, primarily POTWs; large river inputs via the Sacramento-San Joaquin Delta; other freshwater inputs at the Bay margins (smaller perennial streams, along with stormwater inputs and ephemeral wet season streams); and other sources that are less readily quantified but expected to be relatively small (e.g., direct atmospheric deposition, groundwater). N is supplied to subembayments primarily in the form of NO_3^-, NH_4^+, DON, and PON, and the relative proportions will vary by source. Atmospheric N deposition to the
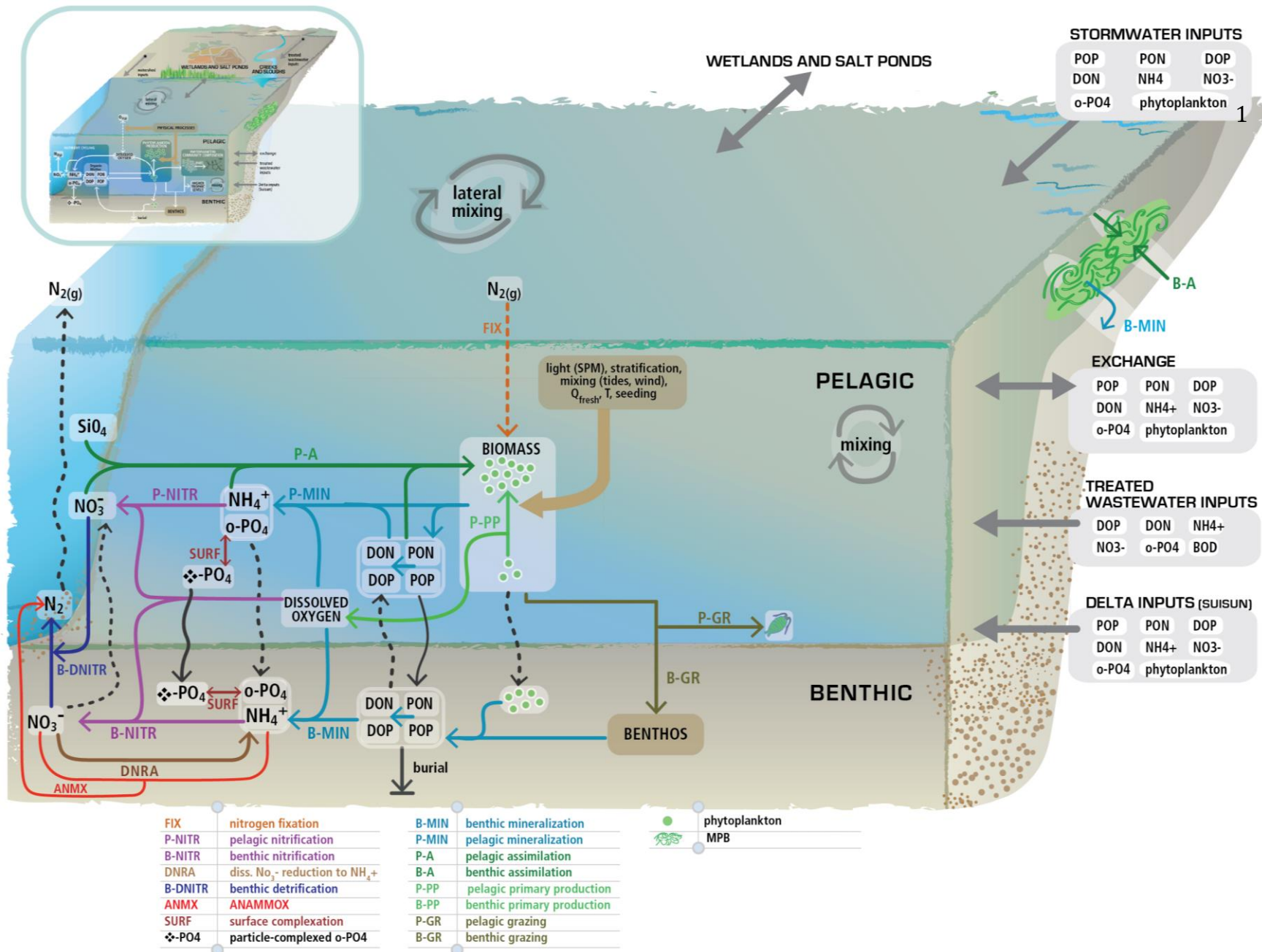
Figure 6.1 Nutrient cycling conceptual model

STORMWATER INPUTS
POP · PON · DOP · DON · NH4 · NO3- · o-PO4 · phytoplankton

WETLANDS AND SALT PONDS

lateral mixing

$N_{2(g)}$

$N_{2(g)}$ · FIX

light (SPM), stratification, mixing (tides, wind), Q_{fresh}, T, seeding

PELAGIC · mixing

B-A · B-MIN

EXCHANGE
POP · PON · DOP · DON · NH4+ · NO3- · o-PO4 · phytoplankton

SiO_4

P-A · BIOMASS

NO_3^- · P-NITR · NH_4^+ o-PO_4 · P-MIN · P-PP

SURF · ❖-PO_4

N_2 · DON PON · DOP POP · DISSOLVED OXYGEN

TREATED WASTEWATER INPUTS
DOP · DON · NH4+ · NO3- · o-PO4 · BOD

P-GR

DELTA INPUTS (SUISUN)
POP · PON · DOP · DON · NH4+ · NO3- · o-PO4 · phytoplankton

B-DNITR

NO_3^-

❖-PO_4 ↔ o-PO_4 · SURF · NH_4^+ · B-MIN · DON PON · DOP POP

B-GR · BENTHIC

DNRA · B-NITR · burial · BENTHOS

ANMX

FIX	nitrogen fixation	B-MIN	benthic mineralization
P-NITR	pelagic nitrification	P-MIN	pelagic mineralization
B-NITR	benthic nitrification	P-A	pelagic assimilation
DNRA	diss. No$_3$- reduction to NH$_4$+	B-A	benthic assimilation
B-DNITR	benthic detrification	P-PP	pelagic primary production
ANMX	ANAMMOX	B-PP	benthic primary production
SURF	surface complexation	P-GR	pelagic grazing
❖-PO4	particle-complexed o-PO4	B-GR	benthic grazing

● phytoplankton
MPB

watersheds that drain to SFB could be an important N source; in this description, we include that source within inputs from the Delta and in freshwater inputs draining catchments that ring the Bay (N that deposited on land and was washed into rivers or streams). While N fixation can be an important source of N to some aquatic systems, it is unlikely to be an important internal source to SFB under current conditions because anthropogenic sources are so large. However, increased nitrogen fixation is a possible ecosystem-level response to nitrogen limitation should fixed N inputs from other sources decrease substantially without concomitant P decreases. Exchange with the Pacific Ocean at the Golden Gate can be either a net source or sink of N depending on coastal processes (i.e., upwelling or non-upwelling time period). Limited analysis to date suggests that SFB should be a net exporter of N throughout most of the year, except during some major upwelling events (Largier and Stacey, 2014). Hydrodynamic processes (tidal, gravitational, advective) transport N between subembayments.

Nitrogen transformations take place within the oxic water column, within the (typically) anoxic sediments, and within the narrow - but geochemically important - transition zone at the sediment:water interface. NH_4^+ and NO_3^- (and some forms of DON) can be readily taken up and assimilated into biomass by primary producers. When dead phytoplankton undergo degradation or mineralization by microbes, a portion of organic N is regenerated as NH_4^+. Some of the regenerated NH_4^+ ammonium released is oxidized to nitrate either in the water column or at the sediment:water interface via the process of nitrification. Nitrification requires oxygen, but can proceed in environments where oxygen concentrations are low, including at the sediment-water interface. Denitrification is a form of respiration used by some heterotrophic microbes. In denitrification, NO_3^- is used instead of oxygen to oxidize organic matter, producing N_2 and carbon dioxide. Denitrification requires organic matter to proceed, and its rate can be limited by the amount and quality of organic matter, but only proceeds in anoxic environments, primarily within sediments, or biofilms, after NO_3^- diffuses from the water column into anoxic zones. Because denitrification converts NO_3^- to N_2, it results in a true loss of N from the system. NO_3^- can also be transformed directly to NH_4^+ through a respiratory pathway used by some microbes called dissimilatory nitrate reduction to ammonium (DNRA). N can also be converted to N_2 through a microbially-mediated process called anaerobic ammonium oxidation (ANAMMOX) by which NH_4^+ and NO_2^- are converted to N_2 (Brunner et al., 2013). [9] The coupled process of ammonium oxidation-denitrification at the sediment:water interface can be responsible for a substantial portion of the denitrification in some estuarine systems (ref). While denitrification is generally thought to be a more important pathway for NO_3^- reduction than DNRA, ANAMMOX could rival denitrification under some conditions (Kuypers et al. 2005), and does not require a labile organic matter source. A portion of the organic nitrogen produced in the Bay accumulates in the sediments where it undergoes gradual decomposition and release of NH_4^+. N burial can take place anywhere in SFB, but burial is more likely in locations where there is net accumulation of sediments. Newly restored tidal salt marshes could be particularly important zones for denitrification because of the anoxic conditions and abundant organic matter in marsh sediments. Some of the buried PON continues to decompose, releasing ammonium into the sediment pore water, which either eventually diffuses back to the water column, or undergoes nitrification-denitrification as described above. PON is also subject to resuspension, especially

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[9] The actual expression is: $1NH_4^+ + 1.3NO_2^- \rightarrow 1N_2 + 0.3NO_3^- + 2H_2O$

in shoal environments. The fraction of sediment PON that is neither regenerated as NH_4^+ nor resuspended of the PON is buried permanently.

Nitrification, denitrification, and possibly ANAMMOX are likely to be quantitatively important processes that influence N form and fate at subembayment scales and at the full Bay scale. However, there are currently few direct measurements of these rates. Quantifying these processes and their influence on N fate will be one key component for determining the N loads that SFB subembayments can assimilate without adverse impacts. The importance of nitrification in SFB is evident, given that in some subembayments (e.g, South Bay) N is loaded as primarily NH_4^+ but is measured in the water column as primarily NO_3^-. Denitrification likely represents a substantial loss route for bioavailable N within SFB. However the magnitudes and importance of nitrification and denitrification relative to other processes (uptake by phytoplankton or microphytobenthos, transport out of the system) are currently poorly known. As a first step, the importance of denitrification and nitrification could be estimated through relatively straightforward biogeochemical modeling. At some point field studies will likely be needed to provide better rate estimates and factors that influence rates over space and time (e.g., Cornwell et al. 2013).

6.2.2 P cycling

The P cycle is also depicted in Figure 6.1. P cycling is relatively straightforward compared to N, since P only commonly occurs in two dissolved forms and does not undergo numerous transformations. P occurs as dissolved orthophosphate (o-PO_4), particle-complexed o-PO_4, other solid mineral phases of P, and dissolved and particulate organic P (DOP and POP). o-PO_4 would generally be expected to comprise most of dissolved P in the water column. However, particle- or colloidally-complexed P, either organic or inorganic, can also be important in the water column. o-PO_4 binds to the surfaces of iron(III)-oxide particles in both the sediments and water column. When complexed by iron(III)-oxides, o-PO_4 is essentially unavailable for uptake by primary producers; however, iron(III)-oxide particles are readily dissolved in anoxic sediments (discussed below), making this form of particle-bound o-PO_4 a temporary state. Other particulate mineral phases of P also occur, but they tend to be relatively refractory.

External P sources to SFB subembayments include: inputs from point sources, primarily POTWs; riverine inputs via the Sacramento-San Joaquin Delta of naturally-derived P (from dissolution of P-rich mineral phases) or anthropogenically-sourced P (fertilizer, livestock excrement, treated wastewater); other freshwater inputs at the Bay margins - perennial streams or rivers, stormwater inputs, and ephemeral wet-season streams; and other sources that are less readily quantified but believed to be relatively unimportant (ground water, atmospheric deposition, etc.). P has no analogous process to N-fixation. Similar to N, exchange with the Pacific Ocean at the Golden Gate can be either a net source or sink of P depending on coastal processes (i.e., upwelling or non-upwelling time period) and conditions within SFB. In addition, hydrodynamic exchange processes (tidal, gravitational, advective) transport P between subembayments.

P form and abundance are influenced by uptake and assimilation, surface reactions with particles, settling, and microbial mineralization and recycling. Within the water column, o-PO4 can be readily taken up and assimilated by phytoplankton. During pelagic grazing on phytoplankton (by zooplankton) or mineralization of dead phytoplankton in the water column or

sediments, DOP and POP are released, a portion of which is converted to o-PO4. Particle-complexed o-PO$_4$ and POP settle in the water column and eventually reach the bed sediments. Respiration using iron(III) is an important anaerobic reaction in sediments, which dissolves iron(III)-oxides and releases dissolved o-PO4 to porewater, where it can then be transported to the water column, or undergo transformations (re-binding to particles, uptake by benthic algae or microbes). Transport back to the water column can occur slowly by diffusion, or, much more rapidly, due to burrowing by benthic organisms ('bioirrigation') or during sediment resuspension that also mixes porewater into the water column. Similar to N, burial of particulate P can take place anywhere in the bay, but is more likely in locations where there is net accumulation of sediments, like wetlands. Some of the o-PO4 produced in sediments returns to the water column and re-enters the cycle of organic matter production and degradation.

6.2.3 Si cycling

Si cycling is also relatively straightforward compared to N cycling, since Si does not occur in multiple dissolved inorganic forms or undergo numerous transformations. However, unlike both N and P, the vast majority of Si comes from natural sources through the weathering of silicate-rich rock, and does not have major anthropogenic sources. Major sources include riverine inputs of naturally-derived Si via the Sacramento-San Joaquin Delta, and other freshwater inputs at the Bay margins. Exchange with the Pacific Ocean at the Golden Gate is a net sink for Si. Hydrodynamic exchange processes can result in net Si exchange between subembayments, although on average down-estuary exchange will be a net Si sink, since its primary source is freshwater inputs.

Si is supplied to subembayments primarily as dissolved silicate (SiO$_4$), solid mineral phase silicates, and reactive or refractory biogenic silicates. In the absence of biological uptake and assimilation, Si should behave conservatively in SFB, with no quantitatively important geochemical transformations other than those related to uptake/assimilation by organisms reliant on Si for growth. Although N and P requirements (C:N:P) can vary substantially among phytoplankton classes, all phytoplankton require N and P for growth. Si is distinct from N and P in this respect: among the major classes of phytoplankton, only diatoms require SiO$_4$ in substantial amounts. Only the growth of diatoms will influence silicate concentrations via assimilation.

The recycling of Si is slow relative to P and N. Si taken up and assimilated by diatoms is less readily regenerated during grazing or microbial degradation of cells. Instead, the silicate-rich frustules settle and accumulate as biogenic Si in the sediments, which tends to be more slowly mineralized than organic N and P. As such, compared to N and P, a larger proportion of biogenic Si that reaches the sediments is ultimately buried.

6.3 Estimated N and P Loads to SFB

Figure 6.2 presents an overview of DIN and DIP loads to SFB, broken into its five main subembayments. A separate report on N and P nutrient loads discusses loads, data gaps, and uncertainties in more detail (SFEI, 2014a). Groundwater and direct atmospheric deposition (i.e., directly to the Bay's surface) loads are expected to be small and are not discussed here. Discharge of treated wastewater effluent by publicly owned treatment works (POTWs) to SFB's subembayments is a major source of N and P. The San Francisco Bay Area has 42 POTWs (Figure 2.2.B) that service the regions 7.2 million people and discharge either directly to the Bay
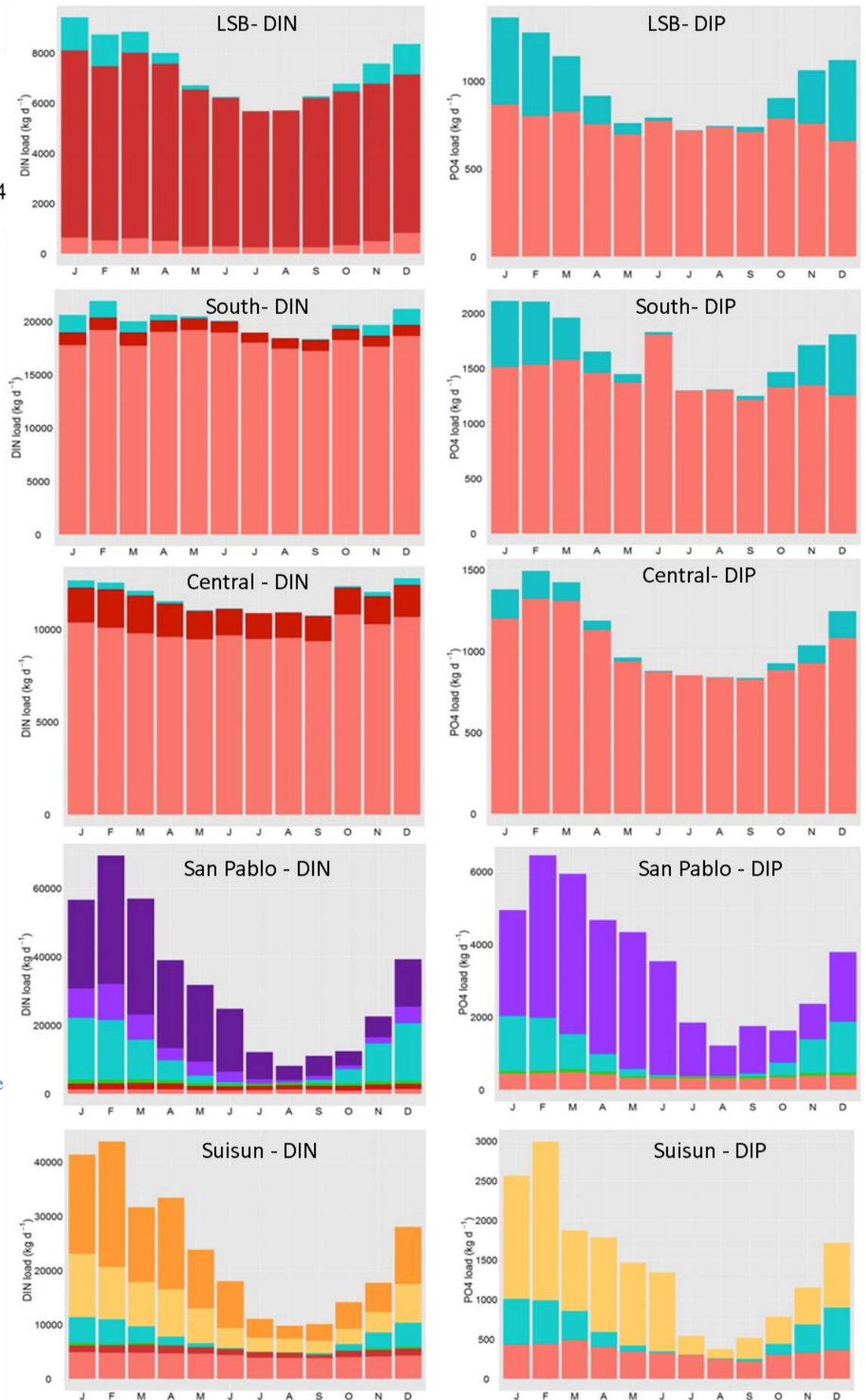
Figure 6.2 N and P loads to SFB subembayments. In the cases of LSB, South Bay, and Central Bay, only direct loads to the subembayments were considered and not exchange between subembayments. Loads to San Pablo Bay include estimates of up-estuary loads from Suisun Bay. See SFEI 2014a for more

or to receiving waters in adjacent watersheds that drain to the Bay (note: these numbers do not include discharges east of Suisun Bay that enter through the Delta). While several of these POTWs conduct nitrification or denitrification plus some forms of advanced treatment that remove a portion of nutrients prior to discharge, most POTWs discharging to SFB carry out only secondary treatment, which transforms nutrients from organic to inorganic forms, but generally does not remove much N or P. Table 6.1 summarizes typical N and P concentrations and forms in effluent subjected to varying degrees of nutrient removal. Bay-wide, POTWs discharged (annual average) 34000 kg d^{-1} NH_4^+, 12000 kg d^{-1} NO_3^-, and 4000 kg d^{-1} total P. Results from detailed effluent monitoring that began in July 2012 suggests ~90% of total N discharged was in the form of DIN and ~80% of total P discharged was in the form of o-PO_4 (SFEI, 2014a). Refineries also contribute N and P loads to Suisun Bay and San Pablo Bay, but their contributions appear to be relatively minor.

Table 6.1 Typical concentrations and forms of N and P in treated wastewater effluent at different treatment levels

Treatment type	NH4 (mg N L^{-1})	NO3 (mg N L^{-1})	TN (mg N L^{-1})	TP (mg P L^{-1})
Level 1: Secondary treatment	20-30	<1	25-35	4-6
Nitrification	<1	20-25	20-30	4-6
Level 2: Nitrification + biological nutrient removal	<1	8-12	10-15	0.5-1
Level 3: Nitrification + Advanced TN/TP removal	<1	3-6	4-8	0.1-0.3
Level 4: "Limit of Technology" not including Reverse Osmosis	<1	<1	<3	<0.1
Reverse Osmosis	<1	<1	<2	<0.02

[1] Based on Falk, M.W., Neethling, J.B., Reardon, D.J. (2011). Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability, WERF research project NUTR1R06n and BACWA 2011 report

The dominant sources of N and P loads, and the form of N, vary substantially among subembayments (Figure 6.2). In LSB, South Bay, and Central Bay, POTWs are the dominant source of N and P. In LSB, NO_3^- is the dominant N form discharged because LSB POTWs carry out nitrification. In South Bay and Central Bay, NH_4^+ is the dominant N form released by POTWs. In San Pablo Bay, direct POTW loads are relatively minor and primary release NH_4^+. In Suisun Bay, NH_4^+ is the primary form of N discharged, and the importance of those direct loads relative to other inputs varies seasonally (discussed more below).

Stormwater flows deliver seasonally-varying N and P loads to SFB. Only rough estimates of those loads have been made thus far due to data and modeling limitations. In most subembayments during most of the year, these estimates suggest that stormwater DIN and o-PO4 loads are substantially less than POTW loads (Figure 6.2), with potential exceptions being loads

to San Pablo Bay and Suisun Bay. In this region, rain generally occurs only in the months of October-April; N and P loads from runoff are highest during this period and generally minor during the dry season, at least when considered at the subembayment scale. The relative uncertainty in the magnitude of stormwater-derived N and P loads is high. Furthermore, it is likely that the stormwater load estimates made thus far poorly represent those from perennial rivers and streams (other than the Delta). While more work is needed if more accurate stormwater N and P loads are a priority, it seems unlikely that these loads will rival POTW loads at the subcatchment scale in LSB, South Bay, and Central Bay. However, while stormwater loads may not play a dominant role at the subembayment scale in these subembayments, a more important role for stormwater-derived N and P loads in certain habitats (e.g., along the Bay's margins, including wetlands) cannot be ruled out.

N and P loads entering SFB from the Sacramento/San Joaquin Delta have the potential to be large and seasonally-dominant nutrient sources to Suisun and San Pablo Bays (Figure 6.3). Delta DIN loads far exceed those from Suisun direct POTWs for approximately half the year, and NO_3^- loads from the Delta exceed those from Suisun direct POTWs year-round. For NH_4^+, however, direct POTW loads are comparable to or exceed Delta loads during late spring through fall. Most of the NH_4^+ entering Suisun Bay from the Delta likely comes from the Sacramento Regional County Sanitation District (Regional San) wastewater treatment plant, which currently does not nitrify and discharges ~70 km upstream of Suisun Bay. New permit requirements for Regional San require treatment upgrades over the next decade including nitrification and nitrogen removal, which will lead to both a shift in the N forms (predominantly NO_3^- instead of NH_4^+) and total N load (2-3 fold lower). Although the Delta load estimates to Suisun Bay are believed to be reasonable first approximations, they need to be further evaluated and refined using hydrodynamic and biogeochemical models for the Delta.

The load discussion thus far focused mostly on direct external loads to subembayments and not exchange between subembayments. Hydrodynamic exchange between subembayments may comprise a large proportion of loads to some subembayments. This is particularly true for San Pablo Bay, which has relatively low POTW direct loads but is down-estuary from Suisun Bay. The loads entering San Pablo Bay from Suisun Bay (which includes those that entered from the Delta) have thus far only been roughly estimated and need refinement through hydrodynamic/reactive-transport models. Nonetheless, the estimates illustrated in Figure 6.2 suggest that loads entering from Suisun could be the dominant source to San Pablo Bay for most of the year. Similarly, the southern reaches of South Bay are likely highly influenced by loads entering from LSB.

In general, SFB is a net source of nutrients to the coastal ocean throughout most of the year (Largier and Stacey, 2014). Exchange of water through the Golden Gate could conceivably act as a substantial net source of nutrients to the Bay during a limited time of the year and only under specific conditions. Freshly-upwelled coastal water contains up to 30 μmol L^{-1} NO_3. However, the extent to which that NO_3-rich coastal water enters SFB depends on a complex set of hydrodynamic and climatological factors. Under maximal conditions, daily NO_3^- loads into the Bay through the GG could be substantial relative to POTW loads (Largier and Stacey, 2014), although the frequency with which the necessary hydrodynamic and climatological drivers align is unknown, and requires further investigation. The fate of the nutrient plume that leaves SFB,

and its potential impacts on biological response in coastal waters, has not received much attention to date and also warrants further investigation if coastal effects are among the issues being considered through the Nutrient Strategy.

6.4 Seasonal and spatial variation in N and P

There are large spatial and seasonal differences in nutrient forms and abundance in SFB (Figure 6.3-6.6). Yet the processes that determine the ambient forms and concentrations of N and P are the same throughout SFB. The observed seasonal and spatial differences because the importance or magnitude of those processes differ considerably within and between subembayments, as well as over a range of time scales (tidal, diurnal, seasonal), due to multiple physical factors, including morphology, freshwater inputs, proximity and magnitude of loads, and mixing (including due to tides).

The seasonal and spatial variations in NH_4^+ concentrations clearly illustrate how the time- and space-varying intensities of physical and biogeochemical processes influence nutrient form and abundance. The maximum NH_4^+ levels seen in Suisun Bay tend to be the highest concentrations observed throughout all of SFB; however Suisun NH_4^+ levels exhibit strong seasonal variability, with spring and summer concentrations being 20-30% of those observed in winter (Figure 6.3). Mass balance estimates suggest that, during spring and summer, ~75% of NH_4^+ that enters Suisun Bay is "lost", presumably through either nitrification to NO_3^- or uptake by phytoplankton (SFEI, 2014b). This seasonality of Suisun NH_4^+ concentrations is likely due to warmer water temperatures and longer residence times in Suisun Bay and upstream of Suisun Bay in spring/summer, with the warmer temperatures favoring higher rates of nitrification, or NH_4^+ uptake by phytoplankton. Longer residence times during this time of year allow those reactions to proceed further, and longer days in May-Oct could also contribute to greater primary production and related uptake of NH_4^+. NH_4^+ concentrations in LSB offer an interesting counter-example to Suisun Bay (Figure 6.3). A strong seasonality in NH_4^+ concentrations is also evident in LSB. Although LSB has one of the highest areal N loads of all SFB subembayments (Figure 3.1), the vast majority of N loaded directly to LSB is in the form of NO_3^- (Figure 6.3). Therefore, a sizable portion of the NH_4^+ observed in LSB is likely due to NH_4^+ regenerated from the sediments. Sediment sources of NH_4^+ may be more evident in LSB not necessarily because they are larger, but because of LSB's morphology. LSB is quite shallow, and has a low ratio of water volume to sediment area compared to other subembayments; thus, any flux from LSB sediments would be mixed over a relatively small volume of water, causing a larger increase in concentration per unit mass of NH_4^+. The local NH_4^+ concentration maximum in June-July is likely due in part to higher rates of mineralization of organic matter in the sediments due to higher water temperatures, and longer residence times during these months allowing the NH_4^+ to accumulate to higher levels. The NH_4^+ concentration minima in April and September coincide with periods of highest phytoplankton biomass (discussed in Section 7), and may be evidence of NH_4^+ uptake by phytoplankton.

NO_3^- concentrations also exhibit strong seasonal and spatial variability (Figure 6.4). LSB has the highest NO_3^- concentrations (40-80 µmol L^{-1}), due to several factors: all POTWs in LSB nitrify before discharging effluent; LSB's volume is small relative to other subembayments and relative to the loads it receives; and there is limited net exchange of LSB water with the rest of the Bay, allowing NO_3^- to accumulate to higher concentrations. After LSB, NO_3^- concentrations are highest in Suisun Bay and South Bay. In Suisun Bay, the substantial NO_3^- loads entering from

the Delta likely contribute to these elevated NO_3^- concentrations. The lowest NO_3^- concentrations (~20 µmol L^{-1}) are observed Central, San Pablo, and northern South Bay, all of which have greater exchange with coastal waters entering through the Golden Gate.

Nitrification and denitrification likely play quantitatively important roles in determining the observed forms of N and the seasonality in concentrations in SFB subembayments. For example, although the vast majority of N loaded to Central Bay and South Bay occured in the form of NH_4^+ (Figure 6.2), ambient N was present primarily as NO_3^- (Figure 6.4), evidence of *in situ* nitrification's importance. Figure 6.5 presents DIN concentrations. Summer DIN concentrations in LSB were 30-40% lower than winter concentrations, with the lower concentrations likely due to a combination of denitrification at the sediment:water interface when water temperatures warm and higher uptake rates by phytoplankton during this time of year. DIN concentrations in southern South Bay (s27) exhibited similar seasonality. DIN concentrations in Suisun Bay are also lower in summer than winter. Initial box-model-derived estimates for Suisun Bay suggest that approximately ~30% of DIN input loads are lost via uptake or denitrification in Suisun Bay during summer months (Novick et al., 2014). These initial observations illustrate why developing accurate estimates *in situ* nitrification and denitrification rates will be important for identifying acceptable loads and apportioning observed concentrations to specific sources. LSB had the highest o-PO_4 concentrations, which were ~4-fold higher than most other subembayments (Figure 6.6). In Suisun Bay, o-PO_4 does not show the same strong seasonality as NH_4^+ or NO_3^- exhibited. In the other subembayments, o-PO_4 concentrations showed more defined seasonality. Minimum o-PO_4 concentrations occur in April and May in San Pablo Bay, Central Bay, South Bay, and LSB, consistent with modest o-PO_4 drawdown occurring due to spring phytoplankton blooms. o-PO_4 concentrations then increase to relatively constant concentrations over summer and fall, before dropping to lower levels in wet season winter months (Nov-Feb).

Concentrations of organic N and organic P in SFB are uncertain, since they have not been consistently measured (except in Suisun Bay). However, because of the large anthropogenic DIN and DIP loads SFB receives, it reasonable to hypothesize that DIN and DIP often dominate total N (TN) and total P (TP).

