

San Francisco Bay Nutrient Conceptual Model

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Synopsis

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. SFB receives high nutrient loads from treated wastewater effluent, agricultural runoff, and stormwater. 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.

Scientific studies and monitoring over the last 40 years have played a critical role in discovering and characterizing the factors that have historically given SFB resistance to the adverse impacts of high nutrient loads: high turbidity, strong tidal mixing, and abundant filter-feeding clam populations, all of which have limited the efficiency with which DIN and DIP are converted into phytoplankton biomass and severely limited food web productivity in the northern estuary.

However, recent observations indicate that SFB's resistance to high nutrient loads is weakening, and that conditions are trending toward increased productivity and potential impairment along multiple pathways. 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; an unprecedented red tide bloom in Fall 2004; and studies suggesting that the chemical forms of nitrogen can influence phytoplankton productivity and composition.

The main goals of this report are: 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 impairment.

The report's main observations and recommendations include:

- Changes in the SFB ecosystem over the past decade, combined with the Bay's high nutrient loads and concentrations, justify growing concerns about elevated nutrients.
- The future trajectory for SFB is uncertain. One plausible scenario is that SFB's resilience will be maintained and no further degradation will occur. A second, equally plausible scenario is that SFB's resilience will continue to decline until moderate to severe impairment occurs in some subembayments. The highly elevated DIN and DIP concentrations Bay-wide provide the potential for such impairments to develop.
- Although evidence is consistent with conditions in SFB moving toward a critical juncture, widespread impairment is not currently occurring. One exception may be changes in phytoplankton community composition and occurrences of harmful algal blooms that may be related to nutrients. The degree to which impairment is occurring along these pathways – needs to be a major and early focus of investigation and monitoring.
- Thus, in either case, there is both the need and the opportunity to conduct investigations to improve our understanding of the system, and for well-informed, science-based management plans to be developed and implemented. That said, the time that would be

required to effectively implement any management strategy (decades) raises the level of urgency such that work should move forward expeditiously.

- The collaborative approach that regulators, dischargers, and stakeholders have developed in the Nutrient Strategy is a forward-thinking and proactive approach, and lays out a logical path and reasonable timeline.
- Given the stakes of no action, and the time required for data collection, analysis, and tools to reach a useable state, work must move forward on multiple fronts of the Nutrient Strategy simultaneously.
- More specifically, effort should be directed simultaneously toward synthesis of existing data, development of nutrient/phytoplankton models, development and implementation of a regionally-funded monitoring program, and undertaking critical field or experimental studies.
- Implementation and coordination of these efforts will significantly improve the knowledge base from which decision-makers can:
 - Base decisions on the changing status of water quality and living resources in SFB as their responses to nutrient pollution continue to evolve;
 - Establish and revise approaches and criteria for assessing impairments based on latest understanding of the contributing factors;
 - Further develop and understand future scenarios within which SFB subembayments may proceed down one or more pathways toward impairment;
 - Where necessary, improve scientific understanding of the underlying mechanisms to better assess the potential for impairment, and the linkages between loads and response;
 - Identify management strategies that are both environmentally-effective and cost-effective for mitigating or preventing impairment.

NOTE: This draft (April 30 2013) has not yet been reviewed by the full technical team that helped develop it. That group will be reviewing the content over the subsequent 1-2 months as the final draft is completed.

Executive Summary

[Will be completed after main document finalized.]

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1 **1 Introduction**

2 San Francisco Bay (SFB) has long been recognized as a nutrient-enriched estuary, but one that
3 has exhibited resistance to some of the classic symptoms of nutrient overenrichment, such as
4 high phytoplankton biomass and low dissolved oxygen. However, recent observations suggest
5 that SFB's resistance to high nutrient loads is weakening. The combination of high nutrient
6 concentrations and changes in environmental factors that regulate SFB's response to nutrients
7 has generated concern about whether the Bay is trending toward, or may already be
8 experiencing, nutrient-related impairment.