Dissolved SiO_4 concentrations vary both seasonally and spatially in SFB (Figure 6.7). The lowest SiO_4 concentrations are observed in Central Bay, with increasingly higher concentrations in more terrestrially-influenced areas of SFB. Suisun Bay has the highest SiO4 concentrations, due to its large freshwater inputs, with lower concentrations observed in summer and fall, as Delta flows decrease and salinity increases. Seasonal drawdowns in SiO_4 concentrations in LSB and southern South Bay appear evident during spring, coincident with periods of high primary production rates and the dominance of diatoms (Sections 7 and 9).
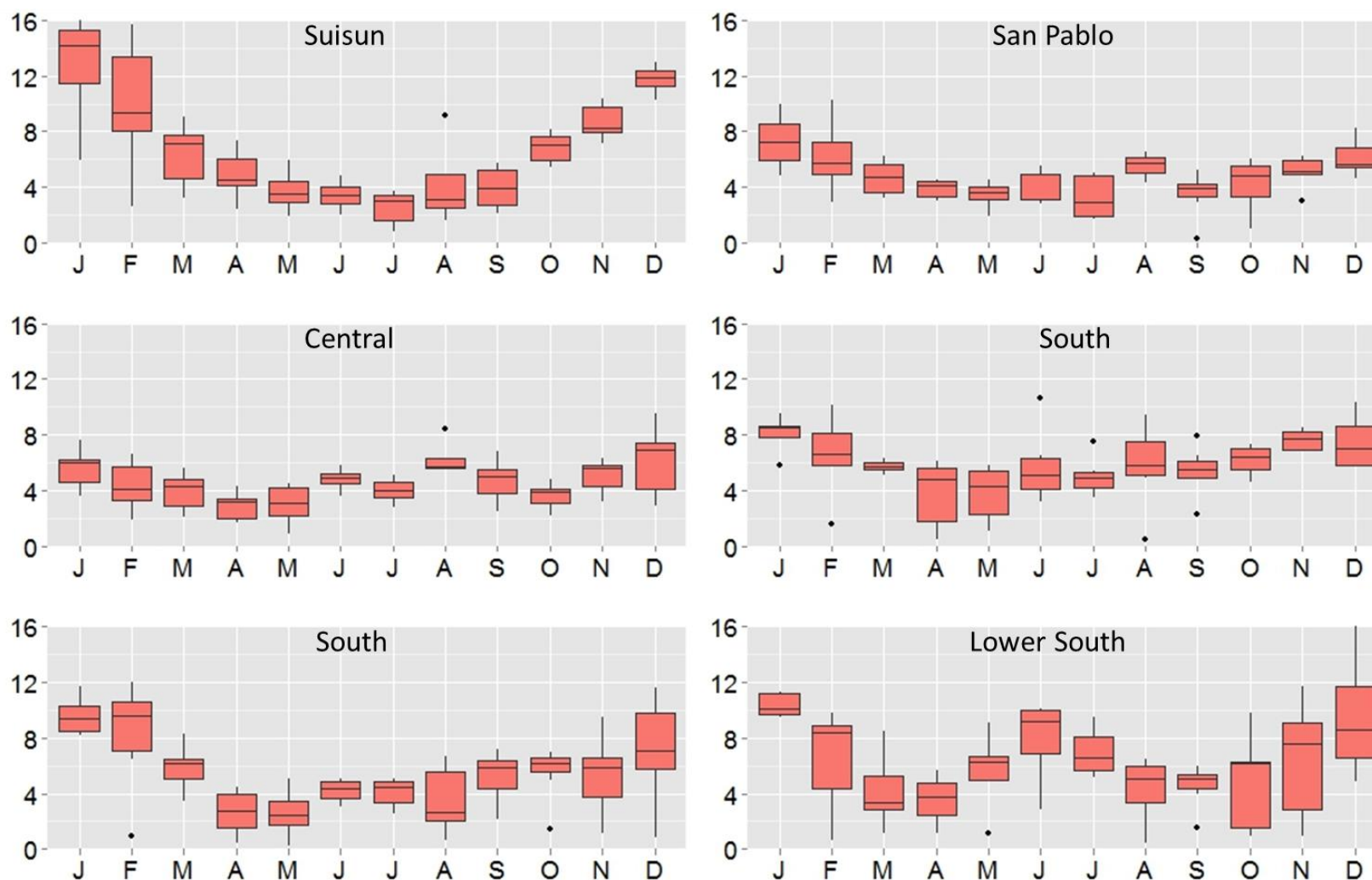
Figure 6.3 Monthly variations in NH$_4^+$ (µM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: http://sfbay.wr.usgs.gov/access/wqdata/
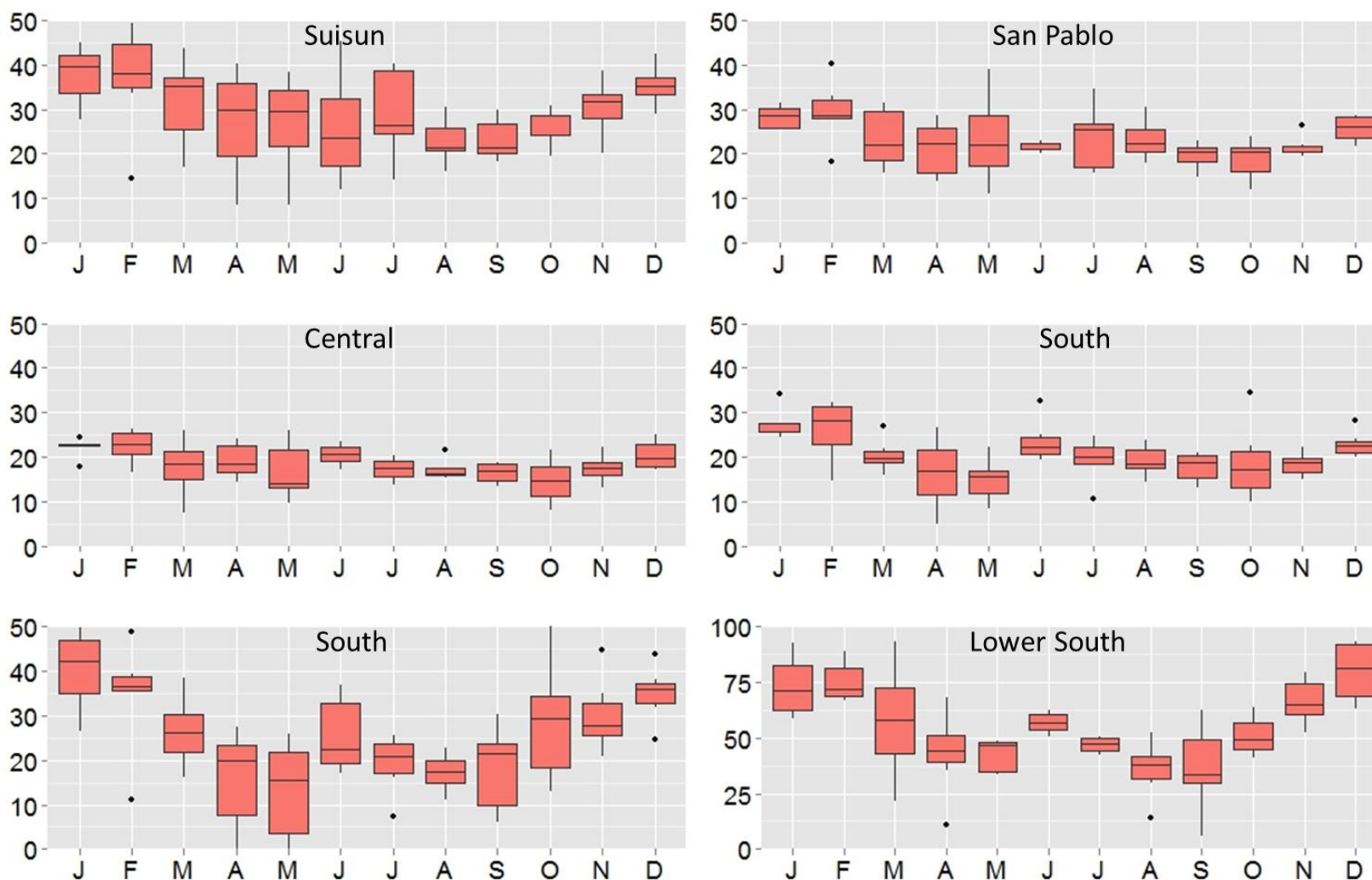
Figure 6.4 Monthly variations in NO_3^- (µM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the vertical different scales. Data source: http://sfbay.wr.usgs.gov/access/wqdata/
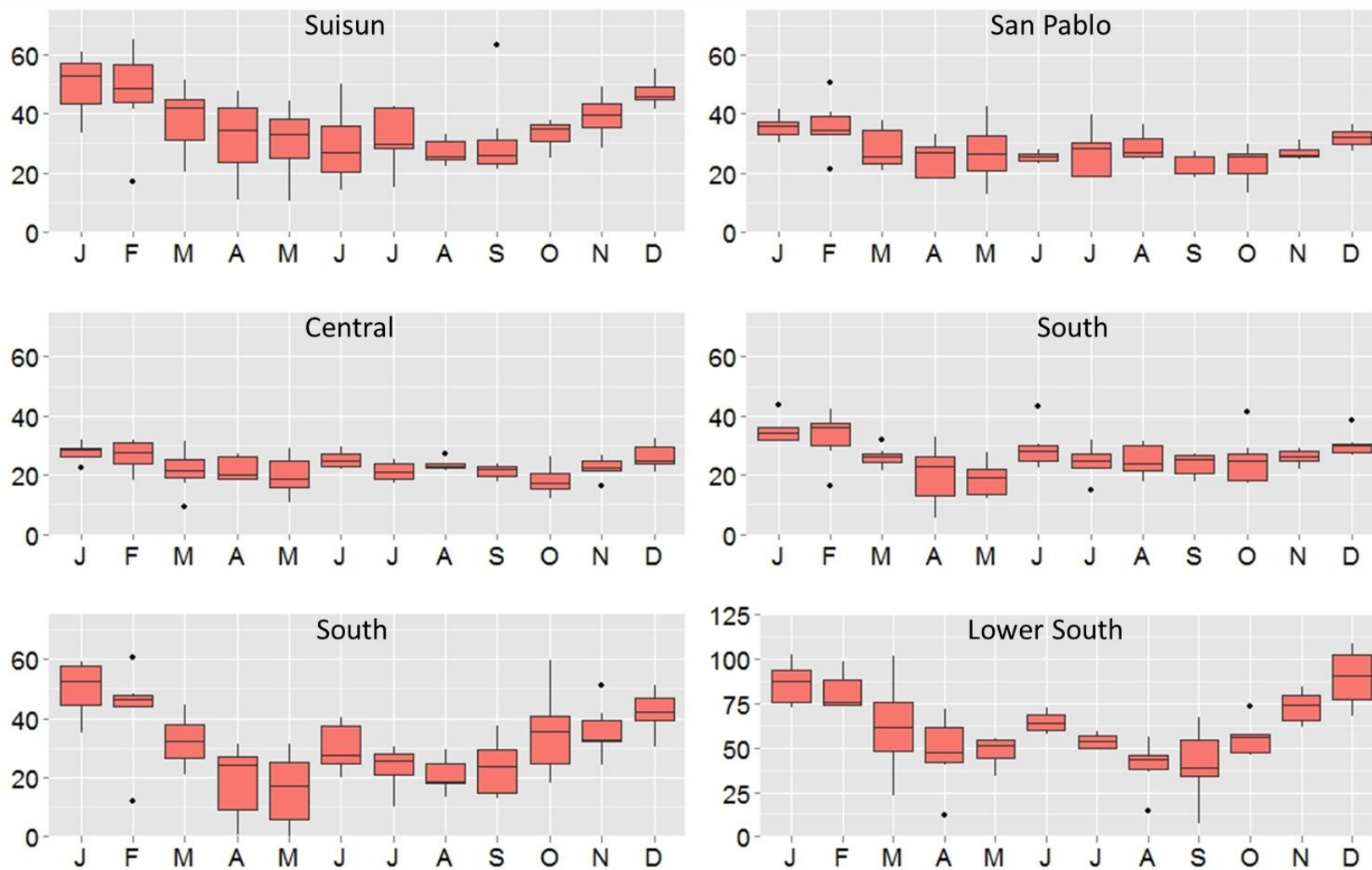
Figure 6.5 Monthly variations in DIN (µM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the vertical different scales. Data source: http://sfbay.wr.usgs.gov/access/wqdata/

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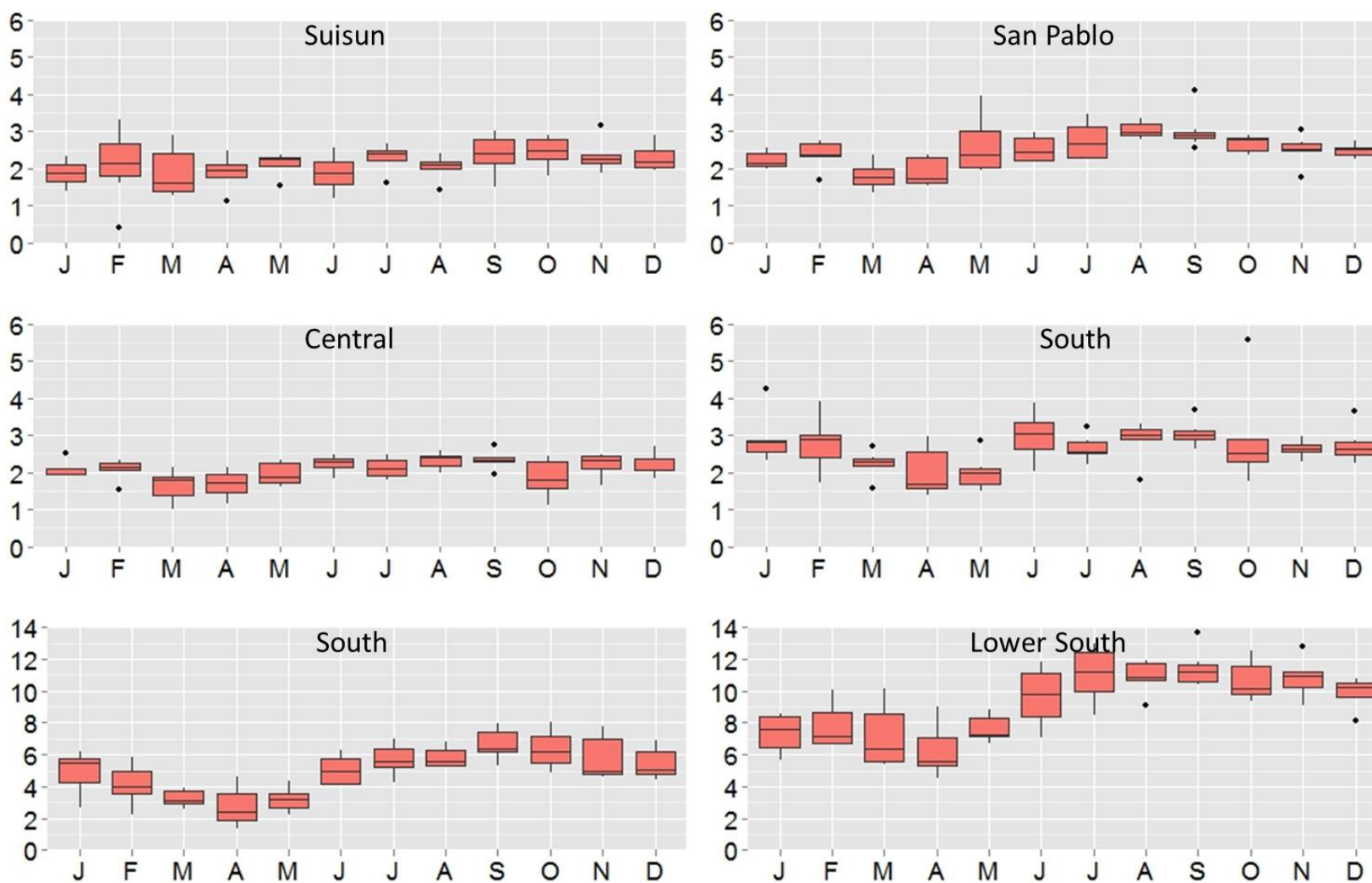
Figure 6.6 Monthly variations in o-PO$_4$ (µM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the different vertical scales. Data source: http://sfbay.wr.usgs.gov/access/wqdata/
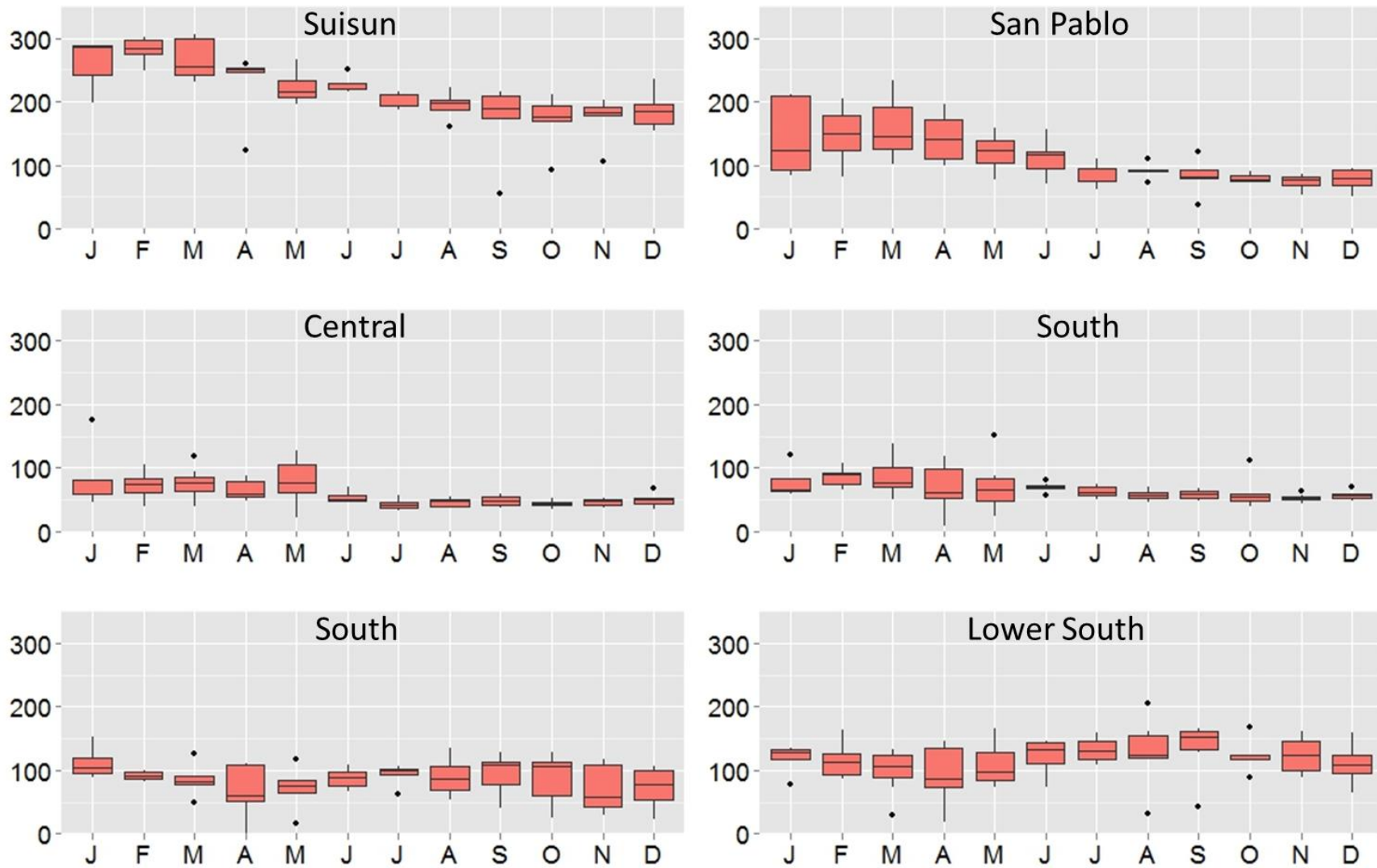
Figure 6.7 Monthly variations in Si (µM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: http://sfbay.wr.usgs.gov/access/wqdata/

6.5 Current state of knowledge

Table 6.2 summarizes the current state of knowledge and data/knowledge gaps related to N and P in SFB. The prioritizations in the rightmost two columns are related to the discussion in Section 11. Nitrification (water column or sediment:water interface) and denitrification (sediment:water interface) likely play important roles in regulating ambient concentrations of NH_4^+ and NO_3^- in the Bay. Developing models, initially basic and gradually more sophisticated, that would allow quantification of these processes is an essential early step for informing decisions about allowable N loads to subembayments and source attribution, and about needs for additional data collection. Assuming that mass balance estimates from modeling suggest that nitrification and denitrification play important roles in N cycling in SFB, field studies will likely need to be conducted to quantify transformations rates. Some work has been conducted to characterize organic matter mineralization and NH_4^+ production in sediments at multiple locations throughout the Bay (Caffrey 1995), and more recent studies have investigated nutrient flux or transformations across the sediment:water interface in Suisun Bay and the Delta (Cornwell et al., 2013). However more work would likely be needed to assess variability in rates as function of space and season.

Limited data exists on nutrient concentrations at time scales shorter than ~1 month. Finer temporal resolution data will be needed to improve understanding about nutrient transformation rates. There is also limited information on nutrient concentrations along the shoals and in shallow margin habitats. Finally, organic N and P (PON, POP, DON, DOP) have not been routinely measured in most locations in the Bay (except at IEP sites in Suisun Bay and San Pablo Bay), and their importance and bioavailability are poorly known.

Table 6.2 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 additional or continued 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**

7 Primary Production and biomass accumulation

7.1 Introduction

Primary production in SFB is carried out by phytoplankton, benthic algae (microphytobenthos, MPB), macrophytes, and macroalgae. In its current form, the primary production module of the conceptual model focuses mostly on phytoplankton, and to a lesser degree on MPB. Macrophytes and macroalgae are not considered in this report. For more on the latter topics, the reader is referred to the SFB NNE Literature Review and Data Gaps Analysis (McKee et al., 2011).

Phytoplankton biomass is an important indicator of ecosystem health with respect to nutrient loads, and is among the potential indicator sof ecosystem health and nutrient-related adverse impacts for SFB (Figure 3.1; Table 2.1). Phytoplankton reside at the base of the food web, and are the predominant food resource for most pelagic and benthic primary consumers in SFB (Jassby et al., 1993). Phytoplankton require nutrients for growth, and in many aquatic systems there is a direct link between phytoplankton biomass and nutrient loads, with nutrient abundance being one of several factors that can regulate both the rate of primary production and the ultimate biomass that can be generated. As noted in Section 3, excessive phytoplankton biomass is one plausible impaired state in SFB. Excessive phytoplankton biomass can have direct adverse impacts, such as coatings on bird wings, odor, and degraded aesthetics. High rates of primary production and accumulation of high levels of phytoplankton biomass are also problematic because they lead to low dissolved oxygen levels in the water column and sediments when phytoplankton die, settle, and are metabolized by microbes (Section 8). By absorbing light, high phytoplankton biomass can also adversely impact the production of submerged aquatic vegetation (SAV), which serves as valuable habitat in some estuaries. However, impacts of high phytoplankton biomass on SAV is not considered to be among the most important adverse impact pathways in SFB because of already low-light conditions due to high turbidity from inorganic particles.

Phytoplankton biomass is actually comprised of multiple species, with complex community responses caused by natural and anthropogenic drivers. Both the biomass and the types of phytoplankton present (community composition) are important for adequately supporting food webs. This section focuses on phytoplankton biomass; Section 9 addresses community composition. Microphytobenthos are discussed in Section 7.3.

7.2 Phytoplankton

Phytoplankton biomass is the concentration of living phytoplankton material in the water column. Phytoplankton biomass is commonly presented in units of mg chl-a m^{-3} or µg chl-a L^{-1}, although it would be more accurate to describe it in units of µg C L^{-1}. The biomass measured at any given point in space and time is the net result of multiple processes (Figure 7.1): growth; settling; pelagic and benthic grazing; sinking and degradation or burial; and exchange or mixing between areas through the movement of water masses (lateral, longitudinal, vertical) (Cloern, 1996). The magnitudes of these processes vary in space and time, and this variation leads to spatial and temporal differences in biomass concentrations.

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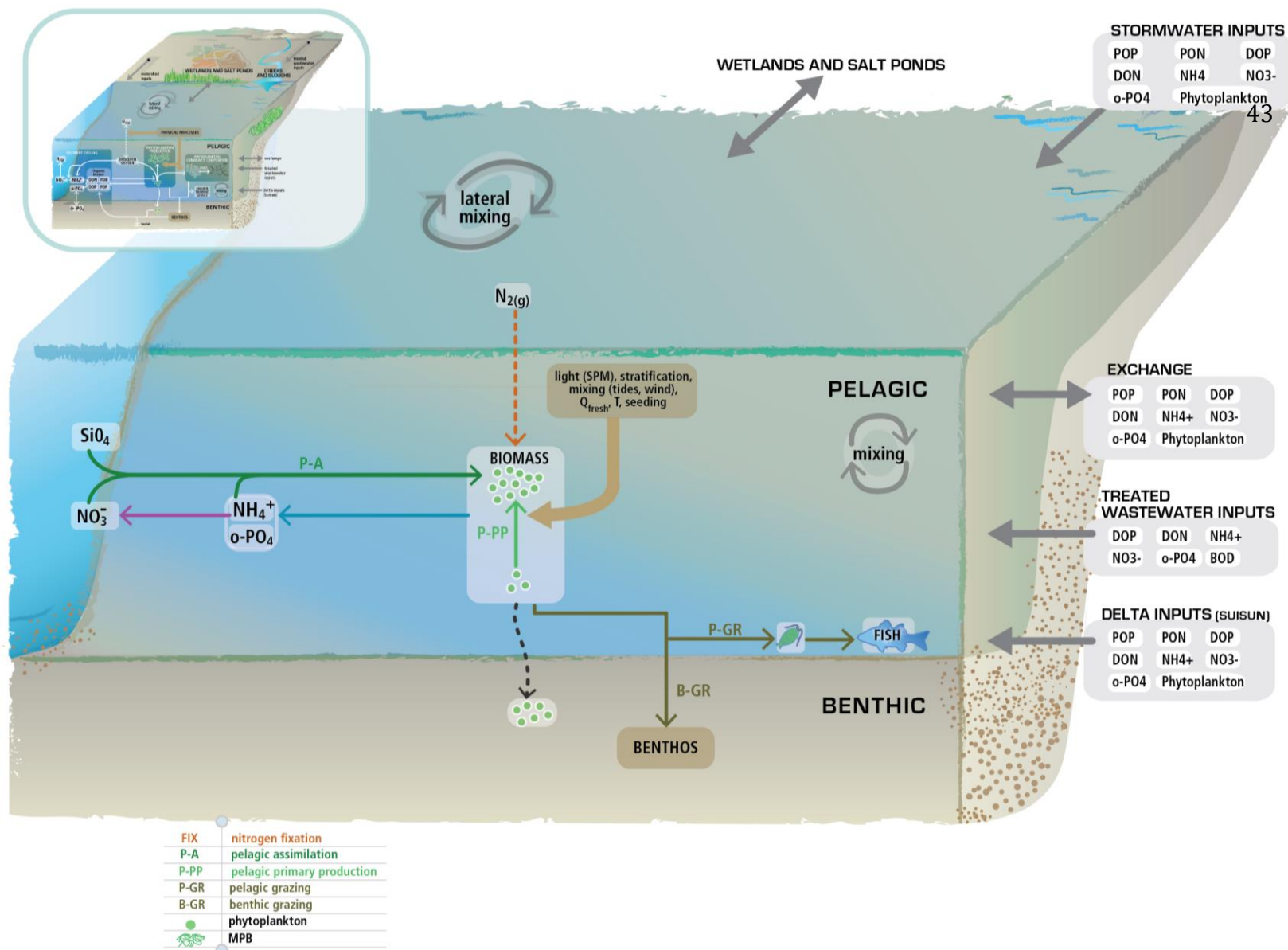
Figure 7.1 Phytoplankton primary production conceptual model. Physical processes play an important role in determining when and where phytoplankton blooms occur, their size, duration, and the concentration of biomass that accumulates. The relationship between physical processes and production are described in more detail in Figure 7.2.

7.2.1 Transport and Loads

Sources of externally-produced phytoplankton biomass to a subembayment include: flow from rivers, perennial streams, and stormwater carrying phytoplankton produced in adjacent systems; hydrodynamic exchange between adjacent subembayments or habitats (e.g., water movement between shoals and channel); and exchange with the coastal ocean. In general, the majority of phytoplankton biomass observed in SFB is produced within the Bay (Jassby et al., 1993). Suisun Bay may serve as a notable exception: Jassby et al. (1993) estimated that the load of phytoplankton-derived particulate organic carbon (POC) exported from the Delta to Suisun Bay could account for 20-80% (median ~ 50%) of Suisun's POC budget, including Suisun *in situ* production. Those estimates were based on data from 1975-1989. Considering the substantial ecosystem changes observed since the late 1980s both in the Delta and Suisun, these estimates likely need to be updated. In addition, the coastal ocean can be a non-trivial source of phytoplankton biomass to Central Bay, especially during the upwelling season (Martin et al., 2007).

7.2.2 Production and accumulation

The processes that control biomass can be divided into those that influence the rate of growth and those that influence the rate of accumulation. Typical modes of phytoplankton productivity and biomass accumulation in SFB are represented in Figure 7.2. The most common condition is low phytoplankton productivity and low biomass (Figure 7.2.A). Blooms develop when the water column becomes periodically stratified (Figure 7.2.B) or when appropriate conditions prevail in shallow areas (Figure 7.2.C and 7.2.D). Major processes and drivers are described below.

7.2.3 Factors that influence production rates

Several factors influence phytoplankton production rates, including temperature; light availability; nutrient concentrations; and potential anthropogenic factors, such as contaminants, that could inhibit or slow production rates, including pesticides or toxic metals (e.g., copper), or the hypothesized inhibition of growth by elevated NH_4^+ (e.g., Dugdale et al., 2007).

Temperature: Phytoplankton maximum growth rates vary strongly with temperature (e.g., Eppley 1972; Behrenfield and Falkowski, 1997). Bay-wide average temperatures vary seasonally from 10 $^\circ$C to >20 $^\circ$C, with as much as a 7 $^\circ$C difference in maximum temperatures between subembayments. These temperature ranges translate into substantial differences in maximum growth rates: annual maximum growth rates could differ by up to a factor 1.4 between subembayments (LSB vs. Central), and by up to a factor of 2 seasonally (LSB summer vs. winter) (assuming Q_{10} = 1.88; Bissinger et al., 2008)

Light levels: Throughout much of SFB and during most of the year, light availability acts as the main limitation on phytoplankton growth rates. A number of field investigations and model-based estimates document the importance of light limitation in SFB (Cloern 1982; Cloern et al. 1985; Cole et al. 1986; Cole and Cloern 1987; Alpine and Cloern 1988; Caffrey et al. 1994; Jassby et al., 2002; Cloern et al., 2007). Phytoplankton growth rates depend primarily on the amount of time cells spend in light-rich zones (Figure 7.3) (e.g., Alpine and Cloern, 1988; Cloern et al., 1985). The amount of light reaching the water column surface (incident light or insolation) varies seasonally due to length of day, and over shorter time scales (hours-days) due to cloud cover (Figure 5.2). From the surface, light levels decrease exponentially with depth, primarily due to light scattering and absorption by suspended particulate matter (SPM).

A. No bloom, baseline

Light   ρ

Dominant condition. Occurs in multiple situations:
- In general, low light availability maintains low growth rates
- Strong vertical mixing prevents prolonged periods of stratification
- Wind and tides resuspend sediments in the shoals and maintain lower light levels there.
- High clam biomass/grazing, with a stronger effect in shallow areas
- In Suisun Bay, high NH4 is hypothesized to additionally limit production rates and prevent blooms. Short residence times in Suisun Bay can also limit blooms.

B. Stratification-induced bloom

Light   ρ

Occurs when there is:
- Weak vertical mixing due to bi-annual minima in tidal energy.
- Sufficient freshwater inputs or appropriate conditions that allow surface waters to warm (calm clear days)

Clam Grazing Rate

Tidal Mixing

Phytokplankton Biomass

Jan   Jul   Dec

C. Shoal-induced bloom

Light   ρ

Requires:
- Moderate to high productivity
- Low clam biomass/grazing

D. Shoal-induced bloom that propagates to channel

Light   ρ

- In the absence of stratification, shoal production must be great enough to offset low productivity in deeper areas
- Low clam biomass/grazing
- Appropriate lateral exchange to sustain biomass in deeper areas but not flush the shoals too rapidly.
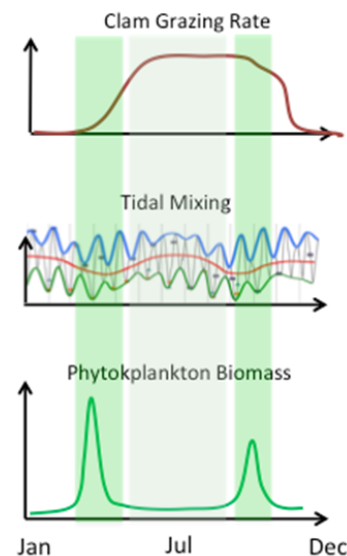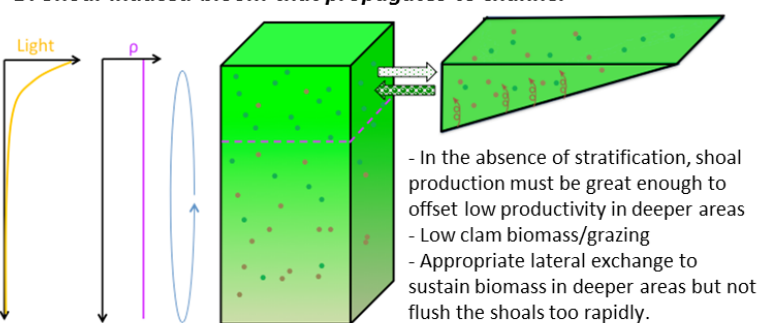
Figure 7.2 Modes of productivity in SFB, and factors influencing timing and magnitude of blooms
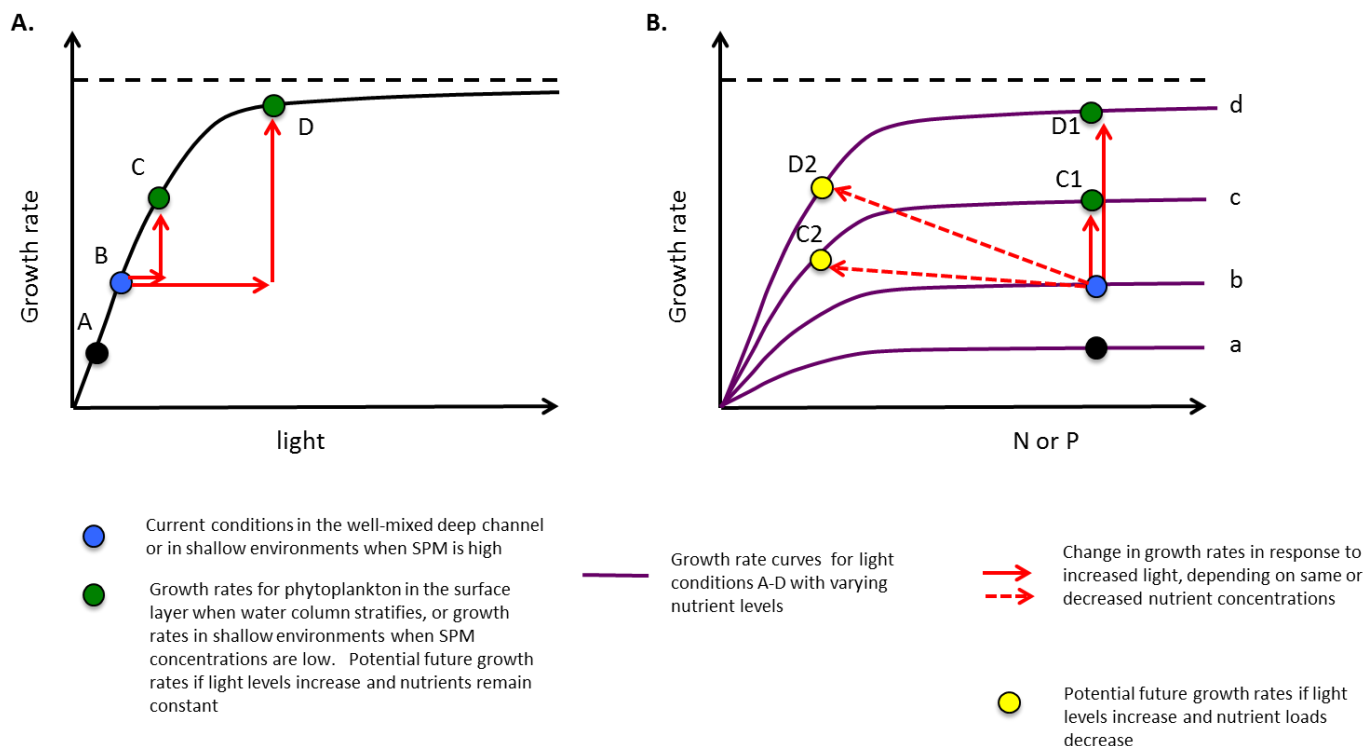
Figure 7.3 Phytoplankton Growth Rates: Light limitation vs. nutrient limitation. In general, throughout most of SFB, light limits phytoplankton growth most of the time. **A.** When nutrients are available at non-limiting levels, phytoplankton growth rate increases as a function of light to some maximum level (this maximum growth rate varies by temperature and species). Growth rates increase as light levels increase. **B.** The four curves (a-d) illustrate growth under four different light levels. At each constant light, growth rate varies as a function of nutrient concentration (x-axis). In SFB, N and P concentrations are typically high enough that growth rates are not nutrient limited. Instead, phytoplankton are thought to grow at their maximum growth rate for that specific light level (i.e., the flat part of the curves). Under current nutrient loads/concentrations, if light levels increase (shift from blue to green dots, due either to decreasing SPM, or in response to periodic stratification), growth rates and biomass accumulation will increase. However, if nutrient loads and concentrations were lower (blue to yellow dots) growth rates and biomass accumulation would not increase as much.

SFB is considered a turbid system, and the photic zone - the depth at which light levels are 1% of incident light - is typically only 1-2 m thick (Cloern et al., 1985). Unlike some other nutrient-rich systems in which phytoplankton cells can themselves contribute substantially to light attenuation, light attenuation in SFB is primarily due to non-phytoplankton SPM (Cloern, 1987).

SPM concentrations and photic zone depth vary substantially between subembayments, within subembayments, and as a function of season (Figure 5.6). SPM concentrations also increase when high winds resuspend more sediments, and show periodic increases and decreases in response to the spring-neap tide cycle (Schoellhamer, 2002). SPM and light attenuation coefficients are often higher along shallow shoals than in deeper areas, due to turbulent energy from wind and tides more readily resuspending particles from the bottom. Despite the higher SPM concentrations along shoals, though, average light levels that phytoplankton experience may still be higher there because they are mixed over a shallower depth. SPM concentrations have decreased significantly in some areas of SFB over the past several decades. For example, SPM concentrations have dropped by on-average 50% in Suisun Bay since 1975 (Figure 5.5;

Cloern and Jassby, 2012), due to decreasing loads, gradual loss of erodible bed sediments already in the Bay, and step declines in turbidity due to "washout events" (Schoellhamer, 2011). This 50% decrease in SPM translates to roughly a doubling of the photic zone depth. The Bay-wide average decrease in SPM is ~35% (Schoellhamer, 2011).

Hydrodynamic controls over phytoplankton's access to light and production rates
The vertical and lateral movements of water masses - and the phytoplankton they contain - within SFB play an important role in regulating overall system productivity by controlling the average amount of time phytoplankton remain within the light-rich photic zone. Variability in the magnitude of vertical and lateral mixing also plays a role in determining if, when, and where phytoplankton blooms develop and terminate (Cloern 1991; Lucas et al., 1998). Thus, understanding and modeling hydrodynamics in the Bay are essential for understanding and predicting productivity and the accumulation of phytoplankton biomass.

The presence or absence of vertical stratification in the water column strongly influences productivity (Figure 7.2.A and 7.2.B). When the water column is vertically well-mixed (Figure 7.2.A), the amount of time phytoplankton spend in the photic zone decreases in proportion to water column depth. Vertical layering of the water column – stratification – develops when less dense layers of water overlay more-dense layers. These density differences arise due to differences in salinity (density increases with increasing salinity) and temperature (density decreases with temperature). The density difference limits vertical mixing and allows phytoplankton to reside in the relatively thin (e.g., 1-3 m), light-rich surface layer, as opposed to being moved over the entire water column. When confined to the surface layer, phytoplankton harvest more light, resulting in higher growth rates (Figure 7.2.B and 7.3.A). (Note: Stratification also positively influences biomass accumulation in the sense that filter-feeding benthos cannot access phytoplankton in the surface layer).

Factors that influence whether stratification occurs, and how long it persists, therefore have an important influence on productivity and biomass accumulation. SFB experiences strong tidal mixing which acts to break down stratification by vertically-mixing the water column (Cloern, 1991). Tidal mixing intensity varies periodically: two tidal cycles per day with different mixing energies; the spring/neap cycle by which tides vary in magnitude on ~14 day cycle; and twice-annual periods of lowest sustained tidal mixing energy (March, September) and maximum sustained mixing energy (December, June; Figure 5.2). Assuming there is sufficient freshwater input (or lateral or longitudinal gradients in salinity) for salinity gradients to be develop, stratification/destratification can occur with the same periodicity as tidal mixing intensity. Thus, the duration of stratification events can vary from hours (semi-diurnal to diurnal stratification) to days and weeks (during the weakest tides twice per year) depending on the strength of stratification relative to the tidal mixing energy. Cloern (1996) observed that blooms along the deep channel of South Bay generally developed in March, when periods of weak tidal mixing co-occurred with sufficient freshwater input to allow stratification to develop and persist for 10-14 days. The termination of these blooms corresponded with increased tidal energy that vertically-mixed the water column (Cloern 1996). This cycle is likely also important in other subembayments. In Suisun Bay, in the 1970s and early 1980s, IEP monitoring data indicates that phytoplankton biomass remained elevated over longer periods, i.e., throughout Spring, Summer, and Fall. Suisun receives larger freshwater inputs than other subembayments

Recently (past 10-20 years), fall blooms have been occurring with increased frequency in southern South Bay and LSB (e.g., Figure 3.7; Cloern and Jassby, 2012). The reason for these fall blooms in LSB and South Bay is unknown, but could be in part due to lower SPM (higher light levels) and lower grazing pressure (Section 7.2.3). If stratification plays a role in the increased biomass in fall, density differences during this time may have been due to surface water heating than freshwater inputs. Clear skies (greater solar insolation) and calm winds would thus be required for stratification to develop and persist. One particularly striking example of a fall bloom occurred in September 2004, when calm winds and weak tides occurred coincident with record temperatures and clear days, allowing a warm surface layer to establish (Figure 3.11). A bloom of the red tide organism *Akashiwo sanguinea* developed, with biomass levels reaching nearly 200 mg chl-a m^{-3} (Cloern et al., 2005), the highest levels observed in this region of SFB over the 40-year period of record. The bloom terminated after only 1 week, once mixing energy levels increased.

SFB's expansive shallow shoals are important zones for phytoplankton production. Large proportions of Suisun Bay, San Pablo Bay, South Bay, and Lower South Bay have water depths of <2 m. Field and modeling studies in South Bay indicate that phytoplankton blooms often originate along the shoals (Figure 7.2.C and 7.2.D), exploiting the relatively light-rich conditions of the shallow water column (Cloern et al., 1989; Huzzey et al., 1990; Lucas et al, 1999; Lucas et al., 2009 ; Thompson et al., 2008). This is well illustrated in South Bay and LSB in Figures 7.4 and 7.5. Under appropriate lateral mixing conditions, production along the shoals can lead to high biomass there, and appreciable biomass transport to the relatively unproductive channel (Figure 7.4; Thompson et al., 2009; Lucas et al., 2009). Figure 7.5 illustrates a sustained bloom (>1 month) with 60 to >100 ug/L over the entire water. Since average light levels in the deep channel, when well-mixed, are too low to support substantial growth, most of this biomass was likely produced along the shoals and subsequently mixed over the water column (i.e., Figure 7.2.D). Because sediments are more readily resuspended in shallow environments, higher turbidity, resulting from tidally- or wind-driven local resuspension of sediments, can decrease productivity on the shoals (Lucas et al., 2009). Furthermore, filter feeding by clams can more efficiently clear the shoal water column than the deep channel water column, and reign in shoal blooms (see Section 7.2.3; and Lucas and Thompson 2013). Despite the apparent importance of productivity along the shoals, there is relatively limited data available from these areas. Increased monitoring (including continuous monitoring with moored sensors, e.g, turbidity, chlorophyll, etc.) is needed to understand when shoal induced blooms (Figure 7.2.C and 7.2.D) drive overall production in subembayments.
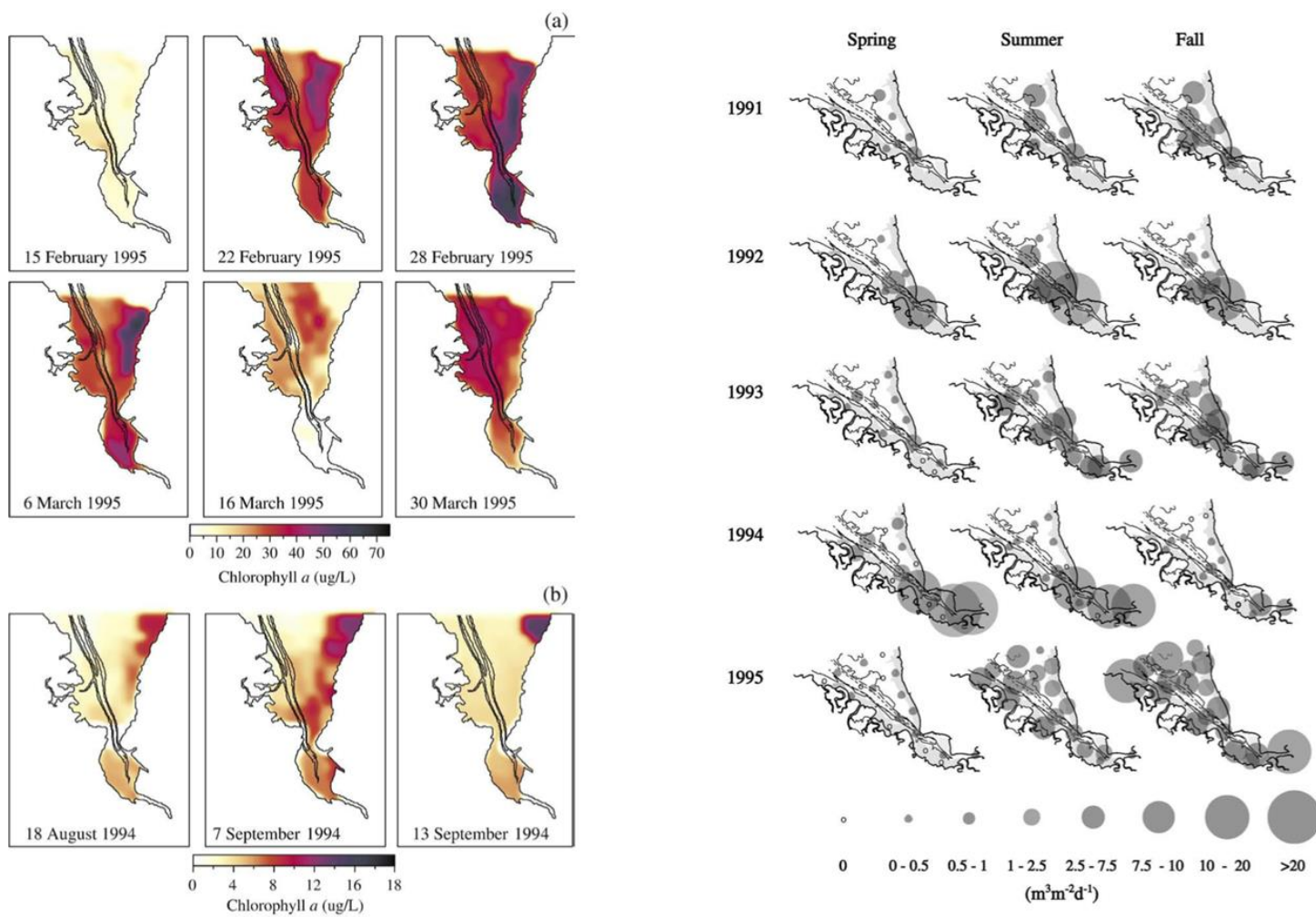
Figure 7.4 A. Phytoplankton biomass South Bay illustrating bloom initiation on shoals and propagating to the channel. **B.** Spatial, seasonal, and interannual variation in bivalve grazing rates in South Bay and LSB. Source: Thompson et al. 2008
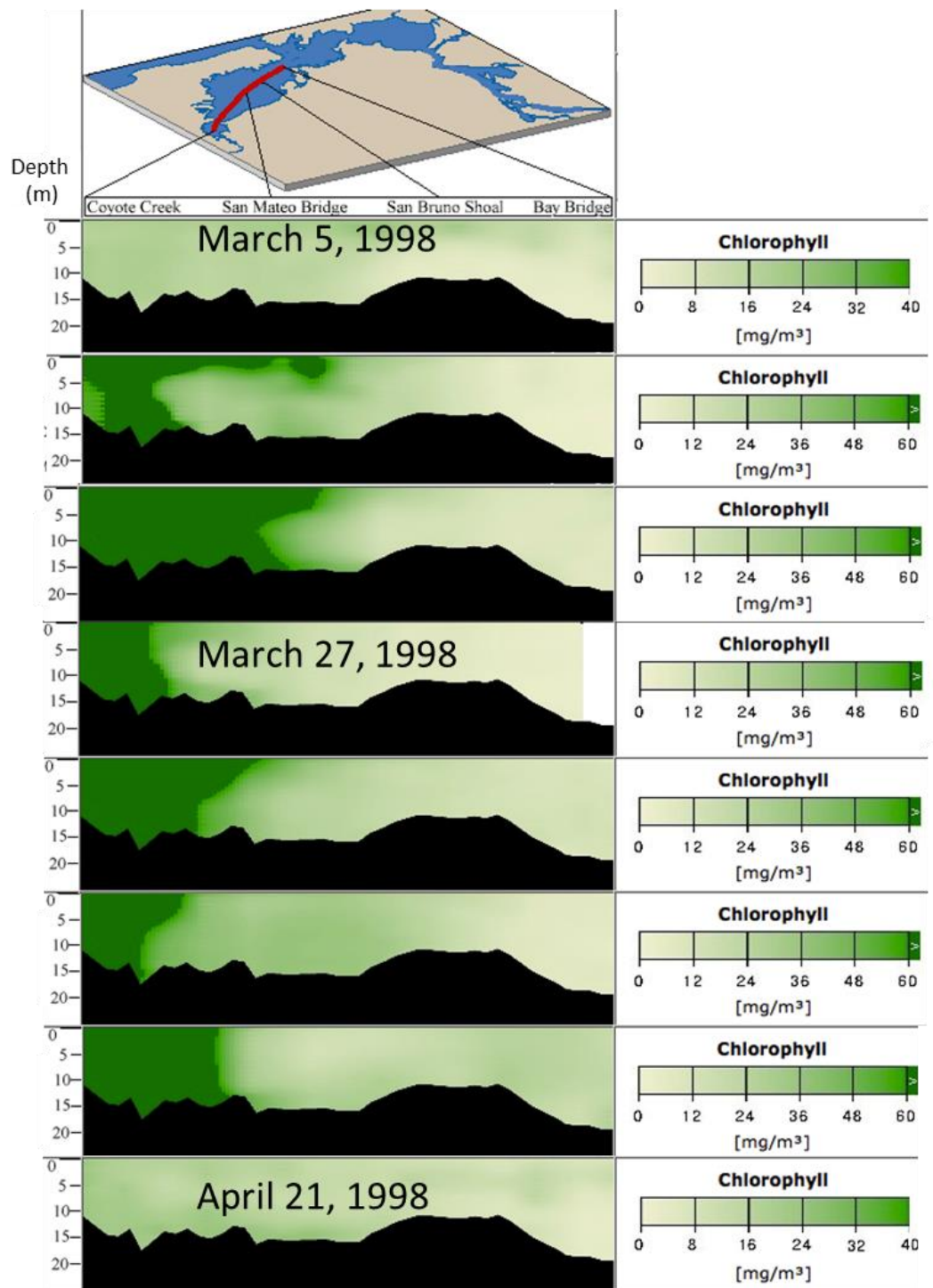
Figure 7.5 Phytoplankton biomass in LSB and South Bay during Spring 1998. Note that chl-a concentrations are constant over the full water column, illustrating the production scenario in Figure 7.2 D. Source: http://sfbay.wr.usgs.gov/access/wqdata/archive/longterm.html.

Cole and Cloern (1984) demonstrated that primary production rates in SFB could be reliably quantified by knowing incident light intensity, depth of the photic zone, and the concentration of phytoplankton biomass (as μg chl-a L^{-1}). This relationship is calibrated using an "efficiency factor", ψ, for new biomass production per unit light energy (expressed in units mg chl-a [Einstein m^{-2}]$^{-1}$), which is specific to the phytoplankton community of the system (Cole and Cloern, 1987; Jassby et al., 2002). Using this ψ-based relationship to estimate productivity is valid as long as ψ remains constant over space and time (Jassby et al., 2002 ; Kimmerer et al. 2012 ; Parker et al., 2012), and C:chl-a is reasonably well-known and constant. Recent studies focused in northern SFB have suggested that both ψ and C:chl-a may have changed considerably over the past 20 years, potentially due to large changes in phytoplankton community composition (Kimmerer et al., 2012; Parker et al., 2012). However, the analytical techniques for measuring production rate differed between Cole and Cloern (1984) and Parker et al. (2012), and some or all of the apparent difference in the calibration coefficients could be the result of these analytical differences. In either case, the overall ψ-based approach remains valid, although it may need to be periodically re-calibrated and validated, and different relationships (i.e., different values of ψ) may need to be developed to account for a range of conditions (light-inhibition, different phytoplankton communities, T).

Nutrients and phytoplankton production rates
In many estuaries nutrient concentrations both influence primary production rates and determine when a bloom terminates (due to nutrient depletion). However, in SFB, nutrients tend to be replete year-round, and thus they seldom control production rates (Figure 7.6, 7.7 and 7.3.B). Nutrient concentrations do exhibit periodic drawdowns in SFB, owing in part to phytoplankton growth (Thompson et al., 2008; Figure 3.14 in SFEI 2014b). However, at least in deep channel environments where most data is available, concentrations infrequently dip to levels that would be expected to substantially slow overall production rates (Figure 7.6 and 7.3.B). Instead, field and modeling studies in SFB suggest that phytoplankton bloom termination at the subembayment scale more commonly occurs due to other factors, especially break-down in stratification (Cloern 1991), and sometimes increase in grazing pressure (Thompson et al., 2008). The tops of the grey shaded areas in Figure 7.6 correspond to 2 times K (half-saturation constant) for N, P, or Si. A value of 10 x K would be a more conservative estimate of when a concentration may begin to slow growth rates. If a value of 10 x K is used, the interpretation of infrequent nutrient limitation remains generally the same, except for DIN in South Bay. Even in the case of South Bay using 10 x K$_N$ ~ 10 μM, though, [DIN] rarely falls below that value (~15% of the time). The case of South Bay and LSB are better illustrated in Figure 7.7, which presents DIN and DIP concentrations at individual stations in terms of their interquartile ranges, 95% confidence intervals and outliers. At all stations the interquartile ranges lie well above the 10 μM; at stations 19-27 and 36, the 95% confidence intervals also lie above 10 μM. DIP concentrations almost always exceed ~2 μM (10 x K$_P$). So, while there are windows in space/time when DIN falls below a potentially growth rate limiting concentration, DIN substantially exceeds rate-limiting concentrations the vast majority of time. Nonetheless, a closer examination chl-a, DIN, and other nutrient time series would be worthwhile for providing insights into when, where, and under what conditions DIN does reach these lower levels.
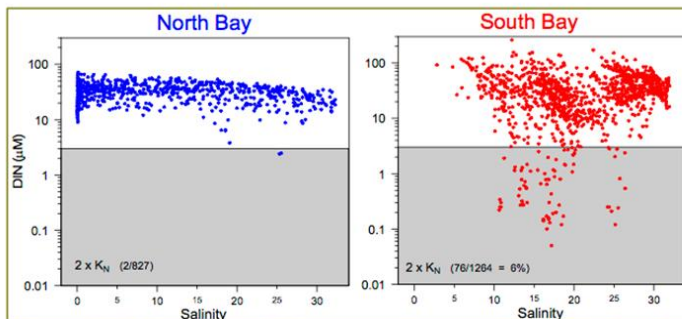
Figure 5.6.5. Near-surface DIN concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential N limitation.
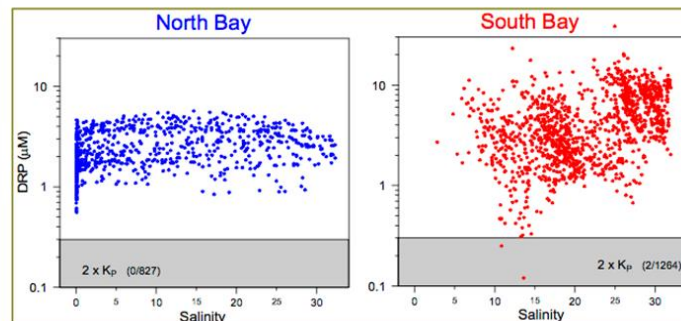
Figure 5.6.6. Near-surface DRP (PO_4^{3-}) concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential P limitation.
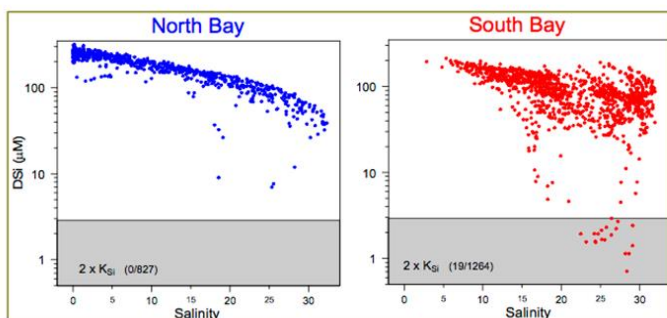
Figure 5.6.7. Near-surface $Si(OH)_4$ (DSi) concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential Si limitation.

Figure 7.6 Nutrient concentrations in SFB compared to thresholds for kinetic limitation of phytoplankton growth. Source: Cloern and Dugdale 2010.
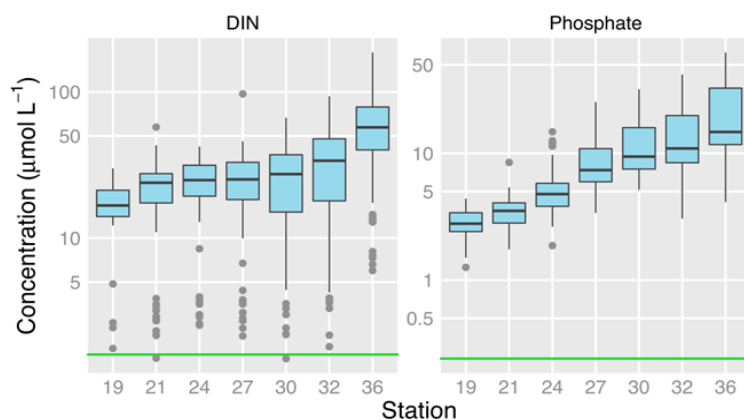
Figure 7.7 "Boxplots showing spatial distributions of DIN and DIP in surface waters (0-3m) of South Bay and LSB, 1969-2010. Green lines represent characteristic K_N and K_P to indicate nutrient concentrations that potentially limit phytoplankton growth." Source: Cloern and Jassby 2012

Low production rates due to elevated ammonium in Suisun Bay

Recent studies in SFB and the Delta have argued that the influence of nutrients on biomass production rate may be more complex than the generally accepted idea of nutrient limitation on growth. Dugdale and colleagues argue that elevated NH_4^+ levels in Suisun Bay and the Delta slow primary production rates and can prevent blooms from developing (Dugdale et al. 2007, 2012; Parker et al., 2012a,b). These studies refer to the phenomenon as the "NH_4^+ paradox": the

crux of the hypothesis is that when NH_4^+ concentrations exceed 2-4 µM, phytoplankton can not access the relatively large NO_3^- pool on which these studies suggest they can grow more rapidly than NH_4^+. The NH_4^+ paradox studies acknowledges that other factors such as light limitation, clam grazing, and residence time also exert influence over phytoplankton production or biomass accumulation. However Dugdale and colleagues hypothesize that NH_4^+-inhibition of productivity could be a quantitatively important mechanism during critical periods, such as during spring, when clam grazing may in fact be low due to seasonal variations in clam abundance (Dugdale et al., 2007).

There remains considerable disagreement within the scientific community – including among this report's authors – about the mechanistic interpretations of the NH_4^+-paradox studies, and about the potential ecosystem-scale importance of the mechanism relative to other factors that regulate phytoplankton growth rates and biomass accumulation. A detailed review of these studies was recently completed, and the reader is referred to that report for more information (SFEI 2014b). Experiments to explore the NH_4^+-paradox are continuing. More integrative studies (e.g., modeling) and controlled experiments are needed to evaluate the importance of hypothesized NH_4^+-inhibition mechanism relative to other processes.

7.2.3 Top-down biological processes that influence biomass accumulation
Benthic grazing
Benthic grazing plays an important and sometimes dominant role in regulating the amount of biomass that accumulates in the water column of some SFB subembayments, or habitats within those embayments. (e.g., Thompson et al. 2008; Kimmerer and Thompson, 2014; Cloern et al., 2007; Lucas and Thompson, 2013). The effect of benthic grazing rates on phytoplankton biomass is dependent on the filtration rates (m^3 g^{-1} d^{-1}) of the species present and the abundance of grazers (g m^{-2}). Grazer abundance varies seasonally and spatially based on individual species' life histories, predation, and habitat preference (salinity, sediment type, etc.). Grazer abundance is also tightly coupled to their food supply: i.e., the biomass of grazers at any point in is related to the amount of food available prior to that time. The influence of the filtration rate on phytoplankton concentrations in the overlying water column also depends on water column depth: at a given filtration rate (which is proportional to clam biomass), a shallow water column will be cleared of its phytoplankton faster than a deep water column. The effect of benthos on phytoplankton biomass also depends on other factors such as benthic boundary layer thickness and stratification, which are themselves influenced by turbulent mixing energy.

Potamocorbula amurensis filtration efficiency is high on relatively large phytoplankton (>5 um = 100%; Kimmerer and Thompson 2014) and lower for smaller phytoplankton (<5 um = 75%; Kimmerer and Thompson, 2014; Werner and Hollibaugh, 1993). This size-dependent filtration efficiency may allow *Potamocorbula* to disproportionately graze larger cells from the water column and potentially influence size distribution of phytoplankton biomass. However, higher settling rates of large phytoplankton classes like diatoms would tend to increase their downward transport (relative to other size classes) to zones where they can be entrained by clams, and this could be an even more important factor on the relative impacts of grazing on different phytoplankton classes.

Three sets of observations offer insights into the strong influence that benthic suspension feeders can have on phytoplankton biomass. The first example is the observation that, based on mass

balances of phytoplankton biomass in South Bay, production paradoxically exceeded losses from zooplankton grazing and transport (Cloern 1982). This implied a missing sink of phytoplankton biomass in South Bay, which Cloern (1982) hypothesized was clam grazing

The second example is the *Potamocorbula amurensis* invasion in Suisun Bay. *Potamocorbula* was which first detected in Suisun Bay in 1987, and its effect on phytoplankton biomass was almost immediate (Figure 3.8). Baseline biomass values dropped considerably, and peak biomass levels decreased by a factor of 5-10. Overall, mean annual biomass and dropped five-fold after the *Potamocorbula* invasion, and the state of chronic low annual primary production has persisted since 1987. While substantial phytoplankton biomass was observed over multiple months (May-September) during most years prior to 1987, blooms have occurred only rarely post-1987. *Potamocorbula* biomass exhibits pronounced seasonality and large interannual variability (Figure 7.8), as well as considerable spatial variability (Figure 7.9). One reason for clam loss during late summer and fall is predation by migratory waterfowl. The seasonality in *Potamocorbula* abundance may allow windows for blooms to develop before clam grazing rates are high enough to draw down phytoplankton biomass. Occasional spring blooms have been observed over the last several years (Dugdale et al, 2012; R Dugdale, pers. comm.). A large fall bloom was also observed in September 2011. *Potamocorbula* tolerate salinities that are commonly encountered in Suisun Bay (Low Salinity Zone, LSZ), and are well-established at all depths throughout Suisun and at locations in San Pablo Bay (Figure 7.9). *Potamocorbula* do, however, have a fairly clear up-estuary boundary, apparently dictated by salinity (Figure 7.9). *Potamocorbula* are voracious filter feeders, and, at their current densities in the LSZ, grazing rates typically exceed phytoplankton growth rates in the LSZ (Figure 7.10; Kimmer and Thompson, 2013).
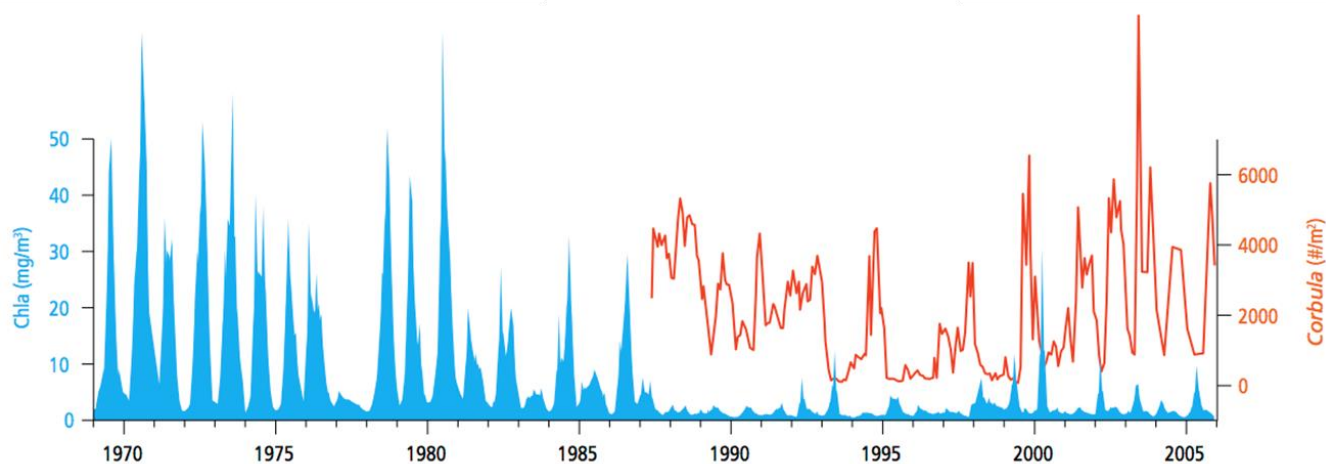
Figure 7.8 Chl-a biomass and Corbula biomass in Suisun Bay. Note the temporal coincidence of *Corbula* biomass minima and phytoplankton biomass maxima. Plot from Werme et al 2011. Data from IEP/DWR.
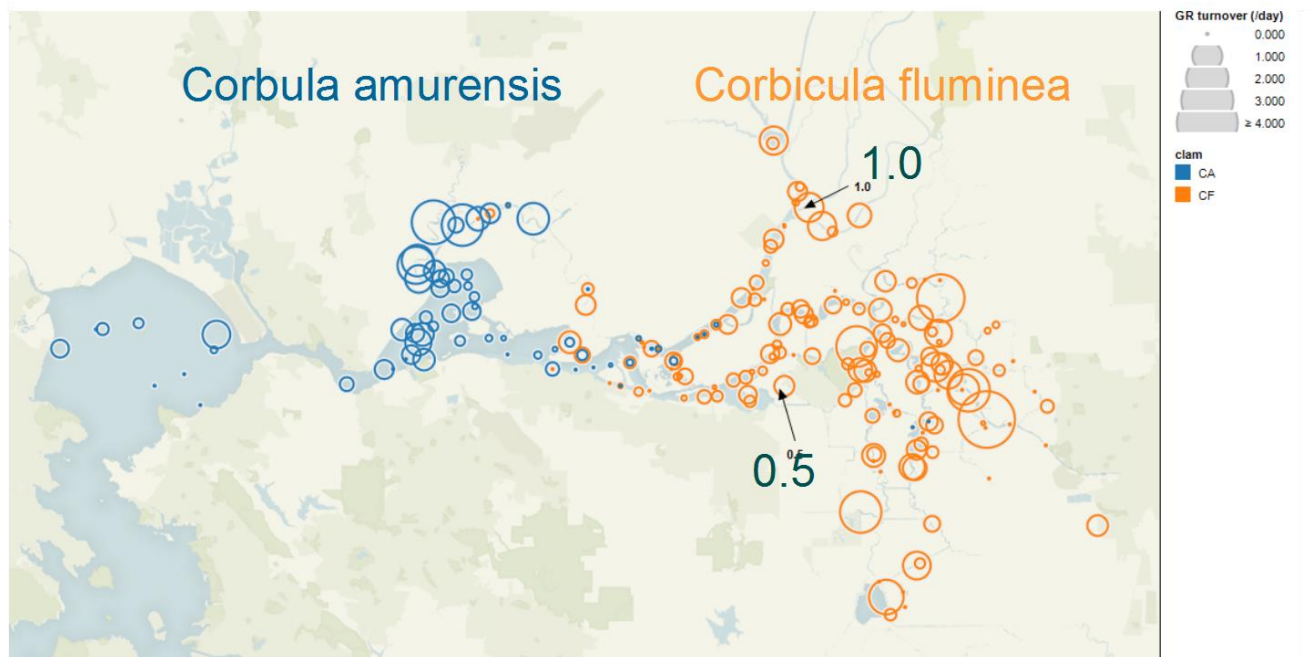
Figure 7.9 Grazing water column turnover rates (units of d^{-1}) for *Corbula* in Suisun *Corbicula fluminea* in the Delta. Source: J Thompson, pers. comm.
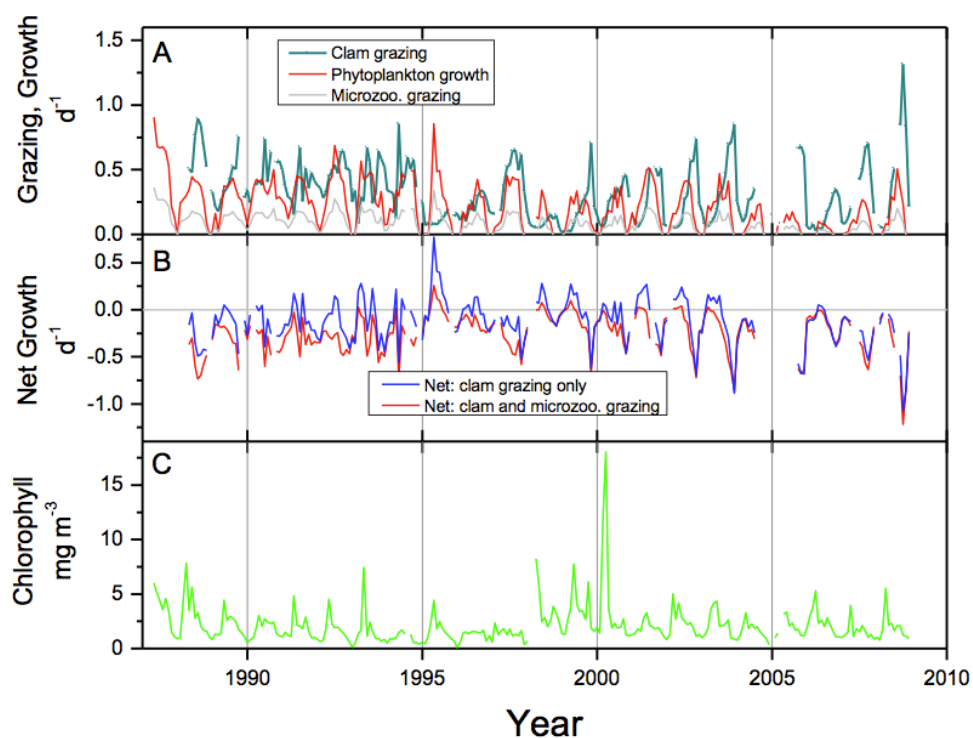
Figure 7.10 Calculated growth and grazing rates in the Low Salinity Zone (essentially Suisun Bay). Source: Kimmerer and Thompson (2014)

The third example of benthic grazer impacts on biomass is from South Bay. Through the mid-1990s, benthic filter feeding was considered to be one of the dominant controls on phytoplankton biomass accumulation and productivity in South Bay (Thompson et al., 2008 ; Lucas et al., 2009). Clams were heavily preyed upon by migrating birds in the fall. Thompson et al. (2008) observed that interannual variations in abundance and timing of spring reestablishment of benthic suspension feeders along the shoals dictated whether or not blooms could form on the shoals, and propogate from the shoals to the channel (Figure 7.4.B). In addition, Cloern et al (2007) observed sharp increases in chl-a and in gross primary production in the South Bay beginning in the late 1990s (Figure 7.11). After ruling out several potential drivers (e.g., changes in nutrient loads), they hypothesized that the increase in phytoplankton biomass was due, at least in part, to a pronounced loss of benthic suspension feeders. They argued that the decline in benthos abundance was due to an observed increase in benthivorous predators (sole, Bay shrimp, Dungeness crab; Figure 7.12), which they argued was attributable to large-scale climate forcings that resulted in increased oceanic production of juvenile predators that migrated into SFB to feed and grow (a change in the North Pacific Gyre Oscillation; Cloern et al., 2010).

The amount of historic data on benthos abundance and on-going benthos monitoring varies spatially in SFB. The IEP has several long-term monthly benthos monitoring stations in Suisun and San Pablo Bays (Peterson and Vayssieres 2010). In recent years there has also been ample additional benthos monitoring by a semi-annual IEP pilot randomized monitoring program in San Pablo Bay, Suisun Bay, and the Delta; it is not yet known if this program will continue in future years. There are no sustained benthos programs in the other subembayments; however, there are multiple years during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008; see Figure 7.4), and other opportunistic sampling efforts after which samples have been archived but not yet analyzed for biomass (J Thompson, personal communication). A consistent benthos monitoring program is needed in these other subembayments, most importantly Lower South Bay and South Bay, to better understand the drivers of recent change, and continue exploring cause and effect.