9
10 The main goals of this report are:

- 11 i. Develop conceptual models connecting nutrient loads and cycling with ecosystem response
12 in SFB;
- 13 ii. Apply those conceptual models to identify scenarios under which nutrient-related
14 impairment may occur in SFB's subembayments, and management approaches that may
15 prevent or mitigate impairment; and
- 16 iii. Identify knowledge and data gaps that need to be addressed in order for well-informed,
17 science-based decisions to be made about how to best manage nutrient loads.

18
19 The approach and structure of the report are summarized in Figure 1.1. It is expected that the
20 conceptual model and this report's recommendations will be updated and refined as nutrient
21 work proceeds in SFB and new information becomes available.

22
23 This report was funded by the San Francisco Bay Regional Monitoring Program.

24 **2. Background**

25 **2.1 San Francisco Bay Nutrient Strategy**

26 SFB receives high nutrient loads from 42 wastewater treatment plants servicing the Bay Area's
27 7.2 million people (Figure 2.1.A). Nutrients also enter SFB via stormwater runoff from the
28 densely populated watersheds that surround SFB (Figure 2.1.B). Flows from the Sacramento and
29 San Joaquin Rivers - which drain ~40% of California, including the agriculture-dominated areas
30 of the Central Valley - also deliver large nutrient loads, and enter the northern estuary through
31 the Sacramento/San Joaquin Delta. Dissolved inorganic nitrogen (DIN) and phosphorus (DIP)
32 are essential nutrients for primary production that supports SFB food webs. However DIN and
33 DIP concentrations in SFB greatly exceed those in other US estuaries where water quality has
34 been impaired by nutrient pollution (Cloern and Jassby, 2012).

35
36 SFB has long been considered relatively immune to its high nutrient loads. For example, the
37 original San Francisco Bay Regional Basin Plan from 1975 stated that limited treatment for
38 nutrients was necessary because the system was considered to be light limited (SFBRWQCB,
39 1975). Scientific studies and monitoring over the last 40 years have played a critical in
40 discovering and characterizing the factors that have given SFB its resistance to the adverse
41 impacts of high nutrient loads. These include high turbidity, strong tidal mixing, and abundant

42 filter-feeding clam populations, all of which limit the efficiency with which dissolved inorganic
43 nitrogen (DIN) and phosphorous (DIP) are converted into phytoplankton biomass.

44
45 However, recent studies indicate that the response to nutrients in SFB's subembayments is
46 changing. These observations include: a 3-fold increase in summer-fall phytoplankton biomass
47 in South Bay since 1999; frequent detections in SFB of algal species that have been shown in
48 other nutrient-rich estuaries to form harmful blooms; an unprecedented red tide bloom in Fall
49 2004; and studies suggesting that the chemical forms of nitrogen can influence phytoplankton
50 productivity and composition.

51
52 To address growing concerns about SFB's changing response to nutrient loads, the San Francisco
53 Bay Regional Water Quality Control Board (Water Board) worked collaboratively with
54 stakeholders to develop the San Francisco Bay Nutrient Management Strategy¹, which lays out
55 an approach for gathering and applying information to inform management decisions. The
56 overarching management questions identified in the Nutrient Management Strategy include:

- 57 ○ Is SFB currently experiencing nutrient-related impairment, or are there signs of future
58 impairment?
- 59 ○ What are appropriate guidelines for identifying a problem?
- 60 ○ What nutrient loads can the Bay assimilate without impairment of beneficial uses?
- 61 ○ What are the contributions of different loading pathways, and how does their importance
62 vary as a function of space and time?

63
64 The indications of changing SFB response to nutrients have come to the fore at a time when the
65 availability of resources to continue assessing the Bay's condition is uncertain. Since 1969, a
66 USGS research program has supported water-quality sampling in the San Francisco Bay. This
67 USGS program collects monthly samples between the South Bay and the lower Sacramento
68 River to measure salinity, temperature, turbidity, suspended sediments, nutrients, dissolved
69 oxygen and chlorophyll a. The USGS data, along with sampling conducted by the Interagency
70 Ecological Program, provide coverage for the entire San Francisco Bay –Delta system (Figure
71 2.2). The San Francisco Bay Regional Monitoring Program (RMP) has no independent nutrient-
72 related monitoring program, but instead contributes approximately 20% of the USGS data
73 collection cost. The Nutrient Strategy also highlights the urgent need to lay the groundwork for a
74 regionally-supported, long-term monitoring program to provide the information that is most
75 needed to support management decisions in the Bay.