Pelagic grazing
Pelagic grazing rates by zooplankton are dependent on the types of zooplankton present, their abundance, and their biomass-normalized grazing rates. Copepods, mesozooplankton that are an important food resource in SFB and the Delta, derive most of their energy from phytoplankton as opposed to detrital organic matter (Mueller-Solger et al 2002; Sobczak et al 2002, 2004), and at least in Suisun Bay and the Delta are often food limited (Mueller-Solger et al 2002; Kimmerer et al 2005). Despite mesozooplankton's reliance on phytoplankton, modeling estimates by Kimmerer and Thompson (2014) suggest that they have only a limited effect on phytoplankton biomass in Suisun Bay. Cloern (1982) reached the same conclusion for South Bay. However, microzooplankton have the potential to substantially influence phytoplankton biomass in Suisun Bay (Figure 7.10; Kimmerer and Thompson, 2014). Outside of Suisun Bay there are limited data on mesozooplankton and microzooplankton biomass and feeding rates. While it may be reasonable to expect that the effect of mesozooplankton grazing on phytoplankton biomass is small Bay-wide, microzooplankton could play a substantial role, based on observations in Suisun Bay. Additional zooplankton monitoring in other subembayments is needed to better constrain pelagic grazing rates.
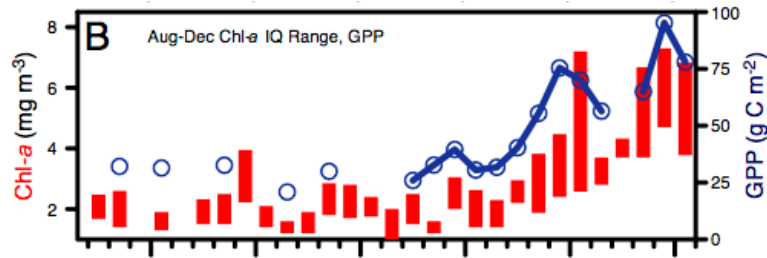
Figure 7.11 Phytoplankton biomass south of the Bay Bridge. Source: Cloern et al., 2007
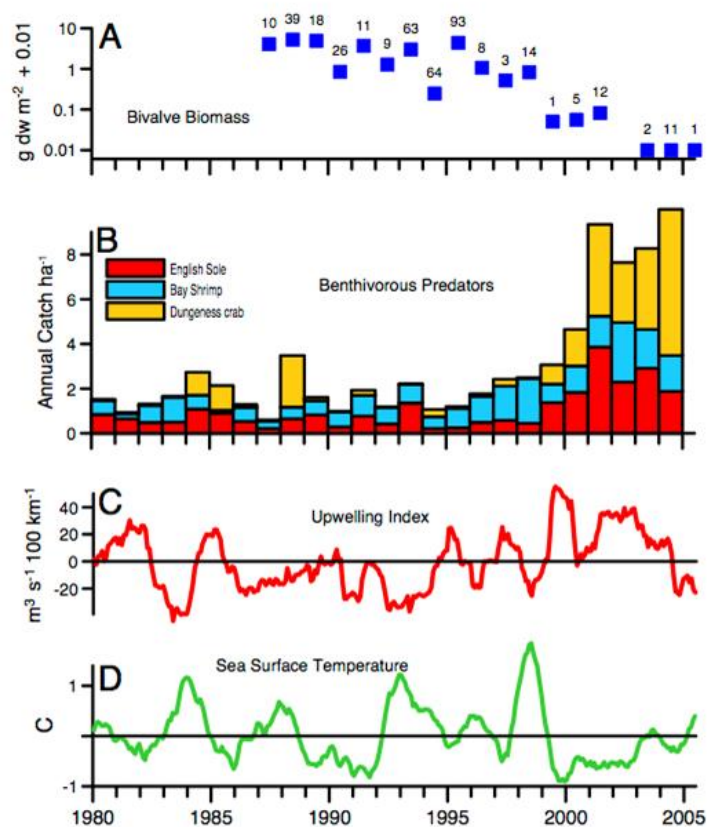
Fig. 3. Indices of biological community change within SFB and physical changes in the adjacent California Current. (A) Annual median biomass of filter-feeding bivalves across shallow habitats in South SFB; numbers above squares indicate sample number per year. (B) Mean annual catch ha⁻¹, normalized to 1980–2005 averages, of English sole, Bay shrimp, and Dungeness crab, from monthly sampling across the marine domains of SFB. (C) Anomalies in upwelling intensity computed by the National Oceanic and Atmospheric Administration from atmospheric pressure fields. (D) Sea surface temperature measured at the Farallon Islands. The bottom series (C and D) are 12-mo running averages of deviations from 1977–2005 monthly means.

Figure 7.12 Bivalve biomass, benthivorous predators, upwelling index, and sea surface temperature time series. Source: Cloern et al. 2007.

7.2.4 Spatial and temporal variations in phytoplankton biomass

Figure 7.13 presents monthly averages of phytoplankton biomass (2006-2011) broken down by subembayment; Figure 7.14 shows time series from 1975-2012. The highest phytoplankton biomass concentrations are generally observed in LSB. Bay-wide, the largest blooms typically occur in spring. Over the last ten years, however, pronounced fall blooms have also been occurring in LSB and South Bay (Figures 7.13 and 3.6). The rate of increase in chl-a concentration (μg L^{-1} yr^{-1}) is greatest in LSB and South Bay. More modest rates of increase are visually-evident in all subembayments based on rising baselines (Figure 7.14), and these increases are also statistically-significant (J Cloern, pers. comm.). Therefore, it is possible that there may be some Bay-wide common explanation that explains at least part of the increase (e.g, decreasing suspended sediment concentrations), and additional subembayment-specific explanations (e.g., decreased clam abundance).

7.3 Microphytobenthos

Microphytobenthos (MPB; i.e., benthic algae) primary production has received little attention in SFB relative phytoplankton production. However, given the large intertidal area in several of SFB's subembayments, primary production by benthic microalgae could represent a quantitatively important component of overall production. Although only roughly quantified due to limited data, Jassby et al. (1993) suggested that MPB production could account for as much as 30% of overall primary production in SFB. Thus, MPB production could have a substantial influence on food web structure (supporting organisms that utilize benthic microalgae), dissolved oxygen budgets, and nutrient cycling.

Many of the factors that influence phytoplankton growth rates will similarly influence MPB growth. These include: light availability, temperature, and nutrients (Figure 7.1). While MPB primarily occur attached to bed sediments, they are also commonly found in the water column due to physical resuspension. Benthic diatoms (mainly pennate, but some centric) have been the major MPB taxa identified in the limited studies carried out to date in SFB (Guarini et al. 2002). The standing stock of MPB biomass (often reported as mg chl-a m^{-2}) is a function of productivity rates (mg chl-a m^{-2} d^{-1}), grazing rates, and exchange with the water column. Light availability strongly influences MPB productivity and is a function of water column depth and light attenuation (i.e., SPM concentration), and of variations in depth due to tides. The amount of MPB resuspension depends on sediment type and consolidation, biofilm production in the sediment, and the magnitude of shear stresses (Macintyre, 1996; Underwood and Kromkamp 1999). Sediment resuspension reduces light penetration for MPB that remain at the sediment:water interface; however, MPB that are resuspended could experience increased light availability. MPB residing on intertidal mudflats experience unattenuated incident light levels during low tide, and productivity would be greatest then. Because of SFB's high turbidity, little MPB growth would occur in subtidal areas. Nutrient limitation is unlikely to be an important constraint on MPB growth, because MPB can readily access NH_4^+ and o-PO$_4$ diffusing out of the sediments and nutrients in the overlying water column. In sandy sediments with low organic matter content, MPB can be nutrient limited (Underwood and Kromkamp, 1999). MPB concentrations have been shown to be lower in sandy silts and sands than in finer, cohesive sediment (Cammen, 1982; Montagna et al, 1983; Cammen 1991; de Jong and de Jonge, 1995; Underwood and Smith, 1998a). Temperature will influence growth rates in way similar to

phytoplankton. CO_2 availability may also limit MPB productivity, but is likely a minor factor compared to light availability. Zoobenthos, some bottom-feeding fish, and birds would be the prime grazers on MPB. MPB biomass, however, would be generally unaffected by filter-feeding clams. Thus, MPB production may comprise a larger proportion of overall production in shallow areas with high abundance of filter-feeding clams.

While MPB production is potentially important in terms of its overall contribution to primary production in SFB, and some estimates of its magnitude have been made, little is known about how much it influences the food web, the net effect it has on dissolved oxygen budgets, or how it might respond to system perturbations (e.g, decreases in SPM). As noted above, Jassby (1993) estimated that MPB production could account for approximately 30% of overall primary production in both southern and northern SFB subembayments. Studies in other estuaries have found that MPB could account for up to 50% of total primary production (Underwood and Kromkamp, 1999). Guarini et al (2002) estimated that MPB productivity (mg C (mg chl-a)$^{-1}$ d^{-1}) could be nearly 4x as large in South Bay as in Suisun Bay, due to spatial differences in MPB assemblage or bathymetry-induced differences in light exposure to intertidal areas. In a more recent study, direct measurements of sediment chl-a (mg chl-a m^{-2}) were made in the Delta and Suisun Bay (Cornwell and Glibert 2014). Benthic chl-a abundance was roughly 30% greater in September 2011 than in March 2012 at both locations, which is consistent with higher expected biomass at the end of the warm season. In addition, Cornwell and Glibert (2014) found that benthic chl-a was approximately 4-fold higher in the Delta than in Suisun Bay, likely due in part differences in depth and light availability.

7.4 Current state of knowledge

Tables 7.1 summarizes the current state of knowledge and knowledge/data gaps related to primary production from phytoplankton biomass and MPB in SFB. The prioritizations in the rightmost two columns are related to the discussion in Section 11.
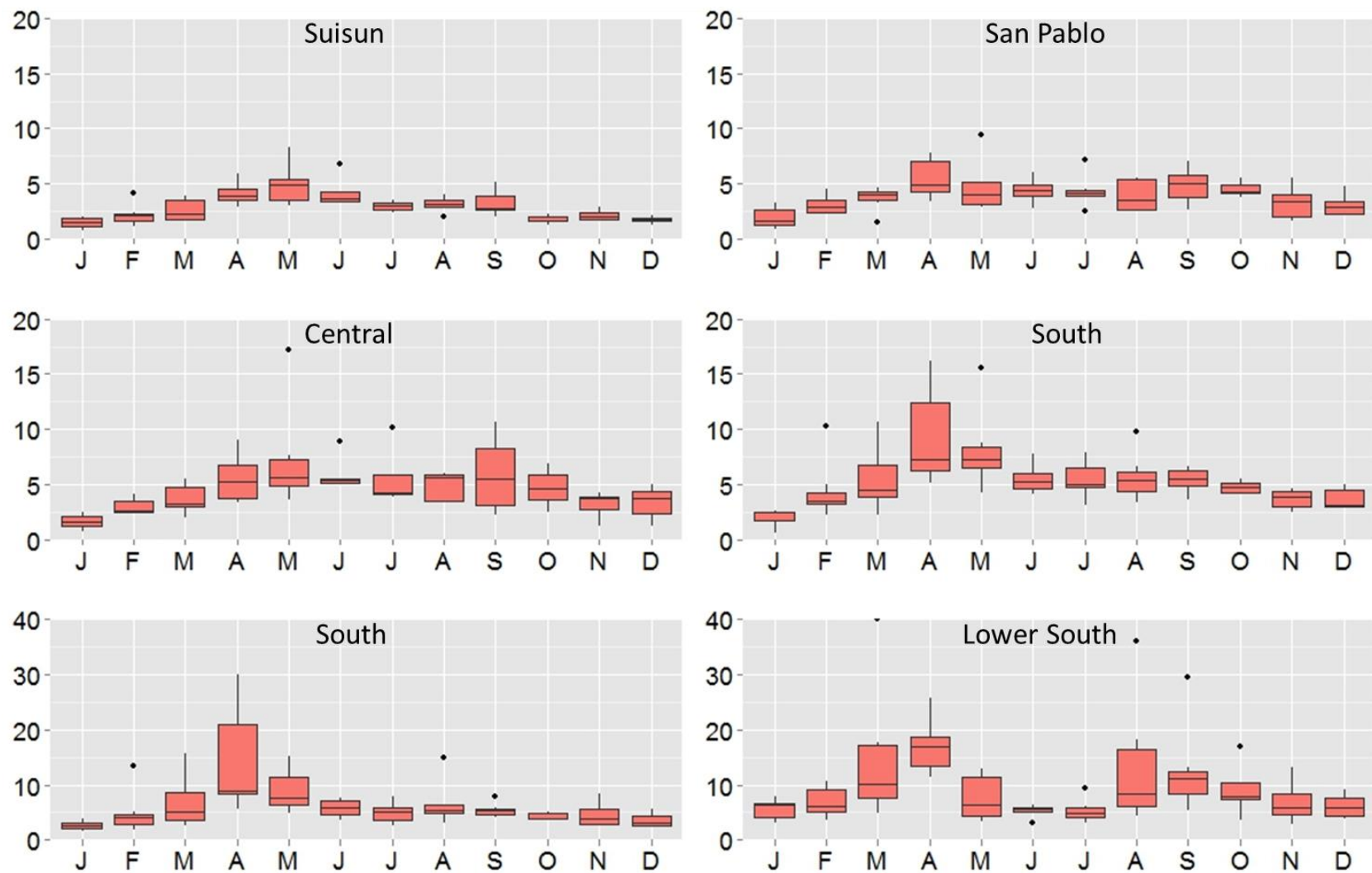
Figure 7.13 Monthly variations in chl-a ($\mu g\ L^{-1}$) 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the different vertical scales. Data source: http://sfbay.wr.usgs.gov/access/wqdata/
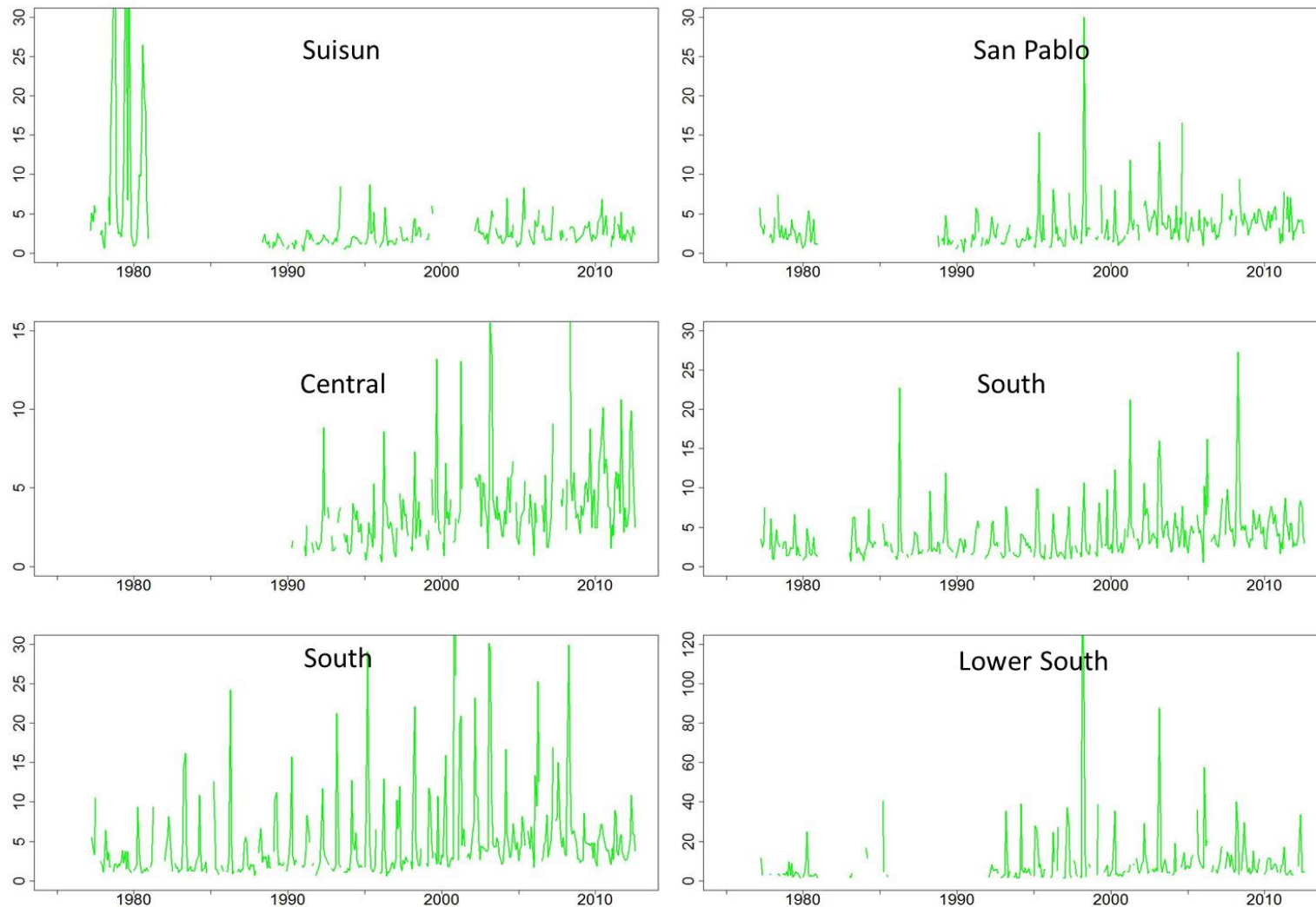
Figure 7.14 Phytoplankton biomass (mg chl-a m^{-3}). Note different y-axes. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: http://sfbay.wr.usgs.gov/access/wqdata/

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Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for <u>additional or continued</u> data collection, process studies, modeling	Priority for study in next 1-5 years
PHYTOPLANKTON - 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/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 frequency 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

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.	**High**	**High**

8 Dissolved Oxygen

8.1 Introduction

Dissolved oxygen concentrations are a highly relevant indicator of nutrient-related impairment, both because maintaining sufficient dissolved oxygen levels is critical for sustaining aquatic life, and because low dissolved oxygen is a common ecosystem response to high nutrient loads. Oxygen is both produced and consumed within the estuary, and also transported into the water column across the air:water interface by gas exchange and by water inputs. If the oxygen loss rate exceeds the oxygen production or input rate, dissolved oxygen levels decrease and hypoxia or anoxia can develop. Persistent hypoxia or anoxia leads to aquatic organism stress or death, or, for organisms that can escape low DO areas, causes the loss of habitat. Anoxia leads to sulfide gas production, which can be toxic to aquatic organisms and causes both odor problems and infrastructure damage (corrosion, discoloration of painted exteriors). In addition, under low DO conditions NH_3 can accumulate to levels that exert direct toxicity on benthos.

Prior to the 1970s, areas of SFB, specifically LSB, did experience low DO (Cloern and Jassby, 2012). Implementation of secondary wastewater treatment addressed the issue of large-scale and persistent anoxia in deep subtidal areas. However, limited information is available about DO levels in margin habitats, including sloughs, tidal wetlands, and managed ponds, and the occurrence and potential impacts of low DO there are unknown.

8.1 General DO conceptual model

Dissolved oxygen concentration, measured at a given point in space and time in the water column, represents the concentration that results from multiple competing production and loss processes, as well as inputs, outputs, and mixing (Figure 8.1).

8.1.1 DO transport

O_2 is readily exchanged across the air:water interface, and is highly soluble in water, with the DO saturation concentration (DO_{sat}; mg/L) varying in direct proportion to the O_2 partial pressure in the overlying air. DO_{sat} decreases with increasing water temperature and salinity. If DO concentrations in the water column are undersaturated relative to O_2 in the overlying air, atmospheric exchange will occur, with O_2 flux from the atmosphere into the water column. If DO concentration exceeds saturation (e.g., after periods of intense photosynthesis), DO flux will occur from water to the atmosphere. In both cases, exchange at a rate proportional to the magnitude of DO under- or over-saturation and the amount of mixing-energy at the air:water interface (determined largely by wind speed in open-water areas).

DO also enters (or leaves) a habitat through fluvial transport (from the Delta, perennial ephemeral streams, stormwater inputs, and treated wastewater effluent), water exchange between subembayments (advective, tidal, gravitational), and mixing or exchange between habitats within a subembayment. Exchange between adjacent subembayments or habitats can result in net increases or decreases in DO depending on whether the prevailing conditions differ substantially between the two systems. During coastal upwelling events, gravitational circulation (i.e., intrusions of denser (colder, more saline) water) has the potential to transport substantial volumes of relatively low DO water far up-estuary, displace an equal volume of relatively DO-
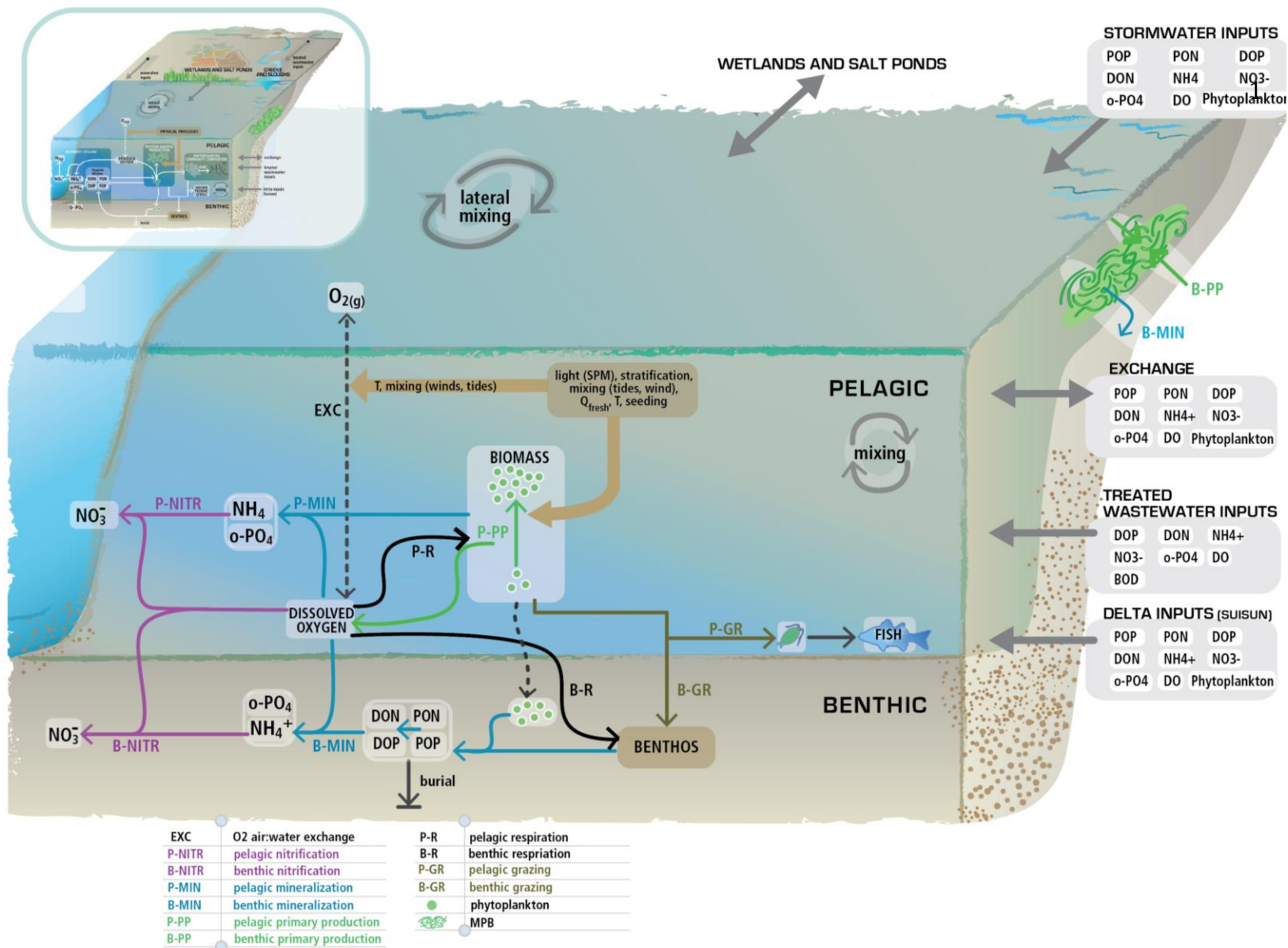
Figure 8.1 Dissolved oxygen conceptual model

rich water down-estuary, and measurably influence DO concentrations when the water column mixes. Tidal exchange between a subembayment and wetlands, salt ponds, and sloughs along its margins could be a net source or sink of DO, depending on the balance of O_2 production and consumption in those systems. This is discussed further below.

8.1.2 O_2 production and consumption

The major processes that result in DO production or consumption are illustrated in Figure 8.1 Primary production - by phytoplankton, MPB, and macrophytes – produces O_2 during daylight hours. The O_2 production rate varies in proportion to the primary production rate, which, for phytoplankton and MPB, is light-limited in most SFB habitats. Thus, analogous to primary production rates (Section 7), O_2 production rates exhibit large variability on hourly and seasonal time scales, respond to weather conditions that influence incident light (cloud cover or fog), and may vary substantially between shallow and deep habitats or in response to stratification.

Respiration by aquatic and benthic organisms consumes DO. Viable phytoplankton respire throughout the entire day, and consume oxygen in the process. During daylight hours, their O_2 production exceeds respiration, resulting in net O_2 production; however, during dark periods only respiration occurs, with net DO consumption. As a result DO levels can exhibit a diurnal sinusoidal-like cycle, with maxima and minima near mid-afternoon and sunrise, respectively. In some habitats, transport of water masses with differing DO concentrations by semi-diurnal tides whose magnitude varies on a spring-neap cycle can mask the diurnal signal generated by respiration and production (SFEI, 2014c).

The balance between O_2 production and consumption is also influenced by microbial respiration of dead organic matter (OM). Microbes consume oxygen while mineralizing or degrading OM derived from two broad source categories: biomass from during primary production by phytoplankton, MPB, and other plants within SFB (autochthonous OM); and terrestrial organic matter (allochthonous OM) carried to the Bay by freshwater inputs and treated wastewater effluent (i.e., the latter of which is commonly referred to as biochemical oxygen demand, BOD)., While BOD loads to SFB from POTWs used to be high, those loads decreased substantially once secondary treatment was implemented in the 1970s. Some OM mineralization occurs in the water column (pelagic respiration), but much of it happens in the sediments and at the sediment:water interface (benthic mineralization) where particulate OM accumulates after settling. Aerobic microbial respiration occurs continuously, although respiration rates are strongly influenced by temperature, the abundance of fresh or readily-degradable OM, and DO concentrations. In the sediments, when the DO supply is exhausted (which often occurs within a few millimeters or centimeters into the sediments), anaerobic respiration occurs using alternate electron acceptors (nitrate, manganese(IV), iron(III), sulfate). Although anaerobic respiration does not directly consume O_2, the reduced compounds produced during anaerobic respiration (Fe(II), Mn(II), sulfide) diffuse upward through the sediments into oxygenated sediment layers or into the water column, and react with and consume O_2 there.

Nitrification of NH_4^+ to NO_3^- by nitrifying microbes also consumes O_2. Major NH_4^+ sources to the Bay include the NH_4^+ discharged in treated wastewater effluent from POTWs and NH_4^+ produced *in situ* during OM respiration. Nitrification of NH_4^+, and associated O_2 consumption, occur in both the water column (pelagic nitrification) and at the sediment:water interface (benthic nitrification).

Sediment oxygen demand (SOD) can play a dominant role influencing the O_2 budget of a habitat. SOD is an overarching term that includes benthic mineralization, benthic nitrification, and benthic oxidation of reduced compounds. SOD tends to exert greater influence over DO concentrations in shallow habitats, where the ratio of overlying water volume to sediment area is relatively small compared to deeper areas. While SOD includes several types of reactions, its magnitude is ultimately driven by the amount of OM loading to the sediments. That OM can be imported to the system (fluvial inputs; allochthonous OM) or produced *in situ* (autochthonous OM). As respiration proceeds, OM in the sediments is consumed. The rate and total amount of SOD depends on the rate and total amount of new OM delivery to the sediments. In SFB, a large portion of SOD likely traces back to autochthonous OM production by phytoplankton and MPB, and therefore to nutrient loads, although allochthonous inputs may contribute more substantially to SOD in margin habitats and in Suisun Bay (due to allochthonous inputs from the Delta).

8.1.3 Spatial differences in O_2 budgets and DO concentrations in SFB

An aquatic ecosystem's O_2 budget can be characterized in terms of whether it acts as a net producer or consumer of O_2, referred to as net ecosystem metabolism (NEM). If a system produces more (NEM > 0) or less (NEM < 0) oxygen than it consumes it is considered net autotrophic or net heterotrophic, respectively. NEM will vary considerably based on the time scale and location considered, because of temporal (e.g., diurnal variability in O_2 production rate) and spatial variability in the magnitudes of O_2 sources and sinks. Past studies have shown that SFB shallow shoals and intertidal areas are likely to have NEM > 0 (Caffrey et al. 2003). Atmospheric exchange, along with high rates of phytoplankton and MPB primary production (due to the shallow water column and higher average light levels), maintain high DO concentrations. While benthic mineralization, benthic nitrification, pelagic mineralization and pelagic respiration also occur in these areas, the DO inputs more than offset these O_2 sinks.

SFB's deep subtidal habitats more frequently have negative NEM (Caffrey et al. 1998), and, as a result, DO is often undersaturated in these areas. Due to light limitation, deep areas generally experience lower rates of pelagic primary production than shallow habitats, and little or no MPB primary production occurs due to insufficient light. As a result, O_2 production rates are lower. At the same time, deep channel areas receive both viable and dead/decaying phytoplankton inputs through lateral exchange with shallow subtidal areas, which exert O_2 demand. Although atmospheric flux of O_2 may occur at similar rates in shallow and deep habitats, the same O_2 flux entering the deep water column is diluted over a larger volume; thus this exchange may not keep pace with respiration losses. Primary production rates in deep channel areas can be higher when the water column stratifies (Figure 7.2.B). However, eventually this OM settles to the bottom where it is respired. During stratified periods, DO concentrations can decrease in bottom waters due to respiration, since DO cannot be replenished through vertical mixing or atmospheric exchange at the surface. Due to the relatively short duration of stratification events in SFB, DO in deep subtidal habitats seldom dip below 80% saturation (Figure 3.12). Low DO can also be observed in SFB bottom waters when plumes or "intrusions" of recently-upwelled and relatively dense (colder, more saline) coastal water containing low-DO enter through the Golden Gate and occupy the bottom layer of some subembayments. Monitoring data from USGS R/V Polaris cruises indicate that these events tend to be fairly short-lived, with the water column mixing fully over the period of days to weeks.

While ship-based measurements indicate that DO levels in deep subtidal areas generally fall above the 5 mg/L Basin Plan standard (Figure 3.12, Kimmerer, 2004), continuous monitoring data at Dumbarton bridge illustrate that DO concentrations do vary substantially. During summer and fall, DO concentrations at Dumbarton Bridge commonly vary by 1-2 mg L^{-1}, with lowest concentrations observed at low tide (Figure 3.13 A), and values occasionally dipping below 5 mg L^{-1}. The variability in DO is strongly associated with tidal stage (SFEI 2014, 2014c). One plausible hypothesis for the correspondence between low DO and low tide is that, at low tide, the water moving past sensors at Dumbarton Bridge has a higher percentage of water from margin habitats where DO may be lower. The large variability suggests that oxygen demand within LSB can be quite substantial at the subembayment scale. In LSB, USGS *Polaris* sampling has most frequently occurred at slack high tide. It is therefore possible that DO concentrations from USGS *Polaris* cruises are biased high. During Summer 2014, USGS sampling cruises detected DO < 5 mg/L at other deep subtidal stations south of the Dumbarton Bridge during two cruises (http://sfbay.wr.usgs.gov/access/wqdata/archive/longterm.html).

SFB's shallow margin habitats – e.g., sloughs, tidal wetlands, and restored salt ponds ringing LSB - experience large DO swings that are influenced by both temporal variability in DO production rates and tidal exchange (Thebault et al., 2008; Schellenbarger et al., 2008). Compared to the abundance of monitoring data available for deep subtidal habitats (Figure 3.12), DO data for shallow margin habitats is quite limited. However, the observations that are available suggest that DO concentrations commonly dip below 5 mg L^{-1} in those habitats, and frequently reach much lower values (Figures 3.14 and 8.2; SFEI 2014c). Continuous DO measurements (moored sensors at a single location) in sloughs provide evidence of large DO swings occurring at a periodicity that points to a strong tidal influence (Figure 8.2). Sloughs are shallow habitats and may have higher average light levels and greater DO production during daylight hours than the open Bay during some low turbidity periods; but sloughs also frequently have elevated turbidity due to sediment resuspension, which decreases light levels. Connection of some sloughs to salt ponds or wetlands could deliver higher loads of dead organic matter to slough sediments, increasing benthic mineralization rates. At night, net O_2 production is negative, which in a non-tidal system would lead to early morning DO minima. However, the diurnal cycle in O_2 production is superposed upon semi-diurnal tidal exchange. During flood tide, relatively DO-rich water from the open areas of LSB moves into the margins and above the sensors (depending on distance upslough from the open water and tidal phase, i.e., spring or neap) and supplements the O_2 budget (Figure 8.2). In the cases illustrated in Figure 8.2, DO minima and maxima occur twice daily, with maxima sometimes occurring at night and minima during the day, suggesting that the tidal influence on DO can be as strong or stronger than the diurnal variations in DO production.

Some highly-altered habitats in SFB, such as restored salt ponds and the surrounding sloughs in LSB, have delicately balanced O_2 budgets. The ponds have extremely high primary production rates and O_2 production rates, made possible by relatively high average light levels because of the shallow environment, and high nutrient concentrations (Thebault et al., 2008). Benthic mineralization rates are also high due to the reservoir of labile OM in the sediments. As a result, large diurnal fluctuations in DO levels occur (Figure 3.15.A and 8.2). While Figure 3.15A shows a diurnal cycle of maxima and minima, DO also drops to low levels for longer periods of time. Thebault et al. (2008) observed that when primary production rates are periodically low

(e.g., during a prolonged period of summer clouds or fog), sustained periods of anoxia can occur (Figure 3.15.B). On the one hand, the high productivity in restored salt ponds supports wetland food webs, including those of migratory birds (Thebault et al. 2008). On the other hand, the extent to which the large diurnal fluctuations in DO, or the more prolonged periods of anoxia that occur on cloudy days (Thebault et al., 2008), may be having adverse impacts is not currently known.

The slough and salt pond examples discussed here were specifically for LSB. However, South Bay, San Pablo Bay, and Suisun Bay also have substantial shallow subtidal margin habitats. Shallow margin habitats commonly experience naturally-low DO concentrations. In these habitats, it will be important to explore several questions: How common is low DO? Are events more severe (frequency, duration, DO deficit, spatial extent) than would be expected under natural conditions? Are the events having adverse impacts on beneficial uses? To what extent are anthropogenic nutrients contributing to or causing these events? Well-designed experiments, monitoring, and modeling may be needed in some of these systems to assess condition, and quantify the major drivers of O_2 budgets.
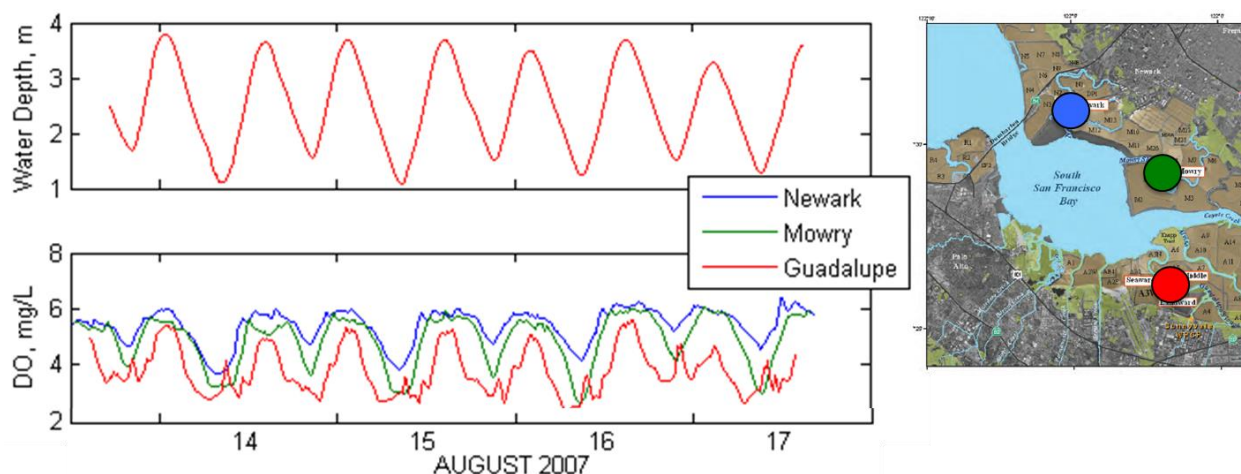
Figure 8.2 Dissolved Oxygen in three slough habitats in Lower South Bay measured using continuous monitoring sensors. Top panel shows water depth. Dissolved oxygen concentrations increase during the flood tide due to water with higher DO from LSB being tidally advected into sloughs. DO concentrations gradually decrease over the outgoing tide interval, likely caused, at least in part, by sediment oxygen demand within the sloughs, and lower DO water from up-slough moving back over the sensor. Colors of lines correspond to location denoted by circle colors in map. Source: Schellenbarger et al., 2008

8.2 Current state of knowledge
Table 8.1 summarizes major knowledge and knowledge data gaps for dissolved oxygen. The prioritizations in the rightmost two columns are related to the discussion in Section 11.