76
77 The timing also coincides with a major state-wide initiative, led by the California State Water
78 Resources Control Board (State Water Board), for developing nutrient water quality objectives
79 for the State's surface waters, using an approach known as the Nutrient Numeric Endpoint
80 (NNE) framework. The NNE framework establishes a suite of numeric endpoints based on the
81 ecological response of a waterbody to nutrient over-enrichment and eutrophication (e.g.
82 excessive algal blooms, decreased dissolved oxygen). In addition to numeric endpoints for
83 response indicators, the NNE framework will include models that link the response indicators to

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

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http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/est

84 nutrient loads and other management controls. The NNE framework is intended to serve as
85 numeric guidance to translate narrative water quality objectives.
86 Since San Francisco Bay is California’s largest estuary, it is a primary focus of a state-wide
87 effort to develop NNEs for estuaries. As part of the state-wide effort, the Water Board is working
88 with regional stakeholders and with State Water Board to develop an NNE framework specific to
89 SFB. This effort was initiated by a literature review and data gaps analysis to recommend
90 indicators to assess eutrophication and other adverse effects of nutrient overenrichment in San
91 Francisco Bay (McKee et al., 2011)². McKee et al. (2011) evaluated a number of potential for
92 several habitat types based on the following criteria:

- 93 • Indicators should have well-documented links to estuarine beneficial uses, ideally at
94 multiple trophic levels
- 95 • Indicators should have a predictive relationship with nutrient and hydrodynamic drivers
96 that can be easily observed with empirical data or a model
- 97 • Indicators should have a scientifically sound and practical measurement process that is
98 reliable in a variety of habitats and at a variety of timescales
- 99 • Indicators must be able to show a trend towards increasing or/and decreasing beneficial use
100 impairment due to nutrients

101 The report recommended focusing on subtidal habitats initially, and proposed the following
102 primary indicators of beneficial use impairment by nutrients:

- 103 i) phytoplankton biomass
- 104 ii) phytoplankton composition;
- 105 iii) dissolved oxygen, and;
- 106 iv) algal toxin concentrations.

107
108 In addition, ‘supporting indicators’ and ‘co-factors’ were identified, and are summarized in Table
109 2.1. Supporting indicators provide additional lines of evidence for trends in primary indicators,
110 co-factors are essential information to help interpret and analyze trends in primary or supporting
111 indicators.

112 **2.2 Audience, anticipated use, and approach**

113 This conceptual model report was identified as an early priority in the Nutrient Strategy
114 implementation to address information needs of technically-oriented decision makers and
115 stakeholders involved with the process of determining whether nutrient-related impairment of
116 SFB’s beneficial uses is occurring or is likely to occur in the future, and, if so, what regulatory
117 and control actions are needed to mitigate or prevent that impairment. With that audience in
118 mind, the report assumes a certain baseline familiarity with SFB as well as some basic
119 understanding of biology, nutrient cycling, biogeochemistry, and physical processes in estuaries.
120 The report was developed collaboratively with a technical team consisting of regional scientists
121 whose areas of expertise cover a range of relevant disciplines and much of whose work has
122 focused on San Francisco Bay (Table 2.2).

123

2

http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/planningtmdls/amendments/estuarineNNE/644_SFBayNNE_LitReview%20Final.pdf

124 [NOTE: This draft (April 30 2013) has not yet been reviewed by the full technical team that
125 helped develop it. That group will be reviewing the content over the subsequent 1-2 months as
126 the final draft is completed.]

127 The main anticipated use of this report is for it to provide an overarching conceptual framework
128 of nutrient cycling and ecosystem response to nutrients that can be used to

129 ○ Inform the development of approaches for assessing nutrient-related impairment in
130 habitats within SFB's subembayments;

131 ○ Through identifying major conceptual and data gaps, inform and help prioritize the types
132 of special studies, monitoring, and modeling that are needed to inform management
133 decisions.

134
135 Figure 1.1 summarizes the approach followed. The report begins by identifying what a nutrient-
136 related problem would look like in SFB. It then explores recent observations in SFB that suggest
137 that ecosystem response to nutrients is changing (Section 3). Focused by this problem statement
138 on beneficial use impairment, and how it might be measured or observed, the conceptual model
139 was developed as a series of linked modules extending from nutrient loads and cycling to
140 ecosystem response (Sections 5-10). The conceptual models were then used to identify scenarios
141 under which impairment may occur, and scenarios under which impairment may be mitigated or
142 prevented (Section 11). Section 12 presents major observations and recommended science
143 priorities for developing the necessary understanding to inform management decisions. The
144 report draws from several decades of research and monitoring in San Francisco Bay by USGS³,
145 multiple academic institutions, and the Interagency Ecological Program⁴. It also builds upon the
146 recent NNE report (McKee et al., 2011).

147
148 Regions of SFB behave quite differently with respect to nutrient cycling and ecosystem response
149 due to a combination physical, chemical, and biological factors (discussed in Sections 5-9). For
150 ease of discussion about spatial trends, in this report SFB was divided into 5 subembayments, as
151 depicted in Figure 2.1: Suisun Bay, San Pablo Bay, Central Bay, South Bay and Lower South
152 Bay (LSB). These subembayment boundaries were chosen based on geographic features and not
153 necessarily hydrodynamic features. This set of boundaries is one of several sets of boundaries
154 that could be used, and happen to coincide with those defined by the Water Board in the San
155 Francisco Bay Basin Plan (although we use different names for the subembayments south of the
156 Bay Bridge). It would be a major oversimplification to suggest that these subembayments are
157 well-mixed water masses, and the subembayment-based descriptions should not be over-
158 interpreted.

159 **3 Problem Statement**

160 **3.1 Introduction**

161 In estuarine ecosystems in the US and worldwide, high nutrient loads and elevated nutrient
162 concentrations are associated with multiple adverse impacts (Bricker et al. 2007). N and P are
163 essential nutrients for primary production that serves as the base of food webs in SFB and other

³ <http://sfbay.wr.usgs.gov/access/wqdata/>

⁴ <http://www.water.ca.gov/iep/activities/emp.cfm>

164 estuaries. However, when nutrient loads reach excessive levels, ecosystem health can decline
165 along the multiple impairment pathways.

166
167 Individual estuaries vary in their response to nutrient loads, with physical and biological factors
168 modulating estuarine response (e.g., Cloern, 1996), and some systems experiencing limited or no
169 impairment at loads that readily translate into impairment elsewhere. Current nutrient loads to
170 SFB as a whole and to some of its subembayments are comparable to or much greater than a
171 number of other major estuaries (Figure 3.1) that experience impairment from nutrient
172 overenrichment, and dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous
173 (DIP) concentrations are highly elevated (Figure 3.2). Yet SFB does not currently experience
174 classic symptoms of nutrient overenrichment, such as massive phytoplankton blooms, or low
175 dissolved oxygen over large areas in the subtidal zone. SFB has been spared the most obvious
176 adverse impacts of high nutrient loads along these pathways due to a combination of factors that
177 have imparted it with a level inherent resistance to these effects (Figure 3.3; discussed further in
178 Section 6 and 8). However, several recent sets of observations indicate that nutrient-related
179 problems may already be occurring in some areas of SFB, or may serve as early warnings of
180 problems on the horizon.

181
182 *Does SFB have nutrient-related problems, or is it likely to have problems in the future?*

183
184 *If so what management actions would be effective at mitigating or preventing impairment?*

185
186 These are reasonable questions to ask, given the high nutrient loads that SFB subembayments
187 receive (Figure 3.1). In addition to determining if there are current nutrient-related problems in
188 SFB, there is a need to anticipate potential future impairment, since any major decreases in
189 nutrient loads will be costly, and will take decades to plan and implement. Furthermore, if
190 problems are on the horizon, carrying out the necessary investigations now will allow
191 management decisions to be made based on the best available science. Implementing
192 management decisions before problems are widely entrenched will also allow for greater
193 flexibility in the approach taken, and increase the likelihood that options that are both
194 environmentally-effective and cost-effective paths are pursued.