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**

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9. Phytoplankton Community Composition

9.1. Introduction and Background

Phytoplankton community composition is highly relevant to the ecological status and function of the greater San Francisco Bay. The importance of community composition follows directly from the general conceptual model for phytoplankton biomass (Section 7), since it is the community at the level of strains, species, and functional types that in aggregate makes up the "phytoplankton biomass". Selection pressure operates on species and has resulted in systematic phylogenetic differences between the red and green "superfamilies" (Quigg et al., 2003). These evolutionary differences in turn drive differences in nutrient assimilation, elemental composition, growth rates, and size (Irigoien et al., 2004; Irwin et al., 2006; Quigg et al., 2003). This has profound effects on ecosystem function. Phytoplankton photosynthesis drives the metazoan food webs of San Francisco Bay (Cloern et al., 2005; Jassby et al., 1993; Kimmerer et al., 2012). Changes in community composition can also alter energy flow from predominantly supporting higher trophic levels to a microbially-dominated, highly regenerating community which in turn leads to increased respiration and hypoxia (c.f. Cloern and Dufford 2005).

There are several potential ways to assess community composition (Figure 9.1). One of the simplest divisions is based on size. As a general rule, increased mean (or median) phytoplankton size is directly related to increased productivity, increased new production, and increased trophic transfer (Chisholm, 1991; Wilkerson et al., 2000). Phytoplankton size is particularly important for SFB because only phytoplankton >~5 μm equivalent spherical diameter (ESD) are available as a food source for copepods (Berggreen et al., 1988). Size-based classification is sometimes coupled with nutritional mode to separate the plankton into heterotrophs, mixotrophs, and photo-autotrophs (Figure 9.2). While this is convenient conceptually, there is increasing evidence that many phytoplankton, including perhaps the majority of dinoflagellates, are facultative mixotrophs, blurring the line between these divisions (Burkholder et al., 2008).

Moving beyond size, a common approach taken when examining community composition is to group organisms into "phytoplankton functional types" (PFTs) such as diatoms, dinoflagellates, cryptophytes, etc., and/or based on trait-differentiated groupings such as high-nutrient, high light, etc. (Reynolds et al., 2002; Smayda et al., 2001). This level of analysis is often convenient for relating phytoplankton composition to ecological forcing functions (e.g. Cloern and Dufford, 2005). Continuing to a finer level of detail, community composition can also be analyzed at the species level, the basis for taxonomic classification. Finally, there is increased interest in the molecular and strain-level variability of phytoplankton. This becomes particularly important when the organism of interest is considered a harmful algal bloom (HAB) species (Burkholder et al., 2006), in part because many of the coastal HAB organisms do not fit well into classic paradigms as a function of PFT or size (Kudela et al., 2010).

For the purposes of this conceptual model, it is assumed that phytoplankton community composition can be adequately addressed using a combination of high-level metrics (size, trophic status, functional category) with the exception of HAB organisms that must be assessed at the species or strain level.

Size	Trophic Status	Functional Type	Genus/ Species/ Strain
Picoplankton (0.2-2.0 µm)	Heterotroph	Cyanophyte	*>500 species,*
		Chlorophyte	*Unknown # of strains…*
Nanoplankton (2-20 µm)	Mixotroph	Cryptophyte	
		Pyrrophyte	
Microplankton (20-100 µm)	Autotroph	Bacillariophyte	

Ecological function

Reproduction — Resource acquisition — Predator avoidance

Trait type:

Morphological: Cell size; Cell shape; Coloniality

Physiological: Photosynthesis; Protein synthesis; Nutrient uptake, requirements; Toxin production; Nitrogen fixation

Behavioral: Mixotrophy; Motility

Life history: Sexual/asexual reproduction; Resting stages
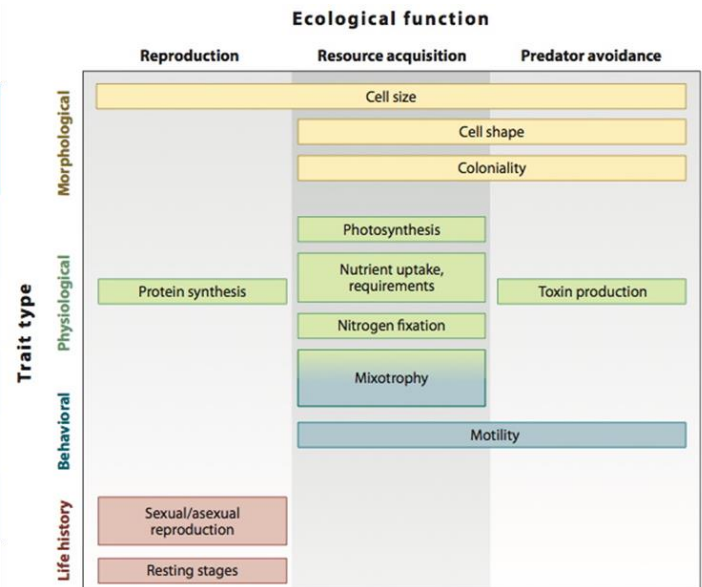
Figure 1
A typology of phytoplankton functional traits.

Figure 9.1. Examples of partitioning phytoplankton community structure. Classification can be based on phylogeny or on ecological function and traits, or some combination. Figure on right is from Litchman and Klausmeier (2008)

Heterotrophs — Mixotrophs — Phototrophs

BENTHIC METAZOANS — PELAGIC METAZOANS

Small cells — Large cells

Bacteria; Synechococcus; Nannochloropsis; Pyramimonas; Cyclotella; Plagioselmis; Teleaulax; Rhodomonas; Cryptomonas; Skeletonema; Euglena; Stephanodiscus; Protoperidinium; Dinophysis; Heterocapsa; Mesodinium; Prorocentrum; Noctiluca; Thalassiosira; Coscinodiscus; Gyrodinium; Alexandrium; Chaetoceros; Gymnodinium

Fig. 7. Phytoplankton classification by size (small cells <15 µm) and nutritional mode that influence pathways through which energy and essential biochemicals are supplied to benthic metazoans (e.g. bivalve mollusks) and pelagic metazoans (e.g. copepods and anchovies). Trophic Pathway A is an efficient direct link from large-cell phototrophs to larval fishes. Other pathways route energy through mesozooplankton: (B) directly from large-cell phototrophs, (C) from heterotrophic algae feeding on large-cell phototrophs, or (D) from mixotrophs or (E) microheterotrophs deriving energy fixed by small-cell phototrophs and routed through the microbial loop. Some images redrawn from Tomas (1993, 1996)

1

Figure 9.2. From Cloern and Dufford (2005).

9.2. General Conceptual Model

In order to use community composition as a metric for ecosystem status it is first necessary to define the spatial extent of the Bay included in the model. While the physical (geographical) boundaries are set, with the open ocean as one (external) boundary and the Sacramento/San Joaquin River and South Bay inputs as the other boundary, there are at least three potential models for describing San Francisco Bay (Figure 9.3):

1) the Bay is a mixture of the ocean and riverine end-members;
2) the Bay is a separate and distinct estuarine community, with mixing (source and sink) of oceanic and freshwater phytoplankton at the boundaries;
3) the Bay is composed of a series of basins (e.g. South Bay, Central Bay, etc.) with distinct community composition.

Under scenario 1, community composition is largely driven by external factors that influence the oceanic and freshwater end-members. Scenario 2 assumes that the phytoplankton are dominated by a distinct estuarine community with transient "invasion" by oceanic and riverine inputs. Scenario 3 is predicated on distinct communities occupying each sub-basin, responding to location-specific forcing, such that Suisun is under fundamentally different control than South Bay (for example). These scenarios are not mutually exclusive, and could (for example) vary seasonally or interannually in response to river flow, residence time, and hydrologic modifications such as the restoration of the South Bay Salt Ponds.
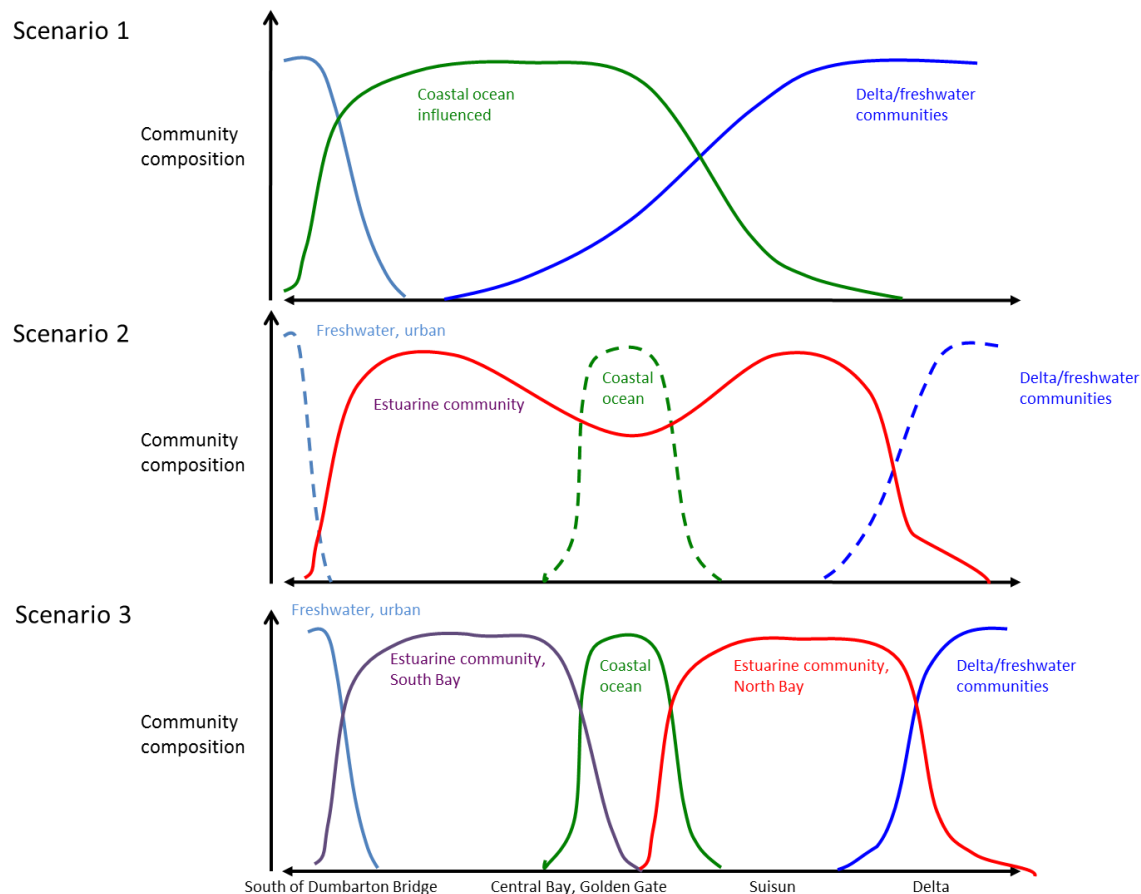
Figure 9.3 Conceptualization of 3 scenarios of spatial variability in phytoplankton assemblage

23 The community composition data necessary to evaluate these conceptual models do exist, and
24 some distinct patterns have been identified between subembayments (e.g. South Bay and North
25 Bay). However, the data are often aggregated to look at large-scale and long-term patterns
26 (Cloern et al., 2005, 2010;Kimmerer,et al. 2012; Winder et al., 2010) unless there is an obvious
27 end-member intrusion impacting the community composition (Cloern et al., 2005; Lehman et al.,
28 2010). *A first-order question that should be examined in more detail is whether a sub-basin*
29 *analysis provides more or less information than the aggregate trends*. For now, it is assumed
30 that a simple model with oceanic, freshwater, and estuarine components is sufficient for
31 development of a community composition conceptual model. This forms the basis for the
32 conceptual model developed by the Phytoplankton Composition working group (Figure 9.4).
33 Specific forcing functions are discussed in more detail below.

34 ### 9.2.1. General trends
35 San Francisco Bay exhibits both a weak seasonal cycle and decadal trends in community
36 composition that generally follow the trends identified for the Biomass conceptual model. Total
37 chlorophyll in the Delta is typically high in summer (Jassby et al. 2002) while chlorophyll in
38 south San Francisco Bay is the highest during (typically) several-week spring blooms and shorter
39 fall blooms (Cloern et al. 2007). Like many nutrient enriched systems, San Francisco Bay is
40 characterized by a bloom-bust cycle of larger cell species periodically dominating a more stable
41 community of small cell species (Cloern and Dufford, 2005; Wilkerson et al., 2006; Kimmerer et
42 al. 2012). These large-cell blooms are superimposed on a picoplankton background population
43 composed primarily of cyanobacteria and small eukaryotes *(Nannochloropsis sp., Teleaulax*
44 *amphioxeia, Plagioselmis prolonga*) that are found across a wide range of salinities and seasonal
45 conditions (Ning et al., 2000; Cloern and Dufford, 2005).

47 San Francisco Bay contains over 500 phytoplankton taxa. Approximately 10-20 phytoplankton
48 species account for between 77% and >90% of the total biomass (Cloern and Dufford, 2005).
49 Diatoms (Bacillariophyta) dominate, accounting for ~81%; dinoflagellates and cryptophytes
50 (Pyrrophyta and Cryptophyta) made up 11% and 5% respectively (Cloern and Dufford, 2005).
51 Picoplankton make up <15% of the Bay biomass (<2% during blooms; Ning et al., 2000; Cloern
52 and Dufford, 2005).

54 At a decadal scale several shifts in community composition are evident. Some phytoplankton
55 taxa (*Prorocentrum aporum*, *Coscinodiscus marginatus*, *Protoperidinium depressum*, *Eucampia*
56 *zodiacus*) have not been seen since 1996 while others (*Protoperidinum bipes, Pseudo-nitzschia*
57 *delicatissima, Scrippsiella trochoidea, Thalassiosira nodulolineata*) have appeared. In addition,
58 the benthic diatom *Entomoneis* sp. similarly was a minor component of the community from
59 1992-2001, comprising 0.1% of the biomass and identified in about 20% of all samples (Cloern
60 and Dufford 2005, as reported in Kimmerer 2012). Kimmerer et al 2012 suggest that, although it
61 is not clear how much it contributes to productivity in the water column, its sudden appearance at
62 a fairly substantial portion of phytoplankton biomass could be an indication of change in the
63 system.

65 Several studies have argued that there is also evidence for abrupt shifts in community
66 composition from the longer time-series. Total biomass decreased substantially in 1986 (Figure
67 9.5) as noted by many others (e.g. Lehman, 2000; Glibert, 2010; Kimmerer, 2012). Lehman
68 (2000) described a decrease in diatom abundance from 1975-1989 and hypothesized a
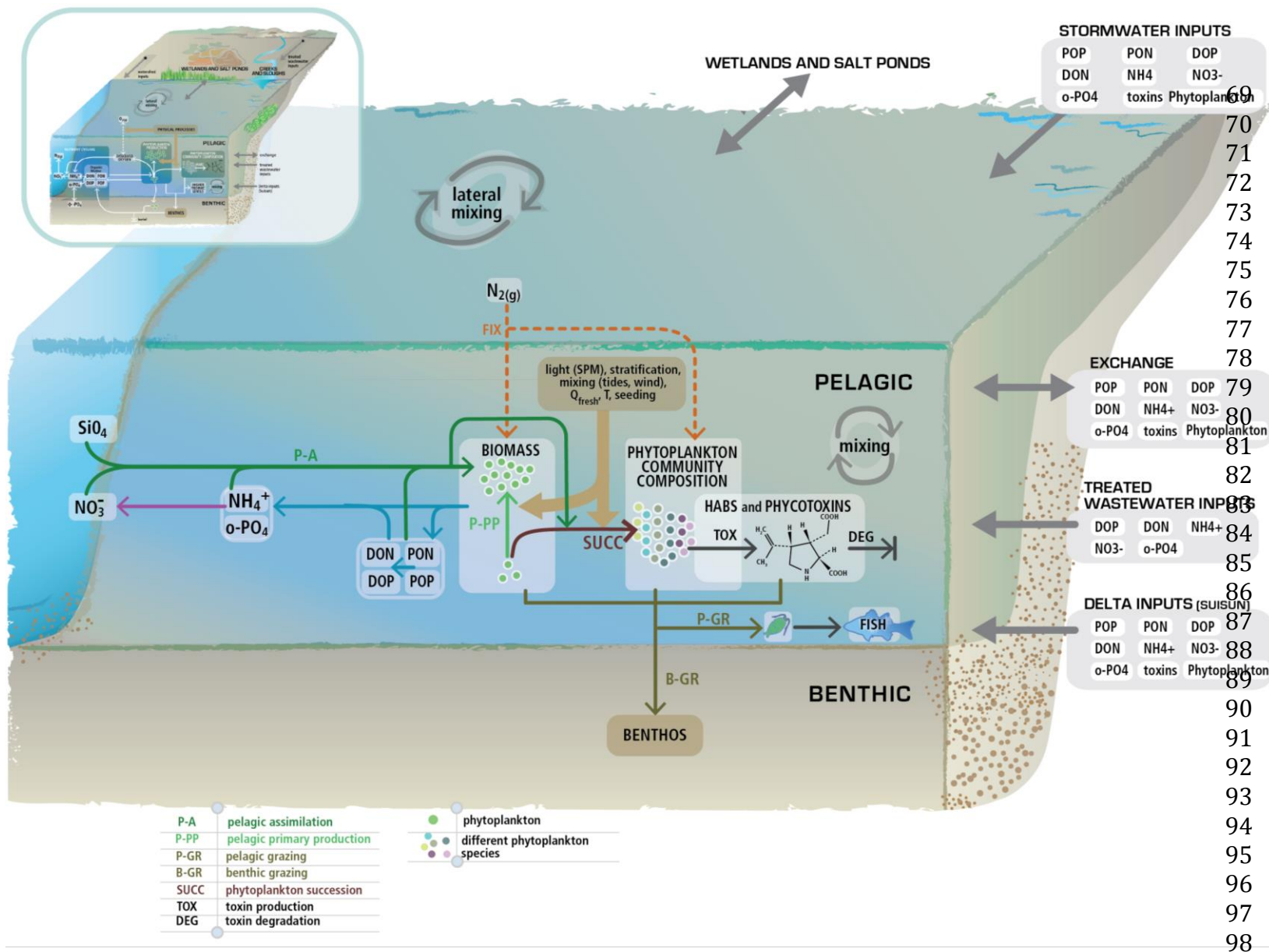
Figure 9.4 Phytoplankton community composition conceptual model

mechanistic link to the 1977 climate regime shift and El Niño, attributing the change to community shifts in high stream flow, wet years (low light, high turbulence, favoring pennate diatoms) and dry years (long residence time, favoring cryptophytes and flagellates). Using the same data, Glibert (2010) described a decline in diatoms, and increase in cryptophytes, chlorophytes, and cyanobacteria after 1986, coincident with an abrupt decline in biomass. These shifts were attributed to changes in nutrient composition and stoichiometry. The proposed phytoplankton community composition changes and hypothesized mechanisms for those trends are based on long-term monitoring data collected by DWR Environmental Monitoring Program (DWR-EMP) at multiple stations throughout Suisun Bay and the Delta from 1975-present. Considering the multi-decade and multi-station record that the EMP dataset offers and the considerable attention the nutrient-focused hypotheses have received over the past several years, the dataset has received relatively limited systematic analysis. That data is currently being reanalyzed to evaluate trends in phytoplankton assemblage and their correspondence with changes in physical, chemical, and biological drivers (Malkassian et al., in preparation; Cloern et al., in preparation).
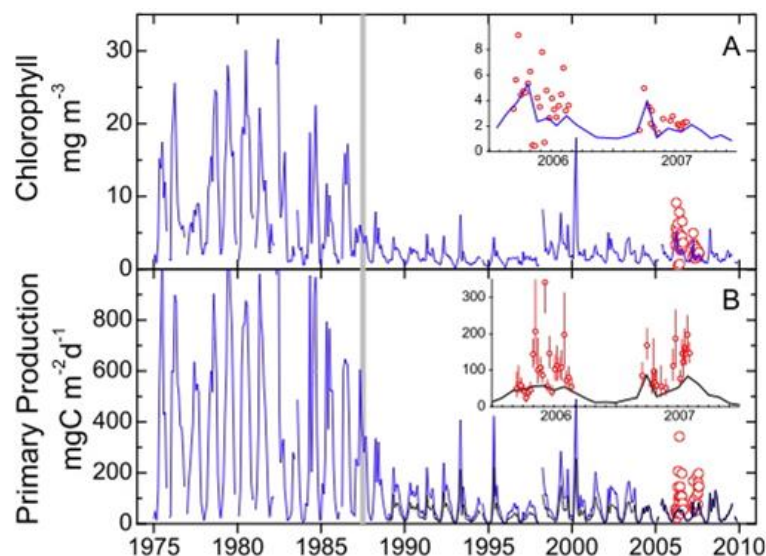
Fig. 9 Chlorophyll concentration (*A*) and estimated primary production (*B*) in this study and from a long-term monitoring program. *Insets* show data for 2006–2007 only. *A Lines* monthly means of chlorophyll from the Interagency Ecological Program environmental monitoring (Sommer et al. 2007) for stations in the western Delta to San Pablo Bay with salinity between 0.5 and 10; *open circles* means by date from all salinities in this study; *B Lines* primary production estimated from IEP data on chlorophyll and Secchi depth and using PAR estimated as in Fig. 7; *line* from 1975 to 1988 and *upper line* to 2004 use the mean value of Ψ determined from data of Cole and Cloern (1984), and the *lower line* and that after 2004 use the mean value of Ψ from our data for 2006 and 2007 combined (Parker et al. 2012). *Error bars in inset* give 95% confidence limits

Figure 9.5. From Kimmerer et al. 2012.

9.2.2. Bottom-Up Controls

Basin-scale oscillations

There is ample evidence that San Francisco Bay community composition responds more or less uniformly (i.e. across the estuary) to both basin-scale and climate-scale trends. As described above, Lehman (2000) identified stream flow as an important indicator of community composition. Low light, turbulence, and short residence times were associated with pennate and single-celled centric diatoms. Cryptophytes and flagellates were associated with "critically dry" periods of increased residence time, light intensity, and water temperature. Cloern et al. (1983)

similarly argued that river flow can regulate community composition by selectively retaining particles (neritic diatoms) near productive shallow bays under low flow, but promotes loss of seed populations during both high and very low flow (drought) because of changes in circulation and the position of the suspended particulate maximum. Within the Delta, low streamflow has also been associated with enhanced *Microcystis* blooms (Lehman et al. 2010), attributed to reduced turbulence and prolonged retention. Basin-scale oscillations also profoundly impact the coastal plankton assemblage. Since the oceanic end-member can serve as a seed population for the estuary, San Francisco Bay is also indirectly influenced by El Niño, the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and other mesoscale changes (Cloern et al. 2005, 2010).

While these observed patterns suggest that community composition is regulated to some degree by bottom up controls (and therefore can be to some extent predicted; Cloern et al. 2011), a larger analysis of coastal estuaries suggests that each estuarine system is unique and responds to some combination of annual forcing, regime shifts and climate trends, and the residual (or stochastic) component (Cloern and Jassby 2008, 2010), suggesting that the low-frequency basin- or climate-scale patterns must be interpreted with caution.

Temperature
Phytoplankton species composition is strongly controlled by temperature, since each species and strain exhibits an optimal growth response to a specific temperature range (Eppley, 1972). In addition to this species-level response, PFTs also exhbit some generalized temperature optima. Diatoms generally prefer colder temperatures, and are associated with cool periods both annually and interannually in San Franicsco Bay (Lehman 2000). Diatoms also exhibit optimal nitrate assimilation at lower temperatures and also reduce nitrate under cold temperatures as an electron sink to maintain optimal energy balance (Lomas and Glibert, 1999). As temperature rises some PFTs respond positively. *Microcystis* and other cyanobacteria appear to be favored by warmer conditions (Lehman et al. 2010; Paerl and Huisman 2008, 2009). Less is known about the temperature-specific response for other PFTs (flagellates, cryptophytes, dinoflagellates) but community composition generally shifts towards more of these groups coincident with increased temperature (e.g. Lehman 2000). Because temperature covaries with several other environmental factors including flow, nutrients, stratification, etc. it is difficult to determine what the impact of rising temperatures would be. ***Experimental manipulations of temperature or temperature and CO₂ would provide useful information about potential shifts in phytoplankton community composition for San Francisco Bay.***

Irradiance
San Francisco Bay productivity is generally considered to be light-limited, and is well described by a "light utilization" productivity model that uses chlorophyll, PAR, and light attenuation (Cole and Cloern 1984). Parker et al. (2012) recently re-evaluated this approach and concluded that while the general model still works, there is considerable variability in the calibration coefficient, possibly due to a shift in the carbon:chlorophyll ratio of the phytoplankton assemblage. Parker et al. (2012) noted that concurrent evaluation of the phytoplankton community composition from 2006-2007 (during their study period) by Lidström (2009) are consistent with PFT-specific shifts in both the C:CHL ratio and P^B_m (light-saturated productivity). The authors conclude that seasonal, interannual, and long-term shifts in community composition from diatoms to flagellates may be linked to changes in the modeled

productivity. It should be noted, however, that the analytical techniques for measuring production rate differed between Cole and Cloer (1984) and Parker et al. (2012), and that some or all of the apparent difference in the calibration coefficients could be the result of these analytical differences. ***In either case, these observations suggest that, if bulk productivity estimates are to be used as an index of ecosystem health, the light-utilization model should be evaluated for its sensitivity to PFT-specific response functions and potentially other factors (e.g., temperature, light levels).***

Mixing/Turbulence

As summarized in Cloern and Dufford (2005), mixing and turbulence become important for phytoplankton community composition primarily through alleviation of light limitation due to runoff-induced salinity stratification, increased light penetration (decreased turbidity), and separation of phytoplankton and benthic grazers. Classically, it is also assumed that diatoms respond positively to turbulence while ephemeral dinoflagellate blooms respond to "windows of opportunity" when environmental conditions, such as reduced grazing, enhanced stratification, and warm conditions, allow these organisms to respond rapidly (e.g. Stoecker et al. 2008; Cloern et al. 2005). As noted above, there is also evidence for shifts between diatoms and flagellates/cyanobacteria linked to changes in retention and mixing (e.g. Lehman et al. 2010). It should be noted, however, that Cloern and Dufford (2005) noted niche-separation of a small number of marine and riverine species, but also noted that a large fraction of the phytoplankton community were "generalists", doing equally well across a broad range of conditions (Figure 9.6). This suggests that canonical descriptions of PFT response to environmental conditions such as mixing are potentially useful but should not be over-interpreted.

9.2.3 Physiological Factors: Nutrients

San Francisco Bay is generally considered to be nutrient-replete. This has been corroborated several times (e.g. Mallin et al. 1993), and is supported by the lack of response between productivity and river flow (Kimmerer 2005; Kimmerer et al. 2012). While this perspective is useful for examining forcing of phytoplankton biomass, this general nutrient-replete condition can mask considerable variability at the species or PFT level of community composition. It is generally assumed that dinoflagellates exhibit low affinity for N-substrates relative to diatoms (Smayda, 1997, 2000) and that nutrient uptake kinetics scale as a function of cell size (larger size equals lower affinity; e.g. Irwin et al., 2006; Litchman et al., 2007), although Collos et al. (2005) argue that at high-nutrient concentrations, such as in upwelling systems and estuaries, multiphasic kinetics may be quite common among a diverse array of phytoplankton species. Kudela et al. (2010) summarized the measured kinetics responses for N-uptake in several algal groups, focusing on harmful algal bloom species from upwelling systems (Figure 9.7). While the general canonical pattern of lower K_s for diatoms and higher for dinoflagellates, there is considerable overlap and the number of recorded species is quite low. It is particularly striking that there appear to be no phytoplankton strains isolated from San Francisco Bay in the National Center for Marine Algae (NCMA). Again, this highlights the need to be cautious when applying canonical patterns for nutrient utilization derived from global data sets.
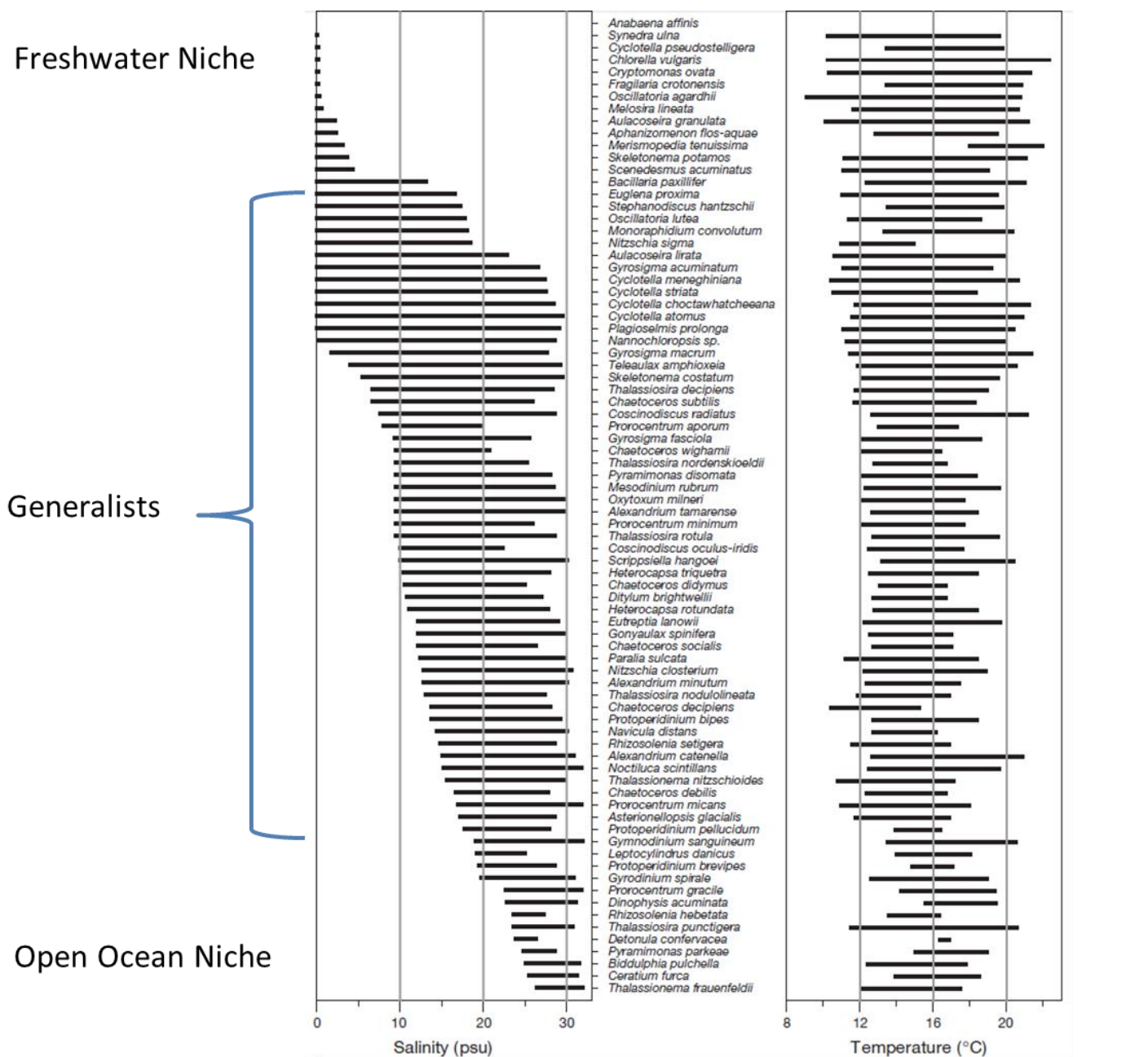
Fig. 6. Salinity and temperature ranges of selected phytoplankton species. Horizontal bars span 10th and 90th percentile salinity and temperature at which each species occurred within 599 samples distributed along salinity gradients of San Francisco Bay (Fig. 2B,C)

Figure 9.6 From Cloern and Dufford 2005.

Despite the nutrient-replete status of San Francisco Bay, several groups have proposed direct or indirect nutrient effects on phytoplankton species composition. While not specific to San Francisco Bay, vitamin B1, B7, and B12 have been implicated in controlling phytoplankton species composition in estuarine (Tang et al. 2010), coastal, and HNLC waters (Koch et al. 2011). The response is greatest in large (>2 μm ESD) cells, and in particular for dinoflagellates. There has been no published evaluation of vitamin B effects in San Francisco Bay.
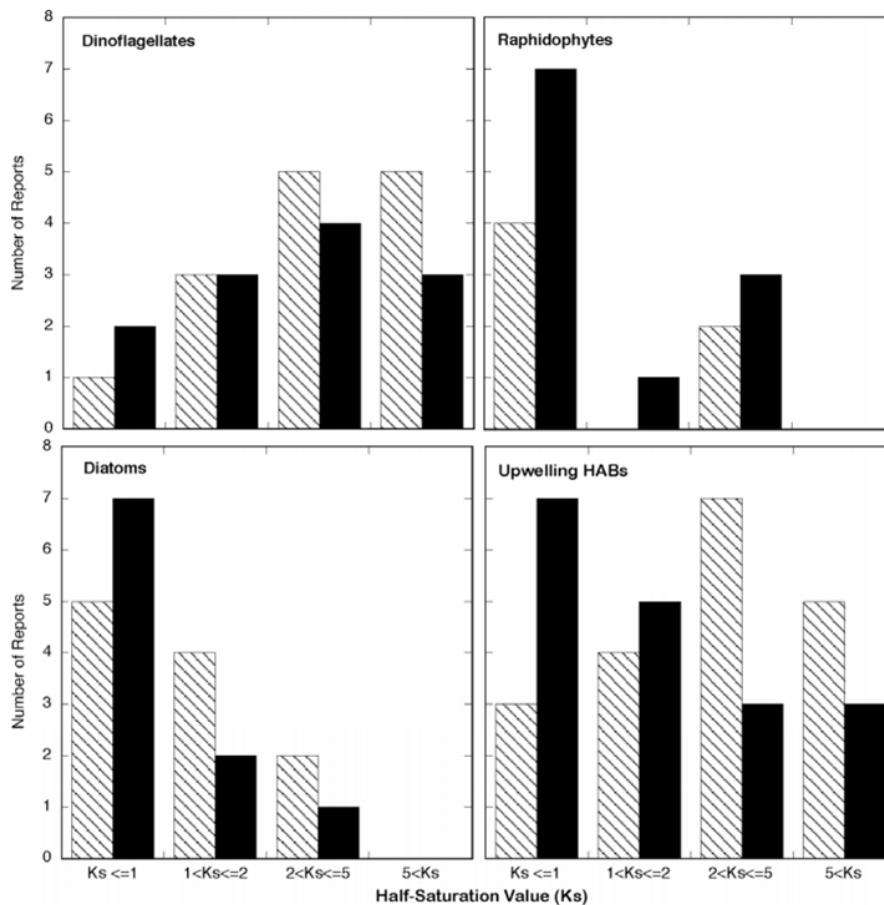
Fig. 1. Kinetics values for nitrate (solid bars) and ammonium (hashed bars) were binned based on the half-saturation (K_s) value using the same categories as Smayda (2000) for Dinoflagellates, Raphidophytes, Diatoms, and Upwelling HABs. Data were obtained from Smayda (1997, 2000), Kudela and Cochlan (2000) and Table 2. Smayda (2000) reported a general trend of low K_s values for diatoms and high K_s values for dinoflagellates, as is seen here. Note that for the Upwelling HAB group, nitrate K_s values more closely approximate the Diatom grouping, while for ammonium the pattern is similar to the Dinoflagellate grouping.

Figure 9.7 A summary of nitrogen kinetics responses reported in the literature for major algal groups, as reported in Kudela et al. 2010.

Other nutrient interactions have also been poorly defined for the estuary. For example, free copper has a strong, PFT-specific response on algae (Brand et al. 1986; Sunda and Huntsman, 1995), and elevated copper concentrations will become toxic to phytoplankton (Brand et al. 1986; Sunda et al. 1987). Brand et al. (1986) demonstrated that neritic diatoms are least sensitive, while cyanobacteria and dinoflagellates were most sensitive to copper. Copepods such as *Acartia tonsa* also exhibit more sensitivity to copper than do diatoms (Sunda et al. 1987), suggesting that copper could subtly impact both the productivity and loss terms, leading to shifts in community composition. Buck et al. (2007) recently reviewed copper trends in San Francisco Bay. They concluded that copper concentrations have declined significantly since 1993, with the North Bay declining 17% and South Bay declining 29-44%; no data were available prior to 1993, but copper concentrations were presumably elevated due to anthropogenic-driven inputs. As copper concentrations dropped, it is at least possible that inhibition of flagellates, cyanobacteria, and zooplankton has been alleviated, leading to increased competition with diatoms.

Two other nutrient relationships have been proposed as regulators of both total biomass and community composition. Dugdale et al. (2007) have proposed that elevated ammonium

concentrations from wastewater discharge is suppressing diatom productivity, while Glibert (2010) and Glibert et al. (2011) have argued that N:P ratios are indirectly controlling community composition. Dugdale et al. (2007) proposed a modified conceptual model of bloom initiation for the North Bay as follows: (1) In spring, increased irradiance and increased river flow (diluted ammonium) promote diatom growth, initially fueled by ammonium; (2) if the ammonium is drawn down to < ~4 μM, nitrate uptake is initiated; (3) if conditions remain suitable (increased irradiance, low ammonium, retention) a bloom develops. This hypothesis was developed primarily with direct field observations, but there are multiple ongoing projects evaluating several aspects with both field and laboratory experiments.

Elevated external NH_4^+ levels are toxic to photosynthetic organisms because the build-up of a charged molecule on one side of cell membranes results in the establishment of a high cross-membrane potential. While NH_4^+ is mostly transported into the cell via active, ATP-dependent transport (as are nearly all charged molecules) it can also passively diffuse into the cell via channels (facilitated diffusion). When external concentrations are elevated, these channels will allow a large influx of NH_4^+ as a consequence of the cross-membrane potential. The influx initiates active pumping to rid the cytosol of NH_4^+ and to prevent an intracellular pH disturbance (Bligny et al. 1997). However, the efflux of NH_4^+ maintains the cross-membrane gradient, thereby the channel influx, and necessitates continued, active efflux pumping at a great energetic cost to the cell, culminating in the cessation of growth and sometimes death of the organism (Britto et al. 2001). Some plant species have adapted to high external NH_4^+ concentrations by preventing the establishment of a cross-membrane potential, eliminating the futile NH_4^+ cycling and high respiratory cost of efflux pumping (Britto et al. 2001). Because the susceptibility to the establishment of a cross-membrane potential varies from organism to organism, susceptibility to NH_4^+ toxicity also varies greatly. For example, susceptibility to NH_4^+ toxicity is known to vary by orders of magnitude in aquatic plant species and in unicellular algae. Freshwater unicellular algae such as *Chlorella vulgaris* isolated from wastewater settling ponds can tolerate NH_4^+ concentrations up to 3 mmol/L (Berg et al. unpublished data, Perez-Garcia et al. 2011). Among marine species, diatoms also tolerate NH_4^+ concentrations in the mmol/L range (Antia et al. 1975, Lomas 2004, Hildebrand 2005, Pahl et al. 2012). In contrast, marine phytoplankton species with a large variety of NH_4^+ transport proteins encoded in their genomes, and with low half saturation constants for NH_4^+ uptake, can be susceptible to toxicity at orders of magnitude lower NH_4^+.[update with recent papers]

While NH_4^+ toxicity at the physiological level has a response time on the order of the cell division time, it can culminate in a much greater, community-level response that builds-up over longer time scales. The community-level response is manifested through a change in phytoplankton community composition to species that are more tolerant to high NH_4^+ concentrations and to primary and secondary consumers that can feed on those species (Glibert et al. 2011). This can also lead to proliferation of Harmful Algal Blooms since many of the noxious and toxic species found in the California Current show a preference for reduced N compounds such as NH_4^+ (Kudela et al. 2010). It is this community-level response that is important for ecosystem function. But, the latter cannot occur if the former, physiological effect is not present.

To date, investigators have used a lack of chlorophyll *a* (Chl *a*) biomass or a lack of nitrate (NO_3^-) uptake as evidence of NH_4^+ stress on the phytoplankton community in Suisun Bay,

(Dugdale et al. 2007). However, both changes in Chl *a* and NO_3^- uptake may be influenced by a multitude of factors including irradiance, community composition, and season, making it difficult to use these indirect measures as evidence of NH_4^+ inhibition (e.g. Kimmerer et al. 2012). In addition, although NH_4^+ inhibition of NO_3^- uptake by phytoplankton has been widely demonstrated, there is also considerable evidence showing that phytoplankton, across the range of taxa (including diatoms), grow at comparable rates on both NH_4^+ and NO_3^- (SFEI, 2014b). Lastly, while the ammonium-inhibition hypothesis has primarily been used to explain observations from the North Bay, it remains unclear why the similar NH_4^+ concentrations found in South Bay and Lower South Bay do not inhibit blooms there. ***A direct comparison between the North and South Bay would likely help to determine whether ammonium concentrations are directly inhibiting diatoms, are indirectly shifting the community towards organisms with lower K_s and higher maximal uptake rates (Figure 9.7), or are covarying or interacting with some other variable such as irradiance, or size-selective grazing (Section 9.2.7).***

A complementary hypothesis linking nutrients and community composition has been proposed based on the stoichiometry of N and P (Glibert 2010; Glibert et al. 2011). Glibert (2010) proposed that decadal changes in phytoplankton community composition altered the food web of San Francisco Bay by favoring varying groups of organisms. Prior to 1982, the community was dominated by a nitrate-driven diatom assemblage (Figures 9.5). With the increasing ammonium loads from wastewater treatment plants the community shifted towards flagellates. As the N:P ratio continued to increase, cyanobacteria were eventually favored. This analysis is based largely on a statistical metric called cumulative sum analysis, and has been criticized by others as flawed (Cloern and Jassby et al. 2012; but also see Lancelot et al. 2012). Glibert et al. (2011) elaborated on this argument by proposing a conceptual model for how estuarine systems respond to changes in N:P ratios. They argue that even though N and P are in excess for phytoplankton growth, the ratio impacts higher trophic levels (and thus the ecological stoichiometry of the system). The authors argue that decadal changes in DIN:DIP ratios correlate with declines in diatoms and chlorophytes, and increases in dinoflagellates, because diatoms and dinoflagellates also exhibit different intrinsic N:P ratios. There are two potential issues with this argument. First, so long as N and P are saturating, the ratio should have no direct impact on species composition, other than by selecting for the organism with optimal growth. Second, Chlorophytes have a higher N:P ratio than either diatoms or dinoflagellates, suggesting that chlorophytes should be dominant under these conditions (Figure 9.8). The authors argue that this is accounted for due to the stoichiometric adjustments and feedback loops that occur between primary producers and higher consumers, and that both the Pelagic Organism Decline and the invasion of organisms such as *Potamocorbula* were triggered by bottom-up control through nutrient stoichiometry. These assertions are controversial, but the conclusion, that phytoplankton community composition is an indicator of ecosystem "health", is nonetheless consistent with other hypotheses.

9.2.4 Top-Down controls

Grazers: Potamocorbula

While Glibert et al. (2011) conclude that the invasion of *Potamocorbula* was triggered by gradual shifts in ecosystem nutrient stoichiometry, others have pointed to the invasion as coincident with the rapid decline of diatoms in San Francisco Bay (Figure 9.5). The long- term shift in phytoplankton from diatoms to flagellates and cyanobacteria and the timing of declines in apparent silica uptake in Suisun Bay (Kimmerer 2005) and in abundance of anchovies in the Low Salinity Zone (Kimmerer 2006) are consistent with an influence of grazing by the clam *Potatmocorbula amurensis. Potamocorbula* exhibits lower feeding rates on bacteria (typically <1 μm) than on phytoplankton (Werner and Hollibaugh 1993). Thus, the phytoplankton biomass available to many grazers is considerably lower than indicated by bulk chlorophyll values. The combination of low productivity and a high proportion of small cells offers poor support to the food web of the upper estuary, likely resulting in shifts in diet and food limitation and contributing to the poor condition of some fish species (Feyrer et al. 2003; Bennett 2005) and the general pattern of decline across species and trophic levels (Kimmerer et al., 2012). This direct modulation of phytoplankton community composition by an introduced benthic predator presents a conceptual model of trophic interactions that is strikingly different from the bottom-up, stoichiometrically driven scenario described above. As detailed below, *Potamocorbula* grazing could also have other indirect impacts on community composition in addition to the size-selective removal of PFTs.

Figure 1 C:N:P composition varies between phyla and superfamilies. Phytoplankton C:P, N:P and C:N (mol:mol) ratios are grouped phylogenetically—Prasinophyceae (Prasino) and Chlorophyceae (Chloro) are members of the green (G) plastid superfamily whereas Dinophyceae (Dino), Prymnesiophyceae (Prymn) and Bacillariophyceae (Diatoms) are members of the red (R) plastid superfamily. Error bars indicate standard errors.

Figure 9.8 Intrinsic C:P, N:P, and C:N ratios for major phytoplankton groupings. From Quigg et al. 2003

Other grazers

Winder and Jassby (2011) document both abrupt and gradual changes in zooplankton composition, abundance, and occurrence in San Francisco Bay. Major shifts coincide with the extended drought from 1987-1994 and the invasion by *Potamocorbula.* The calanoid copepod *Limnoithona tetraspina* increased rapidly in the 1990s to become the numerically abundant zooplankter, presumably due to predator avoidance, low respiration, and a dietary preference for bacteria and mixotrophic ciliates, which were in turn stimulated by the shift from diatoms to flagellates and cyanobacteria (Figure 9.9). Rollwagen-Bollens et al. (2011) also noted the importance of microzooplankton as both a consumer of small autotrophs and a link to metazoans. Microzooplankton grazing is classically assumed to differentially impact small autotrophs, suggesting that microzooplankton grazing has increased in importance as a biomass sink with the decrease in diatom abundance. This could also lead to more stochastic bloom events of other organisms as proposed by Irigoien et al. (2005) and Stoecker et al. (2008), who argued that blooms occur when a particular species of PFT exploits a "loophole" in grazing pressure. This is also consistent with Greene et al. (2011) who reported high mortality rates of microzooplankton due to *Potamocorbula* grazing, thus potentially disrupting trophic transfer and stimulating more nano- and picoplankton by removing grazing pressure on these smaller organisms, even though the nano- and picoplankton are not efficiently grazed by *Potamocorbula* directly. This highlights the potential complex interactions between top-down and bottom effects in relation to the use of phytoplankton community composition as an index of ecosystem health.
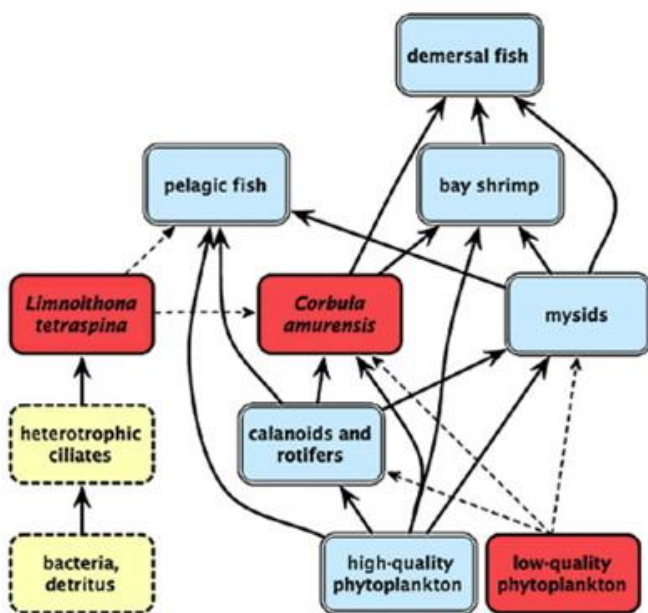
Fig. 11 Trophic interactions of the pelagic food web in the upper San Francisco Estuary at the "suisun" subregion. *Arrows* indicate major energy flow based on gut content analysis or literature data. *Solid lines* represent strong and *dashed lines* weak trophic interactions. *Box colors* reflect long-term taxa trends: *red* are increasing taxa, *blue* decreasing taxa, and *yellow* taxa of unknown trends over the last four decades. Phytoplankton is separated into groups of high (group I; e.g., diatoms) and low (group II; e.g., cyanobacteria, chlorophytes) food quality and/or availability for herbivorous organisms. Biomass trends

Figure 9.9. Shifts in phytoplankton community composition are associated with shifts in grazing pressure. Source: Winder and Jassby 2011

9.2.5 Interactive Effects

Several of the previous sections allude to interactive effects between multiple drivers. For example, water flow in the Northern Bay regulates turbidity, water clarity, residence time, nutrient concentrations and ratios, and benthic-pelagic coupling. Trace metals and vitamins can have subtle influences on phytoplankton community composition, leading to shifts in trophic efficiency as well as shifts in dominant phytoplankton assemblages. The ecological stoichiometry hypothesis proposed by Glibert et al. (2011) assumes a series of interactive effects, ultimately stemming from changes in nutrient forms and ratios. A conceptual model (or models) of phytoplankton community composition must be flexible enough to allow for these interactive effects, and for differential responses spatially and temporally.

A specific example of the potential for interactive effects focuses on light-nutrient-photosynthesis interactions. There is clear evidence for light limitation of phytoplankton productivity in San Francisco Bay, while it is generally accepted that macronutrients are not limiting to productivity. The interactive effects of these processes are rarely examined, but can have a direct impact on phytoplankton community composition. After carbon assimilation, nitrogen metabolism is the second largest sink for photosynthetic reductant (ATP, NADPH) in most photo-autotrophs. Under light limitation (e.g. San Francisco Bay), it is often assumed that ammonium will be a preferred N source compared to nitrate because of the large differential in energy required, since nitrate must be reduced first to nitrite and then to ammonium before being metabolized in the cell. As noted above, diatoms will also reduce nitrate as an electron sink under rapidly changing light environments (such as occurs in a turbulent estuary). Much of this N is subsequently effluxed as ammonium. This could conceivably lead to a scenario where (1) diatoms are initially light-limited in a heterogenous, rapidly mixing environment, leading to (2) efflux of ammonium, nitrite, and DON as an electron sink; as the water column stabilizes, (3) physiological energy balance is restored, ammonium efflux stops, and N is assimilated to produce more biomass, leading to (4) depletion of ammonium followed by depletion of nitrate as a diatom bloom develops. While there is no direct evidence for this occurring in San Francisco Bay, Kimmerer et al. (2012) noted that productivity was positively correlated to light availability and negatively correlated with ammonium concentrations, while Parker et al. (2012) noted a shift towards lower C:N ratios, both of which are consistent with this scenario.

These potentially complex interactions are not limited to diatoms. A previous field study of a "red tide" of the dinoflagellate *Lingulodinium polyedrum* in Southern California demonstrated that, to maintain the bloom, the dinoflagellates had to be using urea, possibly in some combination with other nitrogen sources (Kudela and Cochlan, 2000). This observation would not be evident from direct measurements of nutrients, photosynthetic carbon fixation, or ^{15}N-labeled nitrogen uptake, but could be inferred by comparing the elemental ratio of the algae with nutrient kinetics curves, nutrient versus irradiance uptake curves, and photosynthesis versus irradiance curves (Figure 9.12). In contrast to typical paradigms, the bloom could <u>also</u> maintain balanced growth at very low or very high irradiances using only nitrate, while the classic Michaelis-Menten kinetics would suggest the bloom was using $NO_3 > NH4 > Urea$. While these complex interactions are presumably common in dynamic environments, simultaneous evaluation of these interactive effects is rarely performed. Since every species (and probably strain) of algae has a potentially unique combination of light, nutrient, and carbon assimilation capabilities there is plenty of opportunity for seemingly stochastic selection of species or PFTs in the real world.
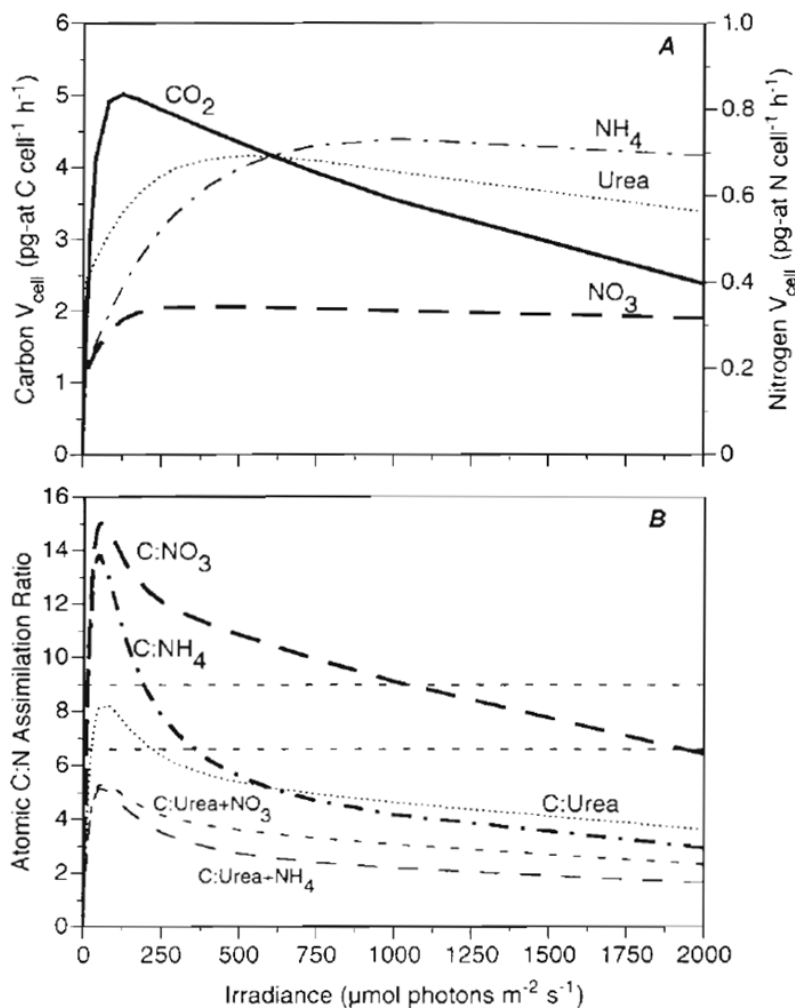
Figure 9.10 The interactive effects of light, nutrient assimilation, and the energetic requirements for N-metabolism (see Figure 9.11) can result in unexpected patterns of nutrient utilization. Panel A shows uptake versus irradiance for a red tide comprised of the dinoflagellate *Lingulodinium polyedrum,* indicating more efficient utilization of ammonium and urea compared to nitrate. Panel B show the C:N assimilation ratio for different combinations of C and N. The lower dashed line is the Redfield ratio, the upper dashed line is the measured C:N ratio of the algae. At very low light, the observed C:N ratio could be maintained with any source of N. At moderately low light (up to 250 µmol photons m-2 s-1) urea is almost certainly utilized, and urea could sustain balanced growth (if sufficiently available) across the full range of irradiances. Note that nitrate alone could only sustain balanced growth at both extremely low and extremely high light levels. In contrast, uptake kinetics (not shown) would indicate preference as NO3>NH4>Urea (based on Ks values). At the time of collection, ambient nutrients were approximately at the Ks value or higher throughout the water column. From Kudela and Cochlan, 2000.

9.2.6 Harmful Algae

A special case within the larger framework of phytoplankton community composition are those organisms classified as harmful algal blooms. This provides perhaps the most direct metric of ecosystem health since sufficiently elevated numbers of these algae and their associated toxins is a clear indication of impacted ecosystem health. HAB organisms are well studied at the species level in terms of both physiological parameters and ecological patterns. Despite the persistent nutrient enriched status of San Francisco Bay, few harmful algal blooms have been reported recently for the estuary. A lack of monitoring, especially for toxins, may play a role, given the large number of potentially harmful algae present in San Francisco Bay (Cloern and Dufford, 2005; Table 3.1 and Figure 3.9). However, there have been historical occurrences (see Cloern et al., 1994 referenced in Cloern, 1996), and recently cyanobacteria and dinoflagellate blooms have been documented. For example, blooms of the cyanobacteria *Microcystis aeruginosa* have been occurring in the late summer/autumn in the northern Bay and Delta since 1999 (Lehman et al., 2005), the raphidophyte *Heterosigma akashiwo* created a red tide in the Central Bay in summer 2002 (Herndon et al., 2003), and the dinoflagellate *Akashiwo sanguinea* caused a red tide in the Central and South Bay areas during September 2004 (Cloern et al., 2005).

Microcystis aeruginosa blooms have occurred in the Delta and the North Bay during July through November of each year since 1999. The colonial form of *M. aeruginosa* is the first recorded toxic phytoplankton bloom in the northern reach of SF Bay and may have been recently introduced because it was not recorded in historic samples taken between 1975 and 1982 (Lehman et al., 2005), although sampling technique during that period may have been suboptimal for detecting *Microcystis* (samples collected at 1m depth, as opposed to surface samples/horizontal tows). *M. aeruginosa* can form surface scums and is a nuisance to recreational users; reduce aesthetics and oxygen; and produce microcystin, a hepatatoxin to humans and wildlife (Lehman et al., 2005; Lehman et al., 2008). Several surveys of *M. aeruginosa* blooms in the Delta have documented that the blooms can be widespread, often with microcystin concentrations that exceed World Health Organization guidelines for risks to humans and wildlife (e.g., Lehman et al. 2005; Lehman et al., 2008). *M. aeruginosa* may also produce cascading effects on the food web (Brooks et al. 2012).

The other well-studied HAB organisms within California waters, *Alexandrium catenella* (causes paralytic shellfish poisoning) and *Pseudo-nitzschia spp.* (causes domoic acid poisoning) are also present in the estuary. Indeed, sampling in South Bay Salt Pond A18 during 2006 (Thébault et al. 2008) revealed the presence of six phytoplankton taxa that can potentially cause harmful algal blooms (HABs): dinoflagellates *Alexandrium* sp. and *Karenia mikimotoi*, pelagophyte *Aureococcus anophagefferens,* raphidophyte *Chattonella marina*, and cyanophytes *Anabaenopsis* sp. and *Anabaena* sp. Microscopic analysis of samples collected by USGS monitoring in 2006 and 2008 revealed seven additional species of phytoplankton (e.g., Figure 3.9 and Table 3.1) that, when present at bloom abundances, have disrupted aquatic food webs, caused mortality of invertebrates, fish and birds, or human illness in other shallow marine ecosystems. In 2007 and 2008 the USGS water-quality sampling program also found HAB species in South San Francisco Bay, including *Karlodinium* (*Gyrodinium galatheanum*) *veneficum* (November 2007), *Chattonella marina* (March 2008), and *Heterosigma akashiwo* (September 2007). Appearances of these taxa are surprising because they were not detected previously in 3 decades of sampling (Cloern and Dufford 2005). These observations, all made after the first salt ponds were opened in 2004, suggest that the salt ponds might function as incubator habitats and a source of toxic phytoplankton to San Francisco Bay as they are opened to tidal exchange. Dinoflagellates, flagellates, and pelagophytes form HABs in other shallow marine ponds that are enriched in organic matter and have long hydraulic residence time (e.g. Gobler et al. 2005). Shallow, semi-isolated systems (such as the salt ponds) can also serve as "biological capacitors", providing innocula for large-scale blooms in nearby bay and coastal waters (Vila et al., 2001). Actions to open these habitats might pose an unanticipated risk to the water quality and living resources of San Francisco Bay and to tidal-ponds created by the South Bay Salt Pond Restoration Program, particularly for water birds and fish assemblages. ***Given the prevalence of HAB organisms in the Bay, the dramatic increase in blooms of Microcystis, and the potential linkages between ecosystem health and HABs (Kudela et al. 2008), it would be prudent to more closely monitor HAB organisms and associated toxins within San Francisco Bay as indicators of water quality.***

9.3 Summary of Major Conceptual or Data Gaps

San Francisco Bay is somewhat unique in that it is well studied for both physical/environmental parameters, and for phytoplankton community composition. Despite this wealth of information, any attempt to develop a conceptual model of community composition runs into the fundamental

issue identified by Cloern and Dufford (2005): "…the problem is hyperdimensional, whereby communities are assembled by selective forces operating on variation in algal size, motility, behavior, life cycles, biochemical specializations, nutritional mode, chemical and physiological tolerances, and dispersal processes…our knowledge base is therefore insufficient for constructing reliable numerical models of phytoplankton population dynamics at the species level, in spite of our recognition that the functions provided by the phytoplankton vary among species." While this issue is not intractable, it is unlikely that we will be able to predict or fully understand the species-level variability in San Francisco Bay in the near future. We can, however, identify important components of a conceptual model for phytoplankton community composition at the level of traits and ecosystem function (Figure 9.4). The immediate challenge is to identify the relative importance of these sometimes conflicting conceptual relationships. A long-term goal should perhaps be the development of sophisticated numerical-biological models that incorporate "evolution" and natural selection. This approach is being increasingly applied to oceanic ecosystems with some success (Follows and Dutkiewicz 2011) and has recently been used to test fundamental questions about community assembly and stability (Barton et al. 2010a,b). Applications of such models in the near term – as synthesis tools for examining multi-dimensional parameter space – may allow us to rule in or rule out hypotheses, evaluate potential drivers of phytoplankton community shifts, and identify the highest priority experimental studies. Several gaps in our ability to develop or apply a conceptual model of phytoplankton community assembly include the following specific issues:

- It is unclear how many spatio-temporal compartments need to be included for San Francisco Bay. The estuary could be modeled as single unit, as North Bay versus South Bay, or as a series of sub-basins. While many authors recognize that algae are both imported and exported from the ocean and riverine end members, it is still very common to describe the mean patterns for the estuary or develop conceptual models based on data from particular locations. The estuary clearly responds to forcing from the oceanic and riverine end-members; any conceptual model of community assemblage for San Francisco Bay must be linked to models of the coastal ocean and the watershed.
- The estuary is generally considered to be nutrient-replete, but there is little or no information available about vitamins, trace-metals, and the influence of anthropogenic contaminants such as pesticides that may be influencing community composition. Several of these factors would likely co-vary with more easily measured parameters and could easily be overlooked.
- Very little is known about the species-specific physiological properties of the community, nor about the potential interactions between (e.g.) light, nutrients, photosynthesis, etc.
- The presence of HABs and toxins has been largely ignored in San Francisco Bay. The prevailing assumption is that the Bay is resilient to these impacts, but this may simply be a lack of monitoring and measurement. Large-scale restructuring such as the opening of the salt ponds has the potential to suddenly and dramatically alter this perspective.
- Several conceptual models have been proposed that could account for the abrupt and long-term trends in community composition, and are diametrically opposed. Similar to the classic paradigm of top-down versus bottom-up control in marine systems, reality is probably somewhere in between, and may change spatially and temporally.

Tables 9.1 summarizes the current state of knowledge and knowledge/data gaps related to phytoplankton community composition. The prioritizations in the rightmost two columns are related to the discussion in Section 11.

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

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
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**
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**

10 Other proposed adverse impact pathways

While other potential nutrient-related adverse impact pathways - including those that have impacted other estuaries or have been hypothesized in SFB – are possible, this report focused on a subset considered to be most relevant or most important in SFB (Figure 3.1, Table 3.2 AI.1-AI.6). Other adverse impact pathways, listed below, may need to be considered at a later date if observations indicate that they are indeed important in some habitats of SFB.

- Loss of submerged aquatic vegetation (SAV) habitat due to shading from phytoplankton or periphyton growth

- Excessive growth of macroalgae

- Excessive macrophyte growth, in particular invasive species

- Nutrient-induced changes in the composition of individual phytoplankton cells that cause adverse outcomes on primary consumers (Glibert et al., 2013)

- Direct NH_4^+ toxicity to copepods (Teh et al., 2011)

11 Priority Science Questions and Knowledge/Data Gaps

11.1 Introduction
The overarching questions that the Nutrient Management Strategy aims to address seem straightforward at first glance (Table 11.1 Column A). But those questions barely scratch the surface. Below the surface, the number of questions, and the information needed to answer those questions, grow exponentially (Table 11.1 Column B), because:

- San Francisco Bay is a large and complex estuary, comprised of distinct habitats that receive different nutrient loads, and that process and respond differently to those loads.
- A broad array of potential adverse impacts (Table 3.2) needs to be considered, and many of those paths have unique knowledge and data gaps;
- There are numerous important physical/chemical/biological processes along the pathways between nutrient loads and response (the conceptual model presented in Sections 5-9), and considerable knowledge and data gaps.

Table 11.1 Overarching Management Questions and next-layer more specific questions for SFB NMS

A. Overarching Questions	B. Next layer of more specific questions
1. Is SFB experiencing nutrient-related impairment under current conditions, or is it likely to in the future?	1.a Which impairment pathways (Figure 3.1 and Table 3.2), and what "conditions" constitute impairment?
	1.b What subembayments?
	1.c Which habitats (deep subtidal, intertidal, margins)?
	1.d What plausible future scenarios need to be considered, how would conditions differ under those scenarios, and would impairment develop?
2. What are the major nutrient sources?	2.a What are the magnitudes of the major nutrients sources, and how do those magnitudes vary temporally: POTWs; stormwater; agriculture; upstream inputs from the Delta; other perennial streams/rivers?
	2.b How do those individual loads contribute to ambient nutrient concentrations as a function of space and time throughout the Bay, considering temporal variability in the physical, chemical, and biological factors that influence their fate and transport once entering the Bay?
3. What nutrient loads or concentrations are protective of ecosystem health?	3.a What is/are the most important or sensitive endpoint(s), which nutrient forms cause or contribute to that adverse impact, and what loads or concentrations would be protective?
	3.b After considering fate and transport, what loads, from the combination of sources, would be protective?
4. What are efficacious and cost-efficient nutrient management options for ensuring that Bay beneficial uses are protected?	4.a What management actions - load reductions and other actions - will protect ecosystem health?
	4.b What actions mitigate or prevent impairment, and do so at the most reasonable cost and/or by delivering the greatest set of multiple net benefits?

When considering both the breadth and depth of monitoring, modeling and special studies that would be needed to address all the issues, it is clear that trying to tackle it all, in-depth, and in parallel would be impossible. Some degree of prioritization is needed to focus effort on the most important issues first.

The goal of this section is to inform the direction of scientific inquiry and monitoring by taking an initial step toward identifying the highest priority issues, the related science questions, critical knowledge and data gaps, and the types of investigations that would most directly target those gap and allow well-informed nutrient management decisions to be made. In Section 3, we explored the following question: *What would nutrient-related problems look like in San Francisco Bay if they were occurring now or in the future?* In response to this question, 8 adverse impact categories were identified (Table 3.2, Figure 3.1). In this section, using the conceptual model as a guide, we identify scenarios (current conditions, future environmental change, management actions) under which those adverse impacts could occur (or may already be occurring), and examine those scenarios to identify highest priority issues warranting further exploration. Based on the set of highest priority issues related we then identify key science questions, major knowledge gaps or data gaps (based on the assessments in Tables 6.2, 7.1, 8.1, 9.1), and identify the types of studies needed to address those questions and gaps.

11.2 Identifying priority scenarios for further consideration
Scenarios were identified and explored as follows:

Current Conditions or Current Trends:
These 'scenarios' address the question: *Based on current observations – current conditions or current trends – are some subembayments or habitat-types already experiencing, or heading toward experiencing, adverse impacts from nutrients?*

In considering the conditions and trends, the analysis does not aim to assess whether impairment is occurring, but rather to frame and present the issue, and its priority level, for comparison with other issues. Four broad categories were encountered: i. Existing data suggest do not suggest a major problem; ii. Existing data may be suggestive of a potential problem but are currently insufficient to definitively answer this question; iii. There is currently little or no data, but adverse impacts are highly plausible based on the conceptual model; and iv. mechanistic-studies are needed to address key conceptual gaps;

Environmental change scenarios
N and P are abundant in SFB, but physical and biological drivers severely limit their conversion into phytoplankton biomass, and generally prevent SFB from experiencing exceedingly high biomass and low dissolved oxygen. Some of those same regulating factors may help prevent potentially harmful phytoplankton, which are regularly detected at low numbers in SFB, from developing into full-blown HABs/NABs. This set of scenarios focuses on uncontrollable environmental change and was developed through exploring the following questions:
What could cause a relaxation of the physical or biological controls that regulate the Bay's response to high nutrients, and thereby contribute to, cause, or worsen adverse impacts?
Future scenarios require serious consideration for several reasons. First, SFB boasts multiple examples of unexpected and substantial environmental changes over the past 20-40 years that have had major impacts on ecosystem response and ecosystem health (see Sections 3, 7, and 9;

e.g., biomass increases in South Bay over the past 20 years; 30-50% decrease in suspended sediment concentrations Bay-wide over past 20-30 years; *Potamocorbula* invasion in Suisun in 1987; shifts in zooplankton community composition and abundance in Suisun Bay due to invasions and other drivers; decline in benthos-feeding organisms in South Bay). Second, the potential effects of climate change need to be evaluated. Third, it will take many years, even multiple decades, to implement major management actions. Taking action only once a problem arrives means years or decades of impairment before 'the fix' can be implemented. If future problems are to be averted, impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset. Lastly, implementing management actions while a problem is still over the horizon, as opposed to already upon us, will allow time for planning, and for a broader range of management options to be considered. Planning ahead will increase the likelihood and feasibility of implementing "the best solution" – a set of management actions that achieve multiple benefits (beyond just nutrients) and are the most cost-effective.