195
196 This report does not aim to answer the question of whether SFB subembayments are currently
197 impaired or will be in the future. Instead, it uses these questions to focus the conceptual model
198 on issues most relevant for assessing current or future beneficial use impairment, selecting
199 ecosystem responses that can be used as indicators of ecosystem health, and identifying data and
200 knowledge gaps that need to be addressed in order to best inform management decisions. An
201 assessment framework for SFB is being developed separately to address that question, and will
202 build upon this report's conceptual model.

203 **3.2 Recent observations in SFB**

204 Observational data from the past 15 years in SFB indicate that statistically significant increases
205 in phytoplankton biomass have occurred in multiple subembayments. Most notably summer/fall
206 phytoplankton biomass has increased 300% since 1998 (Figure 3.4) in South Bay and LSB,
207 representing a shift in trophic status from oligo-mesotrophic (low to moderate productivity
208 system) to meso-eutrophic (moderate to high productivity system) (Cloern and Jassby, 2012).

209 Fall blooms have begun occurring regularly in South Bay and LSB since the late 1990s, where
210 they did not occur previously (Cloern and Jassby 2012, and Figure 3.6).

211
212 In Suisun Bay, extremely low phytoplankton biomass (Figure 3.7a) and highly-altered
213 phytoplankton community composition (Figure 3.7b) have defined the system since 1987 when
214 the invasive clam *Corubula amurensis* became widely established. The low primary production
215 rates and the current species composition provide insufficient support for the food web and may
216 be contributing to the dramatic decline in sentinel fish species in the Bay/Delta since 2000
217 (pelagic organism decline, POD; Baxter et al 2010). Recent studies have argued that elevated
218 levels of NH_4^+ , high nutrient concentrations in general, and altered N:P play an important role in
219 creating this low-biomass (Dugdale et al., 2012; Parker et al. 2012a,b; Wilkerson et al., 2006)
220 and poor-quality (Glibert et al., 2012) food supply situation.

221
222 The harmful algae, *Microcystis spp.*, and the toxin they produce, microcystin, have been detected
223 with increasing frequency in the Delta and Suisun Bay since ~2000 (Lehman et al., 2008). In
224 addition, HAB toxins have been detected Bay-wide (Figure 3.8) although the ecological
225 significances of the concentrations are not yet known. A number of phytoplankton species that
226 have formed harmful algal blooms (HABs) in other systems have been detected throughout SFB
227 (Table 3.1 and Figure 3.9). Although their abundance has not reached levels that would
228 constitute a major bloom or impairment, the fact that they are present and that nutrients are
229 abundant means that HABs could readily develop should appropriate conditions present
230 themselves. In fact, an unprecedented and expansive red tide bloom occurred in Fall 2004
231 following a rare series of clear calm days during which the water column was able to stratify, and
232 chl-a levels reached nearly 100 times their typical values (Figure 3.10; Cloern et al. 2005). In
233 addition, high numbers of harmful-bloom forming species have been detected in salt ponds in
234 LSB undergoing restoration (Thebault et al., 2008), raising concerns that salt ponds could serve
235 as incubators for harmful species that could proliferate when introduced into the open bay.

236
237 While DO in deep subtidal habitats is typically measured at healthy levels, low DO commonly
238 occurs in some shallower margin habitats. For example, studies of salt ponds undergoing
239 restoration in LSB show that they experience large diurnal DO fluctuations (Figure 3.11.A;
240 Topping et al., 2009) and occasionally sustained periods of anoxia (Figure 3.11.B; Thebault et
241 al., 2008). In slough habitats of LSB, DO regularly dips below 5 mg L^{-1} (the Basin Plan
242 standard) and frequently approaches 2 mg L^{-1} (Shellenberger et al., 2008). Under natural
243 conditions, shallow subtidal and tidal wetland habitats often experience large diurnal DO
244 variations and low DO. Plants and animals native to these habitats are typically well-adapted to
245 these DO swings. However, the extent to which the low DO is a result of strictly natural levels
246 of oxygen demand, as opposed to natural plus anthropogenically-derived oxygen demand, and
247 whether the combined effects have adverse impacts have not been explored.

248 **3.3 What would a problem look like in SFB?**

249 To help focus the SFB conceptual model on measurable or observable outcomes, we asked the
250 question:

251 *What would a nutrient-related problem look like in SFB subembayments, if a problem were*
252 *currently occurring, or if one was to occur in the future?*

253 Nutrient-related problems that were identified as plausible and high priority considerations for
254 San Francisco Bay were identified and divided into eight impairment categories (Table 3.2).

255
256 High phytoplankton biomass can be a nuisance (aesthetics, odor), as well as have direct impacts
257 on biota (e.g., coatings on bird wings). However, among the most common and problematic
258 impairments due to high phytoplankton biomass is low dissolved oxygen in deep subtidal areas
259 that results through degradation of phytoplankton-derived organic matter by oxygen-consuming
260 microorganisms. In the case of both high phytoplankton biomass and low DO, the magnitude,
261 duration, and spatial extent are important to consider. Exceedingly low DO (e.g., $<2 \text{ mg L}^{-1}$), and
262 the high phytoplankton biomass that causes it, over large areas for extended periods of time
263 could lead to considerable impairment, whereas moderate DO deficits, or spatially-limited or
264 short-duration events may be less problematic. In addition, naturally low DO is common in
265 certain shallow margin habitats (e.g., sloughs, salt marshes), and native organisms are well-
266 adapted to these conditions. However, elevated anthropogenic nutrient loads could exacerbate
267 these issues by increasing the intensity of these events (lower DO or over larger areas), their
268 frequency, or their duration. Thus, both the severity of events and whether they are natural vs.
269 anthropogenically-induced need to be considered.

270
271 Elevated nutrient concentrations or altered nutrient ratios could increase the frequency with
272 which HABs occur and increase the levels of HAB-produced toxins. Algal toxins, such as
273 microcystin and domoic acid, can bioaccumulate and exert toxicity to consumers at all levels of
274 the food web, including humans; some HAB exudates also exert direct toxicity (e.g., skin
275 contact). High nutrient loads may also increase the frequency of so-called nuisance algal blooms
276 (NABs), which are not toxic but may degrade aesthetics due to surface scums or odors.

277
278 It has been hypothesized that high NH_4^+ levels contribute to the low biomass and infrequent
279 phytoplankton blooms in Suisun Bay by inhibiting primary production, in particular growth of
280 diatoms (Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al., 2012).

281
282 Other groups have hypothesized that high nutrient concentrations, elevated NH_4^+ , or altered N:P
283 in SFB adversely impacts food webs by shifting phytoplankton community composition away
284 from healthy assemblages and toward suboptimal compositions that do not adequately sustain
285 organisms at higher trophic levels (Glibert et al., 2012).

286
287 Finally, other nutrient-related effects on SFB food webs, have been proposed, such as high
288 phytoplankton cellular N:P that adversely affects copepod populations feeding on those cells
289 (Glibert et al., 2012), direct NH_4^+ toxicity to copepods (Teh et al., 2011), and high nutrients
290 encouraging the spread of invasive macrophytes (???). These latter issues do not receive in depth
291 treatment in this report, but may need to do in future iterations.

292 **4. Conceptual Model Overview**

293 The conceptual model modules described in Sections 5-9 establish the mechanistic framework
294 for connecting nutrient loads and concentrations with ecosystem response and beneficial use
295 impairment. The conceptual model is organized around four main modules:

- 296 • Hydrodynamic considerations
- 297 • Nutrients

298 • Primary production, with a major focus on phytoplankton biomass and a secondary
299 focus on benthic primary production.
300 • Dissolved Oxygen; and
301 • Phytoplankton Community Composition, HABs, and HAB toxins
302 Beneficial uses considered include: recreation, fisheries and fish consumption, aesthetics, and
303 habitat for birds, mammals and fish. Several main components of the conceptual modules align
304 directly with the proposed NNE indicators for assessing whether or not beneficial uses are being
305 met or impaired in SFB (Table 2.1; McKee et al., 2011): phytoplankton biomass, dissolved
306 oxygen concentration, phytoplankton community composition, occurrence of HABs or NABs,
307 and algal toxins.
308