To identify environmental change scenarios requiring further analysis, we first used the conceptual model to identify changes to regulating factors that could lead to, or exacerbate, the adverse impacts identified in Section 3 (Table 3.2; Figure 3.1). Figure 11.1 illustrates how shifts in various regulating factors could adversely influence ecosystem responses. Next, we identified environmental change scenarios under which those shifts could occur. Those scenarios are summarized Table 11.1, and mapped to changes in regulating factors in Figure 11.2.
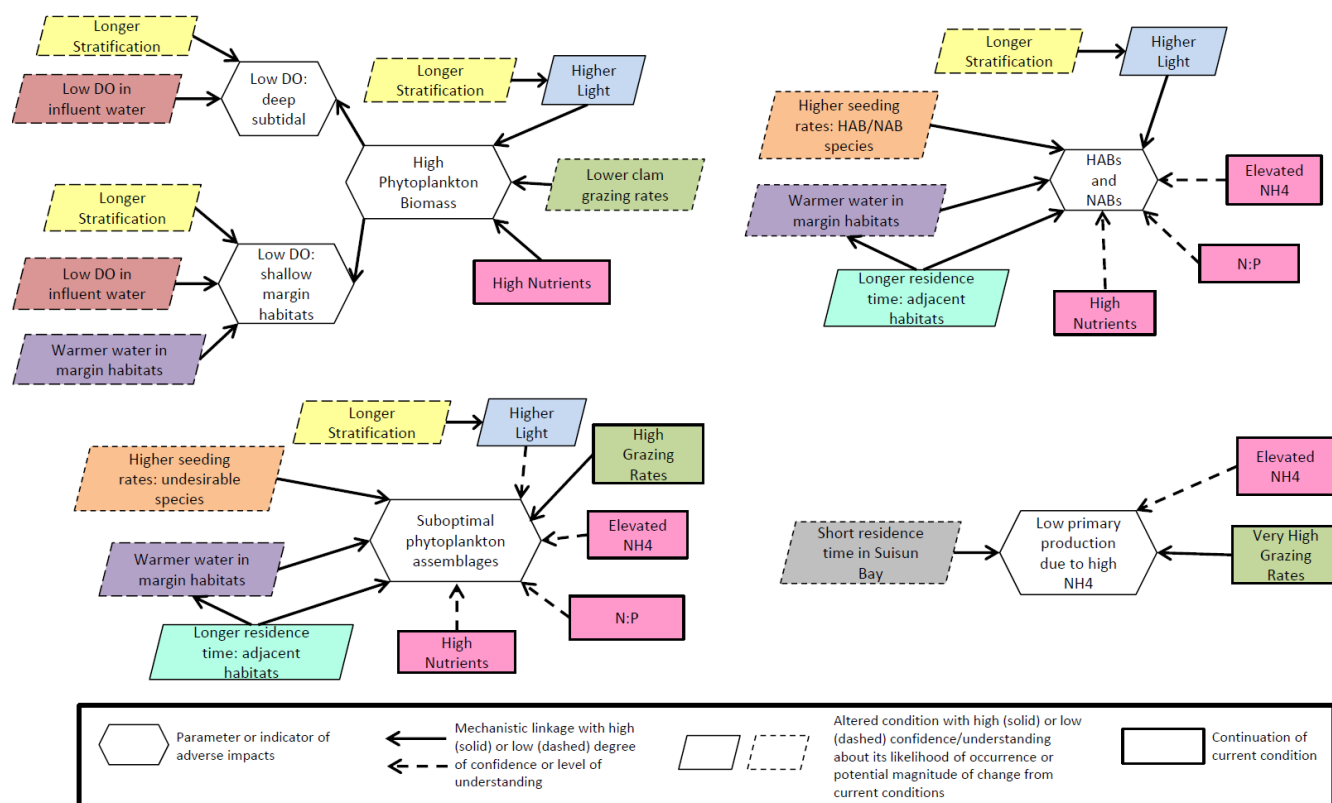
Figure 11.1 Changes to underlying drivers of response that could contribute to adverse impacts.
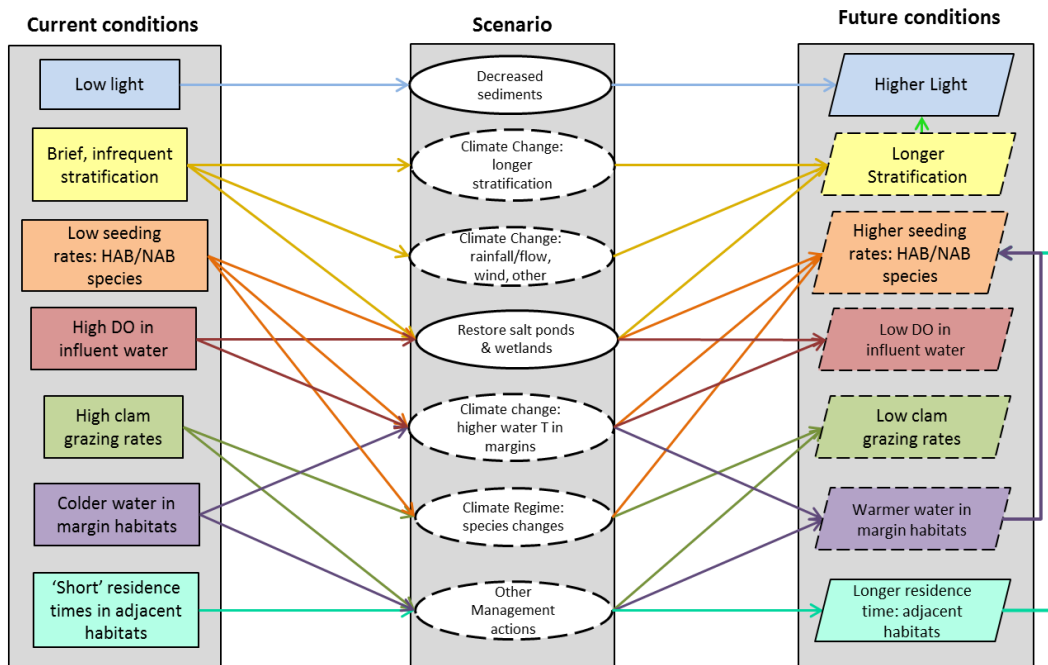
Figure 11.2 On the left, Current Conditions within SFB that have thus far provided resistance to harmful effects of high nutrient loads. In the middle, potential environmental or management scenarios that could create future conditions with weaker resistance to nutrient-related adverse impacts. Likelihood of a scenario is indicated by a solid line (more certain) or a dashed line (unknown likelihood of occurrence, or unknown magnitude or direction). Dashed lines for Future Conditions indicate uncertainty about degree to which condition would change in response to scenarios

Management action scenarios

We considered two broad categories of management actions: management actions that would specifically target nutrient-related problems; and management actions being implemented for other reasons that could have unintended (positive or negative) effects with respect to nutrients (e.g., large-scale habitat restoration projects (SBSP, Deltaplans, BEHGU); flow rerouting in the Delta (ref); shoreline redevelopment (ref). Similar to the approach followed for environmental change scenarios, we used the conceptual model to identify junctures along the path between nutrient loads and adverse impacts where a change to regulating factor could substantially influence ecosystem response (positive or negative). We then identified specific or more general management actions that could act on those factors, which are also summarized in Table 11.2.

Subembayment-Scenario-Response matrix

To organize the numerous issues requiring consideration into a single graphic and facilitate the systematic comparison of issues and their importance, we developed the matrix in Figure 11.3. Figure 11.3 depicts subembayment-scenario-response combinations. Columns represent scenarios, organized into their three categories. Rows represent potential ecosystem responses based on the adverse impact categories in Table 3.2, grouped by subembayment. For each combination, we assessed whether it would result in worsened conditions; would result in improved conditions; or was not highly relevant with respect to nutrients.

Table 11.2 Major scenarios considered

Environmental Change (EC) or Management Scenario (MS)	Description
EC.1	Continued decreasing suspended sediment concentrations in SFB due to a continuation of lower external loads and depletion of the erodible sediment pool.
EC.2	Increased frequency or duration of stratification due to climate change, in particular thermal stratification in fall
EC.3	Climate-change related changes in precipitation patterns (timing, intensity) and timing of snow melt. Potential effects include: altered timing/intensity of freshwater flows from the Central Valley and Sierras that could change stratification duration and residence time in the Delta, Suisun, and other subembayments; changes in freshwater flows from watersheds adjacent to subembayments and influence stratification in particular in LSB and South Bay.
EC.4	Climate regime shifts (el Nino/La Nina, PDO) that cause shifts in biota, such as introducing new phytoplankton species, or changes in abundance bottom feeding macrobiota that have top down controls on food web (e.g., similar to the loss of clams in South Bay, and their eventual return)
EC.5	Climate-change related increases in water temperature in margin habitats
EC.6	Dramatically decreased *Corbula* abundance due to environmental factors (disease, increased predator abundance)
MS.1	N-P load reductions at POTWs discharging directly to SFB subembayments or adjacent watersheds (not including those east of Suisun Bay)
MS.2	Nitrification with no further nutrient removal at POTWs discharging directly to SFB subembayments or adjacent watersheds (not including those east of Suisun Bay)
MS.3	Stormwater load reductions through the use of best management practices, low impact development, etc.
MS.4	Wetland restoration around the Bay margins. Largest scale planned changes in LSB and South Bay, but large areas for potential for restoration in San Pablo Bay and Suisun Bay (See Figure 5.2)
MS.5	Salt pond restoration and reconnection. Largest scale planned changes in LSB and South Bay, but large areas for potential for restoration in San Pablo Bay and Suisun Bay (See Figure 5.2)
MS.6	Managed shellfish beds to increase water column filtration rates to maintain low phytoplankton biomass
MS.7	Sac-Regional upgrades: Nitrification, N-removal
MS.8	Other Central Valley load reductions
MS.9	Delta flow changes, due to changes in water withdrawals or flow routing, or due to restoration

We then ranked the combinations from low to high priority, in terms of the need for further investigation, based on the following factors:

- The combination was considered to be among the most plausible or probable issues to develop into a substantial problem, or among the most feasible mitigation approaches;
- Major gaps in knowledge or data exist that limit our current ability to make further assessments (in terms of determining if there is currently a problem, high likelihood of a future problem, or whether a management action would mitigate impacts), and severely limit the confidence with which science-based decisions can currently be made;
- The combination was a tractable issue to explore, and highly relevant to management decisions. In other words, resources directed toward exploring these issues (monitoring, special studies, modeling) could yield a large return on investment in terms of the knowledge/data gaps filled and scientifically-informed decision-making.

A subset of these combinations is discussed below. First, Section 11.2 explores combinations that represent adverse impacts. Next, Section 11.3 discusses combinations under which adverse impacts would be mitigated or prevented adverse impacts from nutrients. Based on a consideration of the full scenario set, Section 11.4 identifies a subset of highest priority combinations (Section 11.4) and Section 11.5 discusses the related priority science questions and knowledge/data gaps.

11.3 Adverse impacts

The discussion below is organized around the adverse impact pathways (i.e., from Table 3.1). For each pathway, current conditions/trends are discussed first, followed change scenarios that could cause or exacerbate impacts along that pathway.

High biomass and low DO in deep subtidal areas

Current Conditions or Current Trends: Phytoplankton biomass has increased in all SFB subembayments over the past 20-30 years, and small but statistically significant decreases in DO have also been noted (J Cloern, pers. comm.). Biomass increases have been greatest in LSB and South Bay. Current phytoplankton biomass levels in LSB and South Bay do not appear to be having pronounced impacts within deep subtidal areas, since DO concentrations have generally tended to remain above 5 mg/L. However, the rate of change in biomass in South Bay between the mid-1990s and 2005 was rapid (Figure 3.5). Recent data from the past several years suggest that biomass may have reached a new plateau. Nonetheless, the underlying causes of the biomass change over the 20 year, and indeed why it plateaued as opposed to continued increasing, remain highly uncertain, and therefore so does its future trajectory. When conditions are appropriate, LSB and southern South Bay can also experience large and long-lived blooms (50-100 µg/L, 1-2 months; Figure 7.5). High phytoplankton biomass and low DO in deep subtidal areas of LSB and South Bay are thus considered high priority issues based on current conditions and trends. Determining whether LSB and South Bay are trending toward experiencing adverse impacts due to high biomasss and low DO in deep subtidal habitats requires identifying the causes of recent change, forecasting future biomass and DO, and comparing present and future conditions to numeric criteria (being developed separately as part of the SFB Assessment Framework).

Change scenarios: Bay-wide, several scenarios could lead to increased rates of primary production, increased biomass accumulation, and low DO in deep subtidal areas, including (see also Table 11.1 and Figure 11.3): i. continued decreases in suspended sediment concentrations;

ii. increased frequency of climatic conditions that allow stratification to occur more frequently or persist for longer periods of time; iii) changing rainfall patterns that strengthen and lengthen spring salinity stratification; iv.) wetland or salt pond restoration dampening turbulent mixing energy, which would allow stratification to persist longer during its current spring and fall periods, and also outside those times; v. wetland/salt pond restoration and reconnection to the open Bay, and elevated nutrients being more efficiently converted to biomass that is tidally-transported to deep subtidal habitats vi.) loss of benthic grazers (in Suisun Bay). Suisun Bay currently has extremely low phytoplankton biomass. High biomass and low DO would only occur in Suisun if there was an abrupt loss of the *Potamocorbula* clam (e.g., due to disease, predator introduction). Prior to the *Potamocorbula's* establishment, Suisun was highly productive. With the substantial light level increases in Suisun Bay and its higher nutrient concentrations since pre-1987, greater biomass accumulation than pre-1987 would be expected now if *Potamocorbula* disappeared. Further declines in suspended sediment or more frequent or longer stratification would amplify this effect. Indeed, baseline phytoplankton biomass has increased in Suisun Bay over the past 15 years (Figure 3.8), although levels remain far below pre-1987 concentrations.

High Biomass and Low DO in shallow margin habitats

Current Conditions or Current Trends: LSB, South Bay, San Pablo Bay, and Suisun Bay have large shallow margin habitat areas that provide critical ecosystem services (Figure 2.1). To date, these habitats have received limited systematic monitoring. The available data that has been analyzed to date indicate that low DO occurs periodically in LSB's shallow margin habitats, i.e., as sloughs, creeks, and salt ponds undergoing restoration (Figures 3.13 from earlier in report; SFEI 2014c). Low DO is also commonly observed in Suisun Marsh (Tetra Tech 2013). However, it is unknown how the severity (spatial extent, DO concentration, duration, and frequency) of low DO compare to what would be expected under natural conditions. In addition, the impacts of this low DO on habitat quality is unknown, but would depends on both the severity of low DO and how it effects the biota utilizing (or who would otherwise utilize) that habitat. Lastly, if adverse impacts are occurring, the degree to which anthropogenic nutrient loads cause or contribute to those impacts needs to be determined. Given the severe data limitations, limited investigation to date, and the disproportionately high-value of these habitats to biota, current conditions related to low DO in margin habitats emerged as a high priority issue for all subembayments that have substantial areas of shallow margin habitat.

Change scenarios: Many of the same change scenarios that would lead to high biomass and low DO in deep subtidal habitats would similarly affect DO in margin habitats. For example, decreases in SPM concentrations would increase light levels and production rates. Any changes filter-feeding benthos abundance would have an even greater effect on phytoplankton biomass in margin habitats than in deep subtidal areas because of the shallower depth. Reconnection of wetlands and salt ponds through restoration could deliver low DO water or high BOD loads (in the form of reduced compounds or phytoplankton biomass) to sloughs.
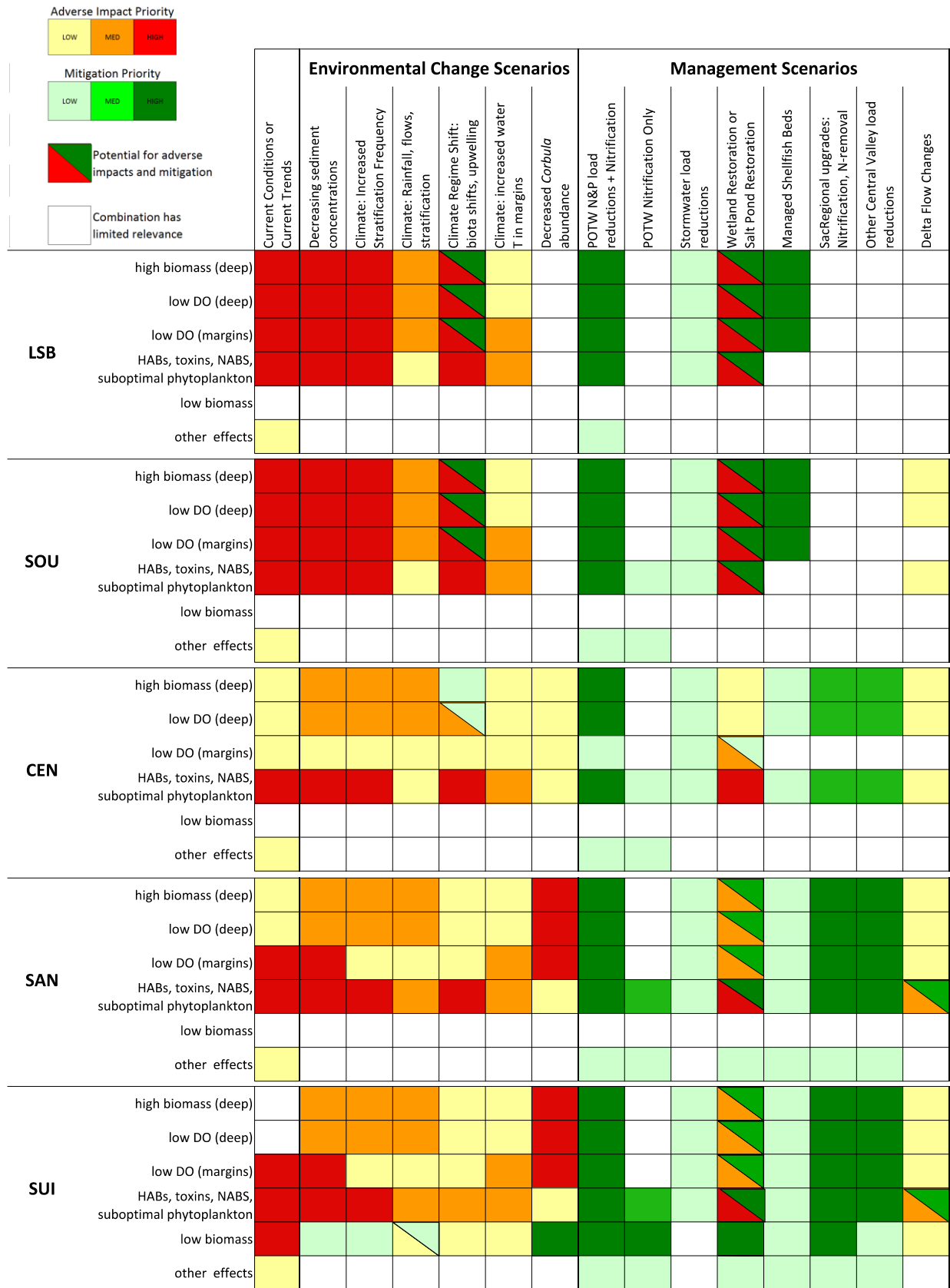
Figure 11.3 Prioritization of subembayment specific response. Columns represent scenarios and rows represent potential ecosystem responses based on the adverse impact categories in Table 3.2

HABs/NABs and phycotoxins

Current Conditions or Current Trends: Recent measurements indicate that HAB toxins, or phycotoxins, occur year-round in all SFB subembayments, plus the Delta (Figure 3.9). The current ecological significance of the observed phycotoxins in SFB is unknown. HAB-forming species are frequently detected throughout the estuary at low abundances (Table 3.1, Figure 3.10), and have been observed in salt ponds undergoing restoration (Thebault et al., 2008). The underlying mechanisms or triggers that determine when a HAB may form, when high levels of phycotoxins are produced, and the relationship with nutrients are among the most poorly understood. Yet the Fall 2004 nuisance red tide bloom in Central Bay and South Bay clearly demonstrated how an undesirable organism can readily take advantage of SFB's high nutrient concentrations when favorable physical conditions allow (Figure 3.11). That bloom was the first of its kind in nearly 40 years of observations, and it remains unknown whether it was a low-probability event that occurred by pure coincidence during that year, or if the underlying factors that contributed to its occurrence in 2004 are related to broader patterns of changing ecosystem response in SFB.

Given the potential magnitude of problems that HABs/NABs can cause when they do occur, the currently poor understanding of the mechanisms that may lead to HAB/NAB blooms and phycotoxin production, and the potential for major blooms that current high nutrient concentrations provide, HABs/NABs and phycotoxins need to be considered among the highest priority issues Bay-wide.

Change Scenarios: Future scenarios that would lead to increased light levels (lower SPM) or longer periods of stratification would favor HABs/NABs through allowing for increased growth rates and fuller utilization of abundant nutrient supplies. In addition, restored salt ponds and wetlands (LSB, South Bay, and San Pablo Bay) have the potential to be HAB and NAB incubators, due to their relatively long residence times, warm water temperatures, high light levels, and abundant nutrients. The potential linkage between large-scale salt pond restoration efforts and increased HAB frequency and elevated toxins need to be examined. Increased water temperatures in margin habitats due to climate change or longer water residence time could also favor HABs/NABs. Lastly, changes in large-scale climate forcings could change – increase or decrease - the seeding-rate of HAB-forming species from the coastal ocean to SFB.

Suboptimal phytoplankton community compositions

HABs/NABs are one category of undesirable shifts in the phytoplankton community. However, other manifestations of nutrient-driven community shifts, such as toward compositions of poor nutritional quality for supporting food webs, have also been proposed. While they are addressed separately in this section, HABs/NABs and other shifts in phytoplankton community compositions are combined in Figure 11.3, and to some degree the knowledge and data gaps related to current and future conditions are similar.

Like HABs and NABs, the combination of factors, including nutrients, that would cause undesirable compositional shifts are poorly understood in SFB. On the one hand, it can be argued that since nutrients seldom limit phytoplankt growth that – from phytoplankton succession viewpoint – nutrients are not a major determinant of which species thrive (Sections 9.2.6 and 9.2.9). On the other hand, it has been hypothesized that nutrients concentrations, forms, and ratios alter phytoplankton community composition through different mechanisms (Glibert 2010;

Glibert et al., 2011; Glibert et al., 2013). If nutrient-related suboptimal phytoplankton composition will be included among the potential adverse impacts that management decisions will aim to address, more investigation is needed into the hypothesized underlying mechanisms and the potential importance of their effects relative to other factors regulating ecosystem response. Mechanisms need to be explored in controlled experiments. Ecosystem-scale observations are also needed, requiring a well-designed and targeted program to collect high-quality data on phytoplankton taxonomy and ancillary data over a wide range of conditions (physical, chemical, and biological).

Low phytoplankton biomass caused by elevated NH_4^+

Current Conditions or Current Trends: In Suisun Bay and the Delta, phytoplankton biomass levels are extremely low and blooms rarely occur (Figure 3.8), and food limitation is considered to be among the factors contributing to fish declines (Baxter et al., 2011). Elevated NH_4^+ concentrations have been hypothesized to play an important role in preventing phytoplankton blooms and maintaining low biomass in Suisun Bay (Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al. 2012). However, there remains uncertainty and disagreement within the scientific community, including among this report's authors, about the mechanism and its importance relative to other processes that regulate biomass accumulation (Section 7.2.3; see also SFEI 2014X). Similar to suboptimal phytoplankton community compositions, if NH_4^+ inhibition will be included among the potential adverse impacts that management decisions will aim to address, more investigation is needed into the hypothesized underlying mechanisms and the potential importance of their effects relative to other factors regulating ecosystem response. Focused experiments are needed to test key aspects of the hypothesis (see SFEI 2014b for further discussion), and modeling is needed to compare the magnitude of any NH_4^+-related effect to other factors that regulate phytoplankton biomass accumulation (e.g., light limitation, clam grazing rate, residence time).

Change Scenarios: Only one of the future scenarios considered in this report could potentially exacerbate low productivity due to elevated NH_4^+ in Suisun Bay: shifts in rainfall patterns that cause increased flows from the Delta which in turn flush phytoplankton from the system faster at a rate faster than they can grow. This future scenario is not currently considered to be among the highest priorities.

Other food web effects

Currently there is limited field or experimental evidence that nutrients adversely affect the food web along additional pathways such as: direct toxicity to copepods (Teh et al., 2011), creating conditions that allowed *Potamocorbula* to become and thereafter remain established in Suisun Bay (Glibert et al., 2011); and changes in individual phytoplankton cell composition that adversely impact copepod populations (Glibert et al. 2013). Similar to suboptimal phytoplankton community composition and NH_4^+ inhibition, if these other nutrient-related food web effects will be included among the potential adverse impacts that management decisions will aim to address, more investigation is needed into the hypothesized underlying mechanisms and the potential importance of their effects relative to other factors regulating ecosystem response. Compared to adverse impacts, at this point were not considered to be among the current highest priorities issues.

11.3 Scenarios that could prevent or mitigate adverse impacts

Scenarios under which nutrient-related adverse impacts could be prevented or mitigated are discussed below, organized by scenarios (as opposed to Section 2's organization around adverse impact pathways)

N and P load reductions from POTWs discharging directly to SFB subembayments

Since POTWs are responsible for ~65% of the nutrients loads entering SFB (Bay-wide, annual average; Figure 6.2), reducing POTW N and P loads is an obvious management scenario to explore. Although some POTWs currently perform nitrification prior to discharge, and several carry out advanced treatment that removes a portion of N and P, most SFB POTWs do not perform nutrient removal. Substantial reductions in POTW N and P loads can be achieved with conventional, albeit still expensive, treatment upgrades (N: 2-5 fold decrease; P: >10 fold decrease; Table 6.1). If nutrient load reductions are deemed necessary, the key challenges will be to determine how much removal is necessary to protect ecosystem health, and to identify the optimal approach for achieving those reductions (including potentially through nutrient trading between POTWs), since costs could differ by billions of dollars among options.

At present, DIN and o-PO$_4$ seldom limit phytoplankton growth in most deep subtidal habitats of SFB and during most times of the year. Therefore, reducing POTW nutrient loads would be unlikely to result in substantially-decreased phytoplankton production - at least in deep subtidal habitats- unless the decreases are very large (e.g., 5-10 fold reduction).

Decreasing POTW nutrient loads would, however, cap phytoplankton production (and biomass) and DO deficits at levels lower than today's potential maxima by decreasing the amount of DIN and o-PO$_4$ available for phytoplankton growth. To the extent that HAB/NAB frequency, or suboptimal phytoplankton composition, are influenced by high nutrients or highly altered nutrient ratios, POTW load reductions would also mitigate these impacts. Direct POTW nutrient load reductions are discussed below for each subembayment. As noted in Section 6.4, this segmentation greatly oversimplifies hydrodynamics and nutrient cycling, but remains instructive for a qualitative discussion.

LSB and South Bay: POTWs are the dominant external sources of DIN and o-PO$_4$ to LSB and South Bay (Figure 6.2; SFEI 2014a). Reducing POTW loads would therefore substantially reduce total subembayment-scale nutrient inputs to LSB and South Bay. The San Jose wastewater treatment has already reduced its N and P loads by ~40% and ~10-fold, respectively, through treatment upgrades in the mid-1990s (SFEI 2014a,c). However, LSB has the smallest volume and slowest net flushing rate of all SFB's subembayments, allowing N and P to accumulate to higher concentrations.

The effects of load reductions may differ between deep subtidal habitats. For deep subtidal habitats in LSB and South Bay, while moderate POTW load reductions may not result in phytoplankton biomass reductions during much of the year, load reductions would create a lower-level cap on phytoplankton production and biomass. Given that the efficiency with which nutrients have been converted to biomass in South Bay and Lower South Bay has increased over the past 10-20 years (Figure 3.5 and 3.6), this may be an important consideration for preventing future potential adverse impacts. Although DO generally remains above 5 mg/L in deep subtidal habitats, recent observations suggest that DO does approaches, and occasionally dips below, 5

mg/L in LSB deep subtidal areas. If such conditions are deemed to be problematic, POTW load reductions could mitigate that impact. In addition, load reductions would presumably (depending on the decrease) have an effect on episodic major bloom events like that depicted in Figure 7.5, to the extent that such events are considered problematic. Similarly, decreased nutrient loads could help cap the magnitude of episodic HAB/NAB events. For these latter two examples, the frequency with which such events occur compared to some "acceptable frequency" (a regulatory decision) would need to be considered in determining the benefit of load reductions.

The situation may be different in shallow margin habitats. The limited data from sloughs rimming LSB indicate that DO concentrations do frequently fall well below 5 mg/L at some locations (Figure 3.14; SFEI 2014c). Based on the conceptual model, it is reasonable to hypothesize that POTW-derived nutrients contribute to low DO in shallow margin habitats, and that POTW load reductions would decrease the severity of those events (spatial extent, DO deficit, frequency, duration). At the same time, multiple factors may contribute to low DO in sloughs, including organic matter entering from adjacent watersheds, and periodic naturally-low DO; therefore, the contribution of anthropogenic nutrients to low DO still needs to be determined. The extent to which low DO in margin habitats is having adverse impacts depends to a large degree on whether it is impacting biota that utilize that habitat (other potential impacts include odor problem from sulfide production). Data on benthos and pelagic macrobiota abundances in margin habitats are extremely limited. In addition there needs to be a systematic analysis of DO tolerances of key organisms.

Suisun and San Pablo Bays: Evaluating the relative importance of direct POTW load reductions to Suisun Bay and San Pablo Bay is less straightforward than for LSB and South Bay. Suisun Bay sizable loads from POTWs discharging directly to Suisun Bay; however it also receives large, seasonally varying NH_4^+, NO_3^-, and o-PO_4 loads from the Delta (Figure 6.3). San Pablo Bay in turn receives seasonally varying loads from Suisun Bay plus the Delta (Figure 6.3). Therefore, an evaluation of the effect that reduced direct POTW loads to Suisun Bay will have on ambient conditions within Suisun Bay needs to consider magnitudes of upstream loads. The planned ~65% N load reductions from Sacramento Regional County Sanitation District (Regional San), which should go on-line within 10 years, are expected to have a major influence on DIN loads that enter Suisun Bay from the Delta (see Figure 6.3; planned decrease at Regional San ~ 10,000 kg d^{-1}). After those reductions, direct POTW loads to Suisun Bay will represent a much larger portion of the total load, at least during low-flow months. The extent to which direct POTW loads to Suisun would mitigate adverse impacts will also depend on the time of year and the adverse impact pathway and nutrient forms that are most concerning (i.e, Figure 3.1). If, for example, the goal is to achieve reduced ambient NH_4^+ concentrations, upgraded treatment at CCCSD could be impactful, since it discharges ~4000 kg d^{-1} NH_4^+ to Suisun, which would be the largest external NH_4^+ source once Regional San's loads are cut. However, if cutting DIN concentrations is the goal, initial estimates suggest that Delta loads will remain a non-trivial contributor, especially during winter and spring, even after Regional San's loads decrease (Figure 6.3; Regional San's current DIN load is ~15000 kg/d, indicating there is a seasonally varying additional source of 5000-20000 kg/d).

Central Bay: Assessing the potential effectiveness of load reductions from Central Bay POTWs on Central Bay conditions is more complex. Central Bay receives direct POTW loads and is the

ultimate recipient of loads that enter northern and southern subembayments. A detailed modeling analysis would be needed to determine the relative contribution of loads from different sources. Coastal upwelling and exchange flows through the Golden Gate can carry oceanic-source NO_3^- and o-PO_4 into Central Bay. However, while upwelling-related loads have the potential to be large under some conditions, on average Central Bay is expected to be a net exporter of N and P to the coastal ocean (Largier and Stacey, 2014).

Nitrification of POTW effluent
Unlike reducing N and P loads from POTWs (Section 11.3.1), nitrification of POTW effluent alone does not decrease nutrient loads, but instead changes the predominant N form from NH_4^+ to NO_3^-. However, to the extent that elevated NH_4^+ concentrations favor HABs/NABs, cause shifts in phytoplankton community composition, or inhibit primary production, nitrification of POTW effluent has the potential to mitigate these adverse impacts.

South Bay and Central Bay: POTWs discharging to South Bay and Central Bay release N primarily in the form of NH_4^+. Thus nitrifying effluent prior to discharge would substantially reduce NH_4^+ loads. The benefit of nitrification prior to discharge needs to be weighed relative to what appears to be fairly efficient *in situ* nitrification, as evidenced by NO_3^- being the major DIN form in these subembayments despite them receiving primarily NH_4^+ loads. In addition, the importance of *in situ* NH_4^+ production (release from sediments, OM matter mineralization in the water column) needs to be considered.

Lower South Bay: All POTWs in LSB have been performing nitrification since the 1980s, although nitrification efficiency at one of those POTWs (Sunnyvale) varies seasonally. So this scenario is not particularly relevant in LSB. Interestingly, though, LSB has the second highest NH_4^+ concentrations Bay-wide (Figure 6.3). Much of the observed NH_4^+ likely comes from organic matter mineralization within LSB. This suggests that nontrivial baseline NH_4^+ concentrations could continue in other subembayments after external NH_4^+ inputs cease. Note, however, that the influence of *in situ* NH_4^+ production on ambient water column concentrations may be most pronounced in LSB because of its shallow bathymetry, which causes sediment processes to have larger effects on water column concentrations.

Suisun Bay: Upgrading Suisun POTWs to include nitrification would likely have a substantial impact on ambient NH_4^+ concentrations in Suisun Bay. Suisun Bay and San Pablo Bay receive large seasonally-varying NH_4^+ loads from the Delta, much of which originates from Regional San's discharge. In evaluating the potential environmental effectiveness of upgrading Suisun POTWs to include nitrification, the seasonally-varying magnitudes of Delta NH_4^+ loads need to be considered, as do planned decreases in Regional San's NH_4^+ loads. Under current loading conditions, direct POTW discharges to Suisun Bay are the major NH_4^+ source during dry months (Figure 6.2). Regional San's NH_4^+ loads will be cut to near zero within 10 years. At that time, POTWs discharging directly to Suisun Bay would be the primary NH_4^+ source, other than NH_4^+ produced *in situ* with Suisun Bay or within the Delta and Sacramento River and transported into Suisun Bay. *In situ* nitrification appears to play an important role in shaping ambient NH_4^+ concentrations in Suisun Bay during summer/fall months (Section 6.4; SFEI, 2014b). In evaluating the benefit of upgrading POTWs to nitrification alone (i.e., no N or P removal), the incremental benefit achieved relative to *in situ* nitrification may need to be considered.

Stormwater load reductions

Stormwater and flow from perennial streams that drain directly to SFB deliver seasonally-varying N and P loads to the system. Only rough estimates of those loads are available at this point. At the subembayment scale, stormwater N and P loads have the potential to contribute substantially to total nutrient loads in Suisun Bay and San Pablo Bay during the wet season (Figure 6.2; SFEI 2014a), and are of lesser importance in other subembayments. Although more work is needed to better constrain loads from stormwater and perennial streams, it seems unlikely that stormwater N and P loads would rival POTW loads at the subcatchment scale unless the current stormwater load estimates substantially underestimate actual loads. In calculating the stormwater loads, only inorganic NH_4^+, NO_3^-, and o-PO_4. Recent stormwater monitoring data suggests that organic N and non-o-PO_4 forms of P commonly comprise more than 50% of total N and P (SFEI 2014d). At the same time, a portion of the organic-N and particle-complexed P pool would be less bioavailable than DIN and DIP, and would be only slowly converted to bioavailable forms. In summary, it is possible that subembayment-scale stormwater loads could be higher than initially estimated and may warrant further examination. For LSB, South Bay, Central Bay, and (to a lesser extent) Suisun Bay, even if stormwater loads were twice as large, their contribution to N loads would remain relatively small compared to POTW loads; however, stormwater P loads could prove non-trivial. Stormwater N and P cannot be discounted in San Pablo Bay.

The discussion of stormwater loads above was focused primarily on their subembayments-scale importance. Stormwater and perennial stream N and P loads have the potential to be more important in shallow margin habitats than they appear to be at the subembayment scale, and a more spatially-explicit evaluation may of their importance may be warranted.

Changes in grazer abundance due to climate forcings or other factors

In some SFB subembayments, grazing plays an important role in limiting phytoplankton biomass accumulation. Cloern et al. (2007) argue that a loss of benthic grazers due to a shift in the Pacific Decadal Oscillation (PDO) could be responsible for much of the increase in phytoplankton biomass in South Bay and LSB (Figure 7.10). A shift in the PDO back to pre-1998 conditions would presumably allow benthic grazers to repopulate South Bay and Lower South Bay, and return phytoplankton biomass to lower levels. On the other hand, a decline in *Potamocorbula* in Suisun Bay due to disease or other factors would eliminate a major sink for phytoplankton biomass, and allow for large blooms to return and better support the food web.

Wetland and salt pond restoration

Wetland and salt pond restoration efforts around the Bay's margins have the potential to reduce N (and to a lesser degree P) concentrations and potentially play a major role in an integrated nutrient management strategy. Denitrification (or annamox) converts NO_3^- to N_2 gas, thus serving as a true N sink. High denitrification rates can occur in wetlands. However, denitrification rates vary over a wide range, with strong dependence on temperature and other conditions (e.g., amount of labile organic matter in the sediments). Furthermore, sufficient hydraulic exchange needs to occur between the nitrate-replete Bay and wetlands to maximize loss by denitrification. This latter limitation could be overcome by moving deep-channel POTW outfalls to locations within wetlands so that they directly discharge effluent to wetlands. However, the issue of seasonally-varying denitrification rates would remain. Wetlands also

retain P. However, unlike N, P has no true sink other than burial, which is inherently inefficient both because of resuspension and recycling.

The largest wetland restoration efforts are currently going forward in LSB and in the southern third of South Bay (Figure 2.1). The scale of planned restoration is such that those areas could potentially serve as major nutrient sinks. Large areas that ring other subembayments are also being considered for wetland restoration. While the use of wetlands to remove nutrients holds promise, its potential to mitigate the adverse impacts of high nutrient loads would needs to be carefully evaluated, initially through modeling work, and subsequently, if warranted, through pilot field studies.

Managed shellfish beds to maintain low phytoplankton biomass

Using managed shellfish beds (e.g., clams, oysters) is an alternative management option being considered in other estuaries to maintain phytoplankton biomass at acceptable levels (Rose et al., 2014). The *Potamocorbula* invasion in Suisun Bay serves as an unfortunate yet compelling example how effective shellfish can be at reducing biomass (Figure 3.8). Managed shellfish beds could be used exclusively as a phytoplankton biomass management tool, or could be a commercial venture that offsets some of the associated maintenance costs. The bed's collective filtration rates would need to be great enough to maintain baseline phytoplankton levels at acceptable levels. The beds would also need to control phytoplankton blooms, which in SFB deep subtidal habitats tend to occur during relatively short windows of time (e.g., 5-10 days). The collective filtration rate of beds would be directly related to shellfish biomass, which would in turn depend on food that had been previously available to support their growth. Pre-growing enough shellfish biomass to handle, for example, a spring bloom would require a well-coordinated program. Shellfish beds would need to be placed in appropriate locations and at appropriate densities so that they could access sufficient phytoplankton. The feasibility and effectiveness of cultivated shellfish beds as a management option could be initially evaluated through basic modeling, and explored through pilot studies thereafter. Given the large amounts of legacy bioaccumulative pollutants (e..g., methyl-Hg, PCBs) in San Francisco Bay, the suitability of shellfish for human consumption or as animal feed needs to be considered. Shellfish are primary consumers and would therefore tend to bioaccumulate lower levels of contaminants than higher trophic level organisms, especially during early life stages when they are steadily increasing their own biomass.

Load decreases from the Central Valley

To the extent that elevated nutrients are having adverse impacts in Suisun Bay along pathways other than those related to high-biomass/low-DO, reductions in the loads entering Suisun Bay from the Delta would have the potential to substantially mitigate these adverse impacts. However, there remains uncertainty and disagreement within the scientific community about several of the hypothesized mechanisms for nutrient-related adverse impacts (NH_4^+ inhibition, phytoplankton community composition, elevated NH_4^+ or N:P allowing Potamocorbula to become and remain established; effects on higher trophic levels of nutrient-induced changes in the N:P of individual phytoplankton cells) and their importance relative to other processes that regulate biomass accumulation. If these hypothesized mechanisms will be included among the potential adverse impacts that management decisions will aim to address, more investigation is needed into the hypothesized underlying mechanisms and the potential importance of their effects relative to other factors regulating ecosystem response.

Delta nutrient loads to SFB influence ambient concentrations most in Suisun Bay and San Pablo Bay. Initial estimates suggest that Delta loads could be the dominant nutrient source to Suisun and San Pablo Bays throughout much of the year (Figure 6.3; SFEI, 2014a,b). Delta loads would also influence ambient concentrations in Central Bay, but likely to a lesser extent than in the up-estuary subembayments. While during very high flows some freshwater from the Delta has been shown to enter South Bay and, less frequently, LSB, the Delta-derived loads likely have relatively low influence there.

Scenarios for load decreases from the Central Valley can be divided into three groups: 1. decreased loads from the Regional San POTW, which is located ~70 km upstream of Suisun Bay along the Sacramento River; 2. reductions from other POTW discharging within the Delta or in upstream watersheds; and 3. reductions in agriculturally-derived loads, originating either within the Delta or within the watersheds drained by the Sacramento or San Joaquin Rivers. As noted earlier, Regional San's current discharge of ~15000 kg d^{-1} DIN, primarily in the form of NH_4^+, travels along the Sacramento River's main stem, and also moves with the river into and through the Delta. During low flow periods considerable nitrification (up to 60%; Parker et al., 2012; SFEI 2014b) and likely some denitrification can occur in transit. The Sacramento River, prior to reaching Regional San's discharge, also carries a large and seasonally varying NO_3^- load, presumably from upstream agriculture loads (Kratzer et al. 2011). The San Joaquin River also delivers large and seasonally varying NO_3^- loads to the Delta (Kratzer et al., 2011), but relatively little NH_4^+. Due to complex flow patterns within the Delta, water withdrawals that alter flow routing, and transformations, losses, and additional loads within the Delta, determining which sources contribute most to loads that eventually enter SFB will be a non-trivial undertaking. That said, it is reasonable to suggest that most of the NH_4^+ load (and some of the NO_3^- due to *in situ* nitrification) appears to originate from Regional San, while other sources, including agriculture, contribute a substantial portion of the NO_3^- load. Recent permit requirements are requiring In response to recent permit requirements, Regional San will nitrify and carry out biological nitrogen removal before discharge, with upgrades implemented by the year 2020. Under this upgraded operation, Regional San will discharge ~5,000 kg d^{-1} NO_3^- and little or no NH_4^+, amounting to a complete shift from NH_4^+ to NO_3^-, and a 2/3 reduction in overall DIN load. The cessation of NH_4^+ loads will represent a considerable reduction in overall NH_4^+ loads to Suisun Bay during much of the year, and will also likely translate into substantial DIN loads to Suisun Bay. The feasibility and effectiveness of agricultural N and P load reductions also need to be considered. Initial estimates indicate that these loads are large during some times of the year (Figure 6.2). Any major reductions in agriculture-sourced loads could therefore have a substantial effect on nutrient concentrations in Suisun and San Pablo Bay. However, achieving those reductions is made more challenging by their nonpoint-source origins. Loads from POTWs that discharge within the Delta are relatively small at the scale of the whole Delta-Suisun system and the loads that enter Suisun. To better understand the effect that load reductions at Regional San will have on nutrient levels in Suisun Bay, nutrient fate and transport within the Delta and Suisun Bay need to be examined through modeling and field studies, since initial mass balance estimates suggest that losses of NH_4^+ and DIN can be substantial (SFEI 2014b, Novick et al., 2014)

11.4 How would San Francisco Bay respond to changes in nutrient loads?
Carstensen et al. (2011) and Duarte et al. (2009) explored multi-decade water quality observations in 6 nutrient-impacted estuaries in Europe and North America over time courses

that included periods of eutrophication and subsequent recovery periods when nutrient loads were reduced through management actions. In all cases they found that the chl-a:nutrient relationship exhibited considerable hysteresis, and the estuaries followed markedly different and slower recovery trajectories in terms of chl-a response than than expected based on the eutrophication trajectories. Duarte et al. (2009) hypothesized that the apparent hysteresis in the chl-a response during the phase when total nitrogen decreased resulted from shifts in baseline conditions over time that made the systems more sensitive to nutrients, and/or "regime shifts" from one relatively stable system state to another. In both cases, they suggest that the altered responsiveness could have been caused or hastened by nutrients themselves or be the result of other physical or biological factors (e.g., invasive species, increased water temperature). Carstensen et al. 2011 observed that the ratio of chl-a:TN actually increased in a consistent manner across the 4 systems they studied, and argued that large-scale changes were the cause (e.g., climate change, or similar types of increased human stress on coastal ecosystems).

Based on observations in other estuaries, it is reasonable to expect that there will be hysteresis in the response:nutrient relationship (e.g., chl-a:TN, HAB-frequency:TN) in SFB during the early stages after any load reductions are implemented. That likelihood needs to be kept in mind when considering incremental management actions and adaptive management to inform next steps. It will also be important to manage expectations of regulators, managers, stakeholders, and the public by communicating the complexities of ecosystems and uncertainties, and foreshadowing the likelihood that responses to management actions may be muted or delayed. It is important to note that, although both Duarte et al (2009) and Carstensen et al. (2011) deliver discouraging news, both studies stress that nutrient load reductions were nonetheless important to have implemented: although conditions may not have improved to the degree originally expected, based on their conceptual models and empirical evidence no action would have led to worsened conditions.

11.5 High priority subembayment-scenario-response combinations

Through evaluating the full range of scenarios summarized in Figure 11.3 (Sections 11.2-11.3), a subset of scenario-subembayment-response combinations emerged as the highest priority issues to address through near-term research and monitoring (e.g., over the next 1-5 years):

Adverse Impact Combinations

1. High biomass leading to low DO or nuisance levels of phytoplankton in LSB and South Bay, based on both current trends and future conditions under several scenarios
2. Low DO, resulting from high phytoplankton biomass, in margin habitats (sloughs, creeks, wetlands, restored salt ponds), under current conditions and potentially exacerbated by several future scenarios.
3. HABs/NABs based on both current conditions/trends and on future conditions under several scenarios, including reconnection of salt ponds, longer stratification, climate regime shift, and climate change.
4. Low phytoplankton biomass in Suisun Bay under current conditions

Mitigation/Prevention Combinations

5. Reductions in nutrient loads from direct POTW discharges, and reduction in nutrient loads from the Delta
6. Reductions in stormwater nutrient loads
7. Other mitigation strategies: wetland treatment and managed shellfish beds

8. Effectiveness of nitrification (at Regional San and Suisun direct POTWs) on NH_4^+ inhibition of primary production.

11.6 Priority science questions

Based on the high priority adverse impact and management scenarios, we identified a set of high-level priority science questions and the types of investigations that are needed to address these questions (Tables 11.3 and 11.4). These questions are not necessarily intended to be an exhaustive list, but rather to serve as a starting point that can be refined as detailed science plans are developed.

Table 11.3 Highest priority adverse impact scenarios, science questions, and types of studies needed to address those 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	Assessment Framework	Technology, cost-benefit analysis
1 High phytoplankton biomass and low DO in LSB and South Bay									
a. What level of phytoplankton biomass (and over what area, for what period of time) would result in adverse impacts in LSB and South Bay habitats?	x	x			x	x		x	
b. 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	x			
c. What is the importance of organic matter produced in margin habitats to biomass and DO budgets in LSB and South Bay deep subtidal habitats?			x		x	x			
d. What will be the response of phytoplankton biomass and DO if suspended sediments continue decreasing at rates similar to the past 20 years? Do adverse impacts become increasingly likely at environmentally-relevant SPM values? Or are adverse impacts unlikely along this pathway under this scenario?			x		x	x			
e. What scenarios could lead to worsened conditions and adverse impacts? - Longer periods of stratification due to salt pond and wetland restoration efforts, higher production/biomass? - Changes in climate patterns, longer periods of stratification, higher T, higher production/biomass? - Salt pond and wetland restoration, greater biomass production in margin habitats that is transported to deep subtidal habitats? - Multiple changes in parallel (lower SPM, longer stratification, biomass from margins, low grazing rates)?		x	x	x	x	x			
f. 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	x			
g. What reductions in nutrient loads are necessary to prevent adverse impacts?			x		x	x			
2 High phytoplankton biomass and low DO in margin habitats									
a. What low DO 'severity' would cause adverse impacts: spatial extent within individual sub-habitats (e.g., %age of slough), DO deficit, frequency, duration? Individual sub-habitats vs. overall condition (e.g., individual slough(s) impacted vs. percentage of total slough kilometers impacted)?	x	x						x	
b. How common (spatially) are low DO occurrences in these habitats? What is the severity of the low DO in each sub-habitat and collectively (within individual sloughs/creeks/salt-ponds, and collectively, what is the spatial extent (e.g., small stretch vs. entire slough), frequency, duration, DO deficit, bottom layer or full water column)?		x	x						

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	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	Assessment Framework	Technology, cost-benefit analysis
c. Are relevant biota adversely impacted by low DO? Field surveys, potentially controlled studies. Avoidance, stress/toxicity, death	x	x	x	x					
d. What mechanisms act to cause the periodicity of low DO, including causing it to develop and dissipate? New organic matter sources (e.g., *in situ* production within sloughs or inputs from adjacent habitats, microphytobenthos vs. phytoplankton), on-going sediment oxygen demand, residence time, stratification, freshwater inputs, tidal exchange		x	x	x	x	x			
e. To what extent do anthropogenic nutrient loads contribute to or cause increased severity (spatial extent, DO deficit, frequency, duration) of low DO?		x		x	x				
f. Based on observed (or modeled) conditions relative to conditions that have adverse impacts, are these habitats (subset or as a whole) adversely impacted by low DO?		x	x		x	x		x	
3. HABs/NABs and phycotoxins									
a. What frequency or magnitude of HABs/NABs or HAB-toxins would be considered to cause adverse impacts?	x	x			x			x	
b. How do the abundances of phycotoxins and the HAB-forming species vary in space and time within the Bay? Have there been detectable changes over time, based on existing data? What are the sources of phycotoxins (in situ production vs. transport into SFB or subembayments)?		x	x	x					
c. What causes/contributes to increased frequency or elevated abundances of HAB/NAB-forming organisms? To what extent do nutrients cause, contribute to, or enable increased abundance/blooms? Seeding rates from the coast, seeding rates from adjacent habitats (including salt ponds), role of physical drivers (T, light, mixing/stratification) and chemical conditions (nutrients) favoring higher *in situ* production specifically of <u>HAB/NAB forming organisms</u>	x		x	x	x	x			
d. What causes/contributes to production of *in situ* phycotoxins production? To what extent do nutrients cause, contribute to, or enable increased phycotoxins production? role of physical drivers (T, light, mixing/stratification) and chemical conditions (nutrients) favoring higher *in situ* production	x		x	x					
e. What future scenarios could increase the frequency or severity of HAB/NAB events or increase phycotoxin abundance? - restoration and reconnection of salt ponds/wetlands? high-light, warm, nutrient-replete incubators? - future water management practices in the Delta (withdrawals, longer residence times) ? - changes in climate patterns? How likely are those changes in the 20-30 yr time horizon?		x	x	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	Assessment Framework	Technology, cost-benefit analysis
h. Based on a comparison of observed conditions and conditions considered to induce adverse impacts, are regions/subembayments/habitats of SFB experiencing HAB/NAB related adverse impacts, or will they in the future?			x					x	
i. What decreases in nutrient loads or ambient nutrient concentrations would decrease adverse impacts, or the risk of adverse impacts, from HABs/NABs?					x	x			
4. Other Nutrient Impact Pathways: Low phytoplankton biomass (NH$_4^+$ inhibition), Suboptimal phytoplankton community composition									
a. What is the underlying mechanism by which NH$_4^+$ slows or inhibits primary production? Characterize NH$_4^+$ concentrations and magnitude of effect. At what NH$_4^+$ concentrations are primary production rates substantially impacted?	x	x		x					
b. 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	x			
c. Are current NH$_4^+$ loads or concentrations adversely impacting biomass levels in Suisun Bay?		x	x		x	x		x	
d. What nutrient load reductions would prevent or mitigate adverse impacts due to NH$_4^+$ inhibition of primary production?					x	x			
e. What constitute optimal, or healthy, phytoplankton assemblages in SFB's subembayments? Conversely, what assemblages would be considered to poorly support desirable food webs?	x	x						x	
f. How have phytoplankton community compositions changed within SFB subembayments over recent years?		x	x						
g. Based on what is known from other systems or from prior experimental/field work (Bay-Delta or elsewhere), what hypothesized mechanisms are most likely to influence phytoplankton community composition in the Bay-Delta, based on ambient conditions (nutrient concentrations, light, temperature, stratification, etc.)? What controlled experiments or observations in SFB are needed to further evaluate these proposed mechanisms in SFB?	x	x							
h. What is the magnitude (or relative importance) of the role that current ambient nutrient concentrations play in shaping phytoplankton community composition?	x	x		x	x	x			
i. What changes to nutrient availability would mitigate or prevent adverse impacts of nutrients on phytoplankton community composition?	x	x		x	x	x			
i. What other adverse impact pathways may require further attention in SFB (aquatic macrophytes, macroalgae, SAV habitat)?	x	x							

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Table 11.4 Highest priority mitigation scenarios, science questions, and types of studies needed to address those 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/Delta	Watershed Modeling:	Assessment Framework	Technology, cost-benefit analysis
5. Reductions in nutrient loads from POTWs and nutrient loads from the Delta									
a. What are the magnitudes of loads from individual POTWs?		x	x						
c. How do internal processes shape nutrient concentration within SFB, how do they vary in space/time: mixing/flushing, nitrification, denitrification, uptake/assimilation, regeneration from sediments, etc.				x	x	x			
b. What are the zones of influence and magnitude of contributions of individual POTWs and Delta loads, and how do these vary seasonally and interannually?					x	x			
d. How do Delta loads to Suisun Bay vary seasonally and interannually? What portions of the loads that enter Suisun Bay from the Delta originate from Regional San, others POTWs? What portions of the loads come from Central Valley agriculture? What are the load contributions from agriculture within the Delta?		x	x		x	x	x		
f. What will Delta loads to Suisun Bay be under future scenarios: restoration, changes to water management practices, changes in agricultural practices?					x	x			
i. Considering areas of influence, zones where impairment may be occurring, and internal processes, what combination of load reductions are needed to mitigate or prevent impairment?					x	x			
g. What is the range of options for achieving various levels of nutrient load reductions from POTWs? What are the costs and multiple benefits (nutrients + other benefits, e.g., recycled water) of individual POTW efforts, and of longer-term integrated sub-regional plans?									x
h. Given the necessary load reductions and cost-benefits, what are the best options for achieving load reductions?									x
6. Reductions in stormwater nutrient loads									
a. Are stormwater nutrient loads potentially important sources to some margin habitats in some subembayments, or at the subembayments scale, and do they warrant further consideration?		x	x		x	x	x		
b. If yes, what are the loads from priority watersheds? What is their contribution to nutrient loads, or organic matter/BOD loads, to margin habitats?		x	x				x		
c. What are the magnitudes of stormwater nutrient contributions to deep subtidal habitats in other subembayments?					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/Delta	Watershed Modeling:	Assessment Framework	Technology, cost-benefit analysis
7. Other mitigation strategies: wetland restoration/treatment and shellfish beds									
a. What is the potential for wetland restoration/treatment to mitigate adverse impacts of nutrients?	x				x	x			
b. What is the potential for managed shellfish beds to mitigate adverse impacts of nutrients?	x				x	x			
b. If wetlands or managed shellfish beds appear to be promising nutrient management options – what do pilot studies, advanced modeling, and economic considerations suggest about their potential to be part of an integrated management program?					x	x			x
8. Influence of nitrification at Regional San and Suisun direct POTWs on NH_4^+ inhibition of primary production or other adverse impacts									
a. What is NH_4^+ fate within the Delta and how does this change as a function of season, flow, etc.?					x	x			
b. What load reductions are necessary to reduce NH_4^+ to ambient concentrations that would not inhibit production or have other adverse impacts?					x	x			

12 Key Observations and Recommendations

12.1 Key observations

1. Changes in SFB's response to nutrient loads over the past decade, combined with the Bay's high nutrient loads and concentrations, justify growing concerns about elevated nutrients.

2. The future trajectory of SFB's response to nutrients is uncertain. One plausible trajectory is that SFB maintains its current level of resistance to the classic effects of high nutrient loads and no further degradation occurs. A second, equally plausible scenario is that SFB's resistance to nutrients continues to decline until adverse impacts become evident. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for future impairment. Any major reductions in loads to SFB will take years-to-decades to implement. Thus, if future problems are to be averted, potential impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed in advance of their onset.

3. By considering current conditions in SFB, trends of changing ecosystem response, and a conceptual model for SFB's response to nutrients, we identified the following highest priority issues:
   a. Determine whether increasing biomass signals future impairment. This issue is most pertinent for Lower South Bay and South Bay.
   b. Characterize/quantify the extent to which excess nutrients contribute now, or may contribute in the future, to the occurrence of HABs/NABs and phycotoxins.
   c. Determine if low DO in shallow habitats causes adverse impacts, and quantify the contribution of excess nutrients to that condition.
   d. Further evaluate other hypotheses for nutrient-related adverse impacts to ecosystem health, including nutrient-induced changes in phytoplankton community composition and ammonium inhibition of primary production. That evaluation – to include data analysis, additional experimentation, or modeling – should assess their potential quantitative importance, and help to determine if they should be considered among the highest priority issues.
   e. Test future scenarios that may lead to worsening conditions through the use of numerical models.
   f. Quantify the contributions of nutrients by sources in different areas of the Bay, considering both their transport and in situ transformations and losses.
   g. Evaluate the potential effectiveness of various nutrient management strategies at mitigating or preventing adverse impacts.

4. Although concern related to changing ecosystem response in SFB is warranted, widespread and severe nutrient-related impacts do not currently appear to be occurring, based on existing sampling locations and parameters commonly measured. This apparent lack of current severe impacts translates into time for conducting investigations to improve understanding of SFB's response to nutrients and allows for sound, science-based management plans to be developed and implemented. That said, the considerable amount of time required to implement any management strategy raises the level of urgency such that work should move forward expeditiously.

5. Given the stakes of no action - and the time required for data collection, analysis, and modeling tools to reach a useable state - work needs to move forward in parallel on implementing multiple aspects of the Nutrient Strategy. A well-coordinated program is needed to maximize the effectiveness and efficiency of this effort. That program needs to integrate seamlessly across what might otherwise be (or become) semi-independent program areas. Specifically, we recommend the following set of highly-integrated program areas:

   a. Monitoring: Develop and implement a sustainably-funded and regionally administered monitoring program that continues routine monitoring, and fills newly-identified data gaps relevant to nutrients;

   b. Modeling: Develop and apply linked hydrodynamic and water quality models to integrate observations, identify critical data gaps (to be addressed through monitoring or experimental studies), quantify processes at the ecosystem scale, and evaluate future scenarios (including management alternatives);

   c. Observational and Experimental Studies: Undertake special studies (field investigations, controlled experiments) to address the highest priority knowledge and data gaps identified in #3; and

   d. Data Synthesis and Interpretation: Analysis of existing and newly collected data (from monitoring and experimental studies), incorporatingmodels, to improve understanding of linkages between nutrients and ecosystem response and to inform the development of an assessment framework.

6. The Delta/Suisun boundary, while an important regulatory boundary, is not meaningful from ecological and loading standpoints. Nutrient loads to and transformations within the Delta exert considerable influence over nutrient loads to and ambient concentrations within Suisun, San Pablo, and Central Bays. Furthermore, the ecology and habitat quality of the Delta and Suisun Bay are tightly coupled. A unified approach – one that spans the Bay-Delta continuum - for evaluating the impacts of nutrients on beneficial uses will best serve both ecosystem health in the Bay-Delta and the information needs of environmental managers.

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 and data gaps to, in a targeted way, inform nutrient management decisions in SFB. The process we followed (outlined in Figure 1.1) consisted of

- Identifying the highest priority scenarios (Section 11) for potential impairment along one or more pathways, and high priority science questions that need to be addressed related to those scenarios (Tables 11.3 and 11.4);

- Prioritizing data or knowledge gaps related to the 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 6.2, 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 6.2, 7.1, 8.1, and 9.1 and Tables 11.3-11.4. 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

Major research and monitoring efforts in San Francisco Bay and the Delta include the USGS research program[10] and the IEP Environmental Monitoring Program (Figure 5.3).[11] The data generated through these programs, and the related interpretations, 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 program designed program to inform nutrient management decisions. Furthermore, future funding of the USGS program is uncertain.

Developing a regionally-administered and sustainably-funded nutrient monitoring program needs to be a major priority. Effort needs to be directed toward developing the institutional and funding frameworks for the program, and developing its primary science goals and activities. 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, there may considerable advantage to achieving some monitoring program goals through fostering close coordination among on-going programs, and augmenting those efforts with additional monitoring. Activities distributed across independent programs need to be well-coordinated, especially in terms of methods, QA/QC, data management and data sharing, synthesis, and reporting.

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

A nutrient 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 goals and data needs may differ considerably from those of the current research and monitoring activities (i.e., USGS, IEP). When evaluating the future program's needs relative to current efforts, particular attention needs to be given to the following issues:

- The optimal distribution of effort and resources among broad monitoring categories (water column vs. benthos, shoals vs. channel, open bay vs. margins, physical/hydrodynamic vs. biological vs. 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.

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

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

For some of these issues, considerable data resources already 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 the necessary spatial and temporal density of sampling). Pilot studies should also be part of planning, to inform which parameters provide important additional information, 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 model, and identifying data/knowledge gaps related to priority scenarios (Tables 6.2, 7.1, 8.1, and 9.1).

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 important insights into the mechanisms that shape SFB's response to nutrients, including physical and biological processes that regulate that response, and how that response has changed over time. Maintaining and building upon this program will be critical for anticipating future changes, and for assessing the effectiveness of any management actions. New parameters may be needed informative, such as size-fractionated chl-a and C:chl-a, organic forms of N and P, 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 assess condition and to improve our quantitative understanding of ecosystem response to nutrients, including the processes that influence phytoplankton blooms, influence oxygen budgets, and regulate nutrient fate. High temporal resolution data will 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), while others are advancing (e.g., nitrate, phosphate, ammonium, phytoplankton counts and identification). Moored sensor systems can telemeter data, allowing for near real-time assessment of conditions. The data from moored sensors are not a substitute for ship-based sampling, but rather provide strongly complementary information about physical and biological processes that influence key water quality parameters (chlorophyll, DO, T, SpC) over time-scales (hours) that are too short to effectively monitor or study through ship-based sampling. While there are currently multiple stations in Suisun Bay and the Delta that measure some nutrient-related parameters, there are only 3 newly-added stations south of the Bay Bridge for measuring chl-a or nutrients (added in September 2013), and few that measure DO and other parameters (T, SpC, turbidity).

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 boat/ship-based transects or with moored sensors, and the best approach will vary depending on the questions 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 AUVs in SFB would be useful for assessing the feasibility and cost effectiveness of this approach, and to inform planning.

R.1.2.4 Coordinated monitoring in shallow subtidal habitats.
Some agencies (e.g., stormwater, wastewater) carry out periodic monitoring in shallow habitats, and several focused 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 systematic monitoring in shallow margin habitats either at the subembayments scale or Bay-wide. Data collection on productivity (e.g., chl-a, light levels) and DO concentrations in select systems would help inform whether adverse impacts are occurring in these systems due to low DO, and help ascertain the causes of low DO. Before embarking on this effort, it would be worthwhile 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 HAB/NAB-forming species, phycotoxins, and phytoplankton community composition in general
Given the prevalence of HAB-forming organisms in the Bay and the frequent detection of phycotoxins Bay-wide, it would be prudent to more closely monitor phytoplankton composition, the occurrence of HAB-forming organisms and phycotoxins within San Francisco Bay. Composition and biovolume data collected for HAB-related work would also support assessment and improved mechanistic understanding of other hypothesized nutrient-related shifts in phytoplankton community composition. The abundance and forms of nutrient are two among many factors that can influence phytoplankton community composition and the occurrence of HABs. The relative contributions of those factors toward causing adverse shifts in composition or HAB occurrences are poorly understood. More frequent (in space and time) analysis of phytoplankton composition and phycotoxins, 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. Flow cytometers and digital imaging tools are also available. These systems - which measure optical properties and capture images of individual cells, and employ image-recognizing software to identify and count phytoplankton down to the species level - 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. 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.[12] 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 been initiated recently that are measuring phycotoxins in SFB (Figure 3.8), and an algal pigment pilot study is underway. 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 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 costly. A pilot study to test the feasibility of using benthic cameras may also be worth considering (alongside traditional sample collection for calibration/validation), 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).

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

R.2. Develop and implement a science plan for SFB that targets the highest priority management and science questions

The size of SFB, and the complexity and diversity of its nutrient-response issues, create a situation in which there are numerous 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 a science plan that: identifies the highest priority management issues, and associated science questions; and identifies the sets of studies and data collection/monitoring needs that efficiently target those questions. In some cases, the management issues, science questions, data gaps, and studies may be similar Bay-wide. In other cases, the science questions or data gaps may be subembayment- or habitat-specific. The science questions listed in Tables 11.3-11.4 and the recommendations in this section could serve as a starting point in what would be an iterative Science Plan development 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 scientific studies and monitoring on addressing the most critical knowledge and data gaps.

R.3. Develop hydrodynamic, nutrient cycling, and ecosystem response models

Tables 11.3-11.4 illustrate that modeling will play a central role in addressing a wide range of science questions. Models can also be used to prioritize data collection needs. While there are multiple hydrodynamic models available for SFB, there are currently no integrated hydrodynamic-phytoplankton-nutrient models. Considerable progress could be made toward addressing several important science questions through using "simplified-domain" models that are built upon simplified (spatially-aggregated), but still accurate, hydrodynamics. Potential applications of these simplified domain models include (not an exhaustive list):

R.3.1 Quantitative analysis of nutrient budgets (including losses/transformations of nutrients);

R.3.2 Quantifying the relative importance of major processes that control primary production in Suisun Bay (light, clams, flushing, NH_4^+ inhibition), and explore which factors may explain the changes in phytoplankton biomass in South Bay over the past ~20 years.

R.3.3 Performing sensitivity/uncertainty analysis, and identifying highest priority monitoring activities, process level studies, or rate measurements to minimize model uncertainty.

R.3.4 Forecasting ecosystem response under future scenarios, and narrowing the list of high priority scenarios;

In developing such models, there is a benefit to "starting simple", and adding complexity as needed. LSB/South Bay and South Bay could serve as good initial focus areas for basic model development and application, because of the abundance of data for those systems and since these two subembayments are where concerns about adverse impacts from nutrients 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 explore several important issues, including:

R.3.5   Determine the zones of influence of individual POTWs under a range of hydrodynamic forcings and estimated transformations/losses

R.3.6   Test future scenarios under which adverse impacts may develop Bay-wide or in individual subembayments

R.3.7   Evaluate the effectiveness of different nutrient control strategies for achieving desired reductions in ambient concentrations as a function of space and time.

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   Quantify the importance of net nutrient loads from the coastal ocean to SFB under a range of commonly-occurring forcing scenarios, and 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 11.3-11.4, viewed alongside the data/knowledge gap priorities in Tables 6.2, 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.3.9*). An overview of special study priorities is provided below; however, the reader is also referred to the Tables 11.3-11.4, 6.2, 7.1, 8.1, and 9.1.

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.

Productivity of phytoplankton and MPB

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, assess the variability or uncertainty in the Cole and Cloern (1987) productivity relationship due to factors such as different phytoplankton assemblages, temperature, light levels, etc.

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 O₂

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 Monitoring and targeted mechanistic studies of DO in shallow margin habitats to assess the severity of low DO (concentration, spatial extent, frequency, duration).

R.4.9 In cooperation with other efforts or as special nutrient-related studies, determine the degree to which low DO in margin habitats (or in open water areas of some areas of the Bay, specifically LSB) adversely impact biota. To a certain degree, this work could be carried out based on existing data from other studies on DO tolerances of key organisms. Field surveys of fish or benthos abundance may also be warranted.

R.4.10 Through field experiments and modeling, quantify the degree to which anthropogenic nutrients contribute to occurrences of low DO.

HABs, toxins, and phytoplankton community composition

R.4.12 Rigorous analysis of existing phytoplankton community composition data – for HAB-forming species and composition more broadly – to test qualitative and quantitative agreement with various conceptual models, and refine those conceptual models as needed.

R.4.13 Field studies (collecting phytoplankton composition data at higher temporal or spatial resolution) to test mechanisms of HAB development and 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 mixed cultures and monocultures from SFB, that mechanistically explore the interactive effects of nutrient availability (including variability in concentrations and forms), light, and temperature on HAB/NAB development and phycotoxins production, or other shifts toward assemblages that poorly support food webs. 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. Such information is also essential for identifying nutrient concentrations or loads that would decrease the risk of HAB occurrences or other adverse assemblage shifts.

R.4.16 Apply the information from R.4.1.5 within 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).

12.2.2 Grand Challenges

During the conceptual model development and identification of knowledge gaps, data gaps, and monitoring needs, four so-called "Grand Challenges" emerged related to understanding and managing SFB ecosystem health. While there is overlap between the underlying management issues that motivated the more specific recommendations above and those that motivated the Grand Challenges, the Grand Challenges represent a somewhat different, more holistic perspective or framework for considering science and data collection needs. 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.

Grand Challenge 1: What do we need to know in 10-20 yrs to make improved decisions related to water quality management or ecosystem health, including those related to nutrients? 1-2 decades is approximately the time scale over which large capital improvement projects are planned and implemented. 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 (Figure 3.4). 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 lead to improved or worsened condition?

Grand Challenge #2: The northern estuary is poised to experience major changes due to management actions and environmental change. Anticipated changes include: nitrification and nutrient load reductions at Sac Regional wastewater treatment plant; numerous large scale restoration projects and changes in water management in the Delta; 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?

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 2.1), it is reasonable to expect that proposed restorations along the margins will have measurable impacts on water quality and ecological health in the open Bay. 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 these higher trophic level indicators of ecosystem health. Those changes could also encourage more denitrification and decreased N within the Bay, which could be considered within integrated nutrient management plans. As discussed earlier, there may also be unintended and undesirable consequences, including: restored/reconnected salt ponds acting as incubators for HAB-forming phytoplankton species; exceedingly high primary production rates and high biomass, causing periodic low DO in wetlands and sloughs; and increased duration of stratification due to dampening of tidal mixing energy. What hypotheses of adverse impacts need to be tested, as part of restoration planning, so that the risks of severe unintended consequences can be minimized?

Grand Challenge #4: Similar to Grand Challenges 1-3, what baseline observational data is needed to detect climate-related changes in habitat quality in SFB and to disentangle them from other anthropogenic drivers? What types of modeling simulations should be done to anticipate effects? The CASCaDE II[13] project is exploring these issues, largely focused in the Delta. Similar studies may be warranted in the Bay.

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

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