309 Hydrodynamics play an often dominant role in dictating ecosystem response to nutrients in SFB.
310 Section 5 provides an introduction to hydrodynamic considerations, and hydrodynamic controls
311 are woven throughout the discussions in Sections 6-9. Similarly, grazing by benthos and
312 zooplankton have an important influence on response in SFB, and are discussed within the
313 context of relevant modules.
314

315 For practical reasons, the detailed modules extend as only far as far along the food web as
316 phytoplankton biomass and community composition. Whether or not to develop zooplankton,
317 benthos, and fish conceptual models was considered, and it was deemed unnecessary at this
318 stage. Instead, the linkages further along the food web were carefully considered at the
319 beginning of the conceptual model development. The linkages between the phytoplankton
320 biomass, phytoplankton community composition, and dissolved oxygen modules and the higher
321 trophic levels and beneficial uses were identified and used to focus the discussion. The role of
322 benthic and pelagic grazing were explicitly considered in as much as they influence
323 phytoplankton biomass, phytoplankton community composition, and carbon flow in the system.
324 Modules for submerged aquatic vegetation, emergent macrophytes, and macroalgae have not
325 been developed, although may be necessary in future versions. They are discussed briefly in
326 Section 10.
327

328 Although SFB's 5 subembayments have very different physical, biogeochemical, and biological
329 characteristics that shape their individual responses to nutrients, a single set of conceptual
330 modules was developed for all of SFB. The choice of a single conceptual model comes from the
331 recognition that the same fundamental processes operate in each subembayment. The inter-
332 subembayment differences in response arise from, and are explored here through discussion of,
333 differences in the relative importance of major drivers.

334 **5 Hydrodynamics Considerations**

335 **5.1 Physical setting of San Francisco Bay**

336 Characteristics of the 5 SFB subembayments considered in this report are presented in Table 5.1.
337 San Francisco Bay has an open water surface area of approximately 1100 km² and an average
338 depth of roughly 7m, resulting in a total volume of approximately 7400 km³ (Smith and
339 Hollibaugh, 2006). Water column depth varies sharply between the central channel and the
340 shallow habitats (Figure 5.1), and large proportions of LSB, South Bay, San Pablo Bay, and

341 Suisun Bay are comprised of shallow shoals (see also Figure A.1 in Appendix for higher
342 resolution bathymetry).

343
344 Residence time and exchange with the coastal ocean vary greatly among the subembayments.
345 Suisun Bay and San Pablo Bay are river-dominated estuaries. The Sacramento and San Joaquin
346 Rivers, enter SFB through Sacramento/San Joaquin Delta east of Suisun Bay. Those two rivers
347 together drain ~40% of California, and 90% of the annual freshwater to SFB enters through the
348 Delta. Additional freshwater inputs to SFB come from smaller perennial tributaries that drain
349 the immediate surrounding watersheds, and stormwater runoff. Suisun Bay hydraulic residence
350 times range from less than 1 day during high-flow periods to ~1 month during dry periods
351 (Cloern 2012). While low salinity conditions generally define Suisun Bay, San Pablo Bay is
352 relatively more influenced by seawater due to exchanges with Central Bay, which exchanges
353 with oceanic waters through the Golden Gate Bridge. Compared to the northern estuary,
354 freshwater inputs to Lower South Bay and South Bay are quite limited and consist mainly of
355 wastewater treatment plant effluent and stormwater during the rainy season. LSB and South Bay
356 behave more like tidal lagoons, and residence times can range from weeks to months (Cloern
357 2012).

358
359 Urban residential and commercial land uses comprise a large portion of the Bay Area
360 watersheds, in particular those adjacent to Central Bay, South Bay and Lower South Bay (Figure
361 2.1.a). Open space and agricultural land uses comprise larger proportions of the areas draining to
362 Suisun Bay and San Pablo Bay. The San Joaquin and Sacramento Rivers carry waters draining
363 the agricultural-intensive land use areas in the Central Valley. Flows from several urban centers
364 also enter these rivers, most notably Sacramento which is ~100 km upstream of Suisun Bay
365 along the Sacramento River.

366 **5.2 Overview of hydrodynamic considerations**

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

379
380 Hydrodynamics play a critical role in determining San Francisco Bay's direct and indirect
381 responses to nutrients. The intensity of vertical mixing and the length of time that a stratified
382 water column (i.e., a surface layer and bottom layer) can be maintained strongly regulate the
383 timing, magnitude, and duration of phytoplankton blooms in deeper sections of this turbid (light-
384 limited) yet nutrient-rich estuary. Suspended sediment loads, tidal mixing, and wind-driven
385 mixing maintain high levels of particles in the water column resulting in light-limiting conditions
386 for phytoplankton growth. Exchange between the Bay's channels and broad shallow shoals –

387 where higher average light availability allows for faster phytoplankton growth – can influence
388 the degree to which blooms develop in the shoals and propagate to the channels. Vertical mixing
389 rates, duration of stratification, and rates of exchange or flushing between subembayments and
390 habitats determine the extent to which low oxygen levels can develop. A comprehensive review
391 of the hydrodynamics of San Francisco Bay is beyond the scope of this document. Instead, this
392 section first describes four major physical forcings (tides, wind, freshwater flow, and coastal
393 ocean exchange). We then focus on three issues that are particularly relevant to consideration of
394 ecological change in response to shifting nutrient regimes: flushing times, density stratification
395 and suspended sediment.

396 **5.3 Major drivers**

397 **5.3.1 Tidal forcings**

398 The spring-neap (~14 day) cycle in San Francisco Bay produces large diurnal asymmetries in the
399 tides during the springs, which are characterized by one large tide and one small tide in each 24
400 hour cycle. The neaps, on the other hand, have more symmetric tides, which are intermediate in
401 magnitude to the two tides seen each day during the springs.

402
403 Spatially, there is an important distinction to be made between North Bay and South Bay in their
404 response to tidal forcing. North Bay features a progressive tide, with the amplitude gradually
405 dissipating as the tide propagates through each of the subembayments, eventually being
406 completely dissipated in the Delta. South Bay, by contrast, amplifies the tides by about 50%
407 from the Golden Gate. This amplification is due to the specific geometry of South Bay and the
408 nature of and position of the South Bay shorelines through a combination of reflection and
409 funneling of the incoming tide. As a result, shoreline changes, whether development or wetland
410 restoration, will have very different effects between North and South Bay. For example, wetland
411 restoration in North Bay will reduce tidal energy primarily through increases in tidal dissipation
412 due to friction. In South Bay, wetland restoration could alter the fundamental tidal dynamics in
413 the basin, potentially reducing the tidal amplification significantly (with potential benefits for
414 inundation, but negative effects on marsh habitat). The large areas of salt ponds slated for
415 restoration in Lower South Bay and southern South Bay make changes in tidal dissipation a
416 major consideration there (Figure 5.2).

417 **5.3.2 Wind**

418 Wind forcing is strongly diurnal during the summer months due to the afternoon sea breezes
419 (Figure 5.3), which are from the west but modified by local topography. During the winter
420 months, the dominant wind events are tied to storms, and they frequently are characterized by
421 wind out of the south (on the leading edge of low pressure systems moving off of the Pacific).
422 Winds during the fall and spring are more variable, but tend to be smaller in magnitude. The
423 effects of the winds on transport include both direct effects on mixing and sediment resuspension
424 and indirect effects on circulation, through the development of a surface tilt in response to
425 sustained wind forcing.

426 **5.3.3 Freshwater flow**

427 Freshwater flow enters the Bay primarily through the Sacramento-San Joaquin Delta. Outflow to
428 Suisun Bay can be quantified using CA Department of Water Resources “DAYFLOW”⁵
429 estimates, which calculates based on a combination of daily averaged inflows into the Delta, for
430 water use, gauged flow estimates within the Delta and modeled flow routing, and considering
431 consumptive losses (i.e., evapotranspiration). Other sources of freshwater flow around the
432 perimeter of the Bay include several moderate rivers (Napa, Petaluma, Guadalupe, Alameda and
433 Coyote Creek), small inflows from local watersheds and water treatment returns. Each of these
434 categories of sources has its own distinct seasonal variability. The flows in the small and
435 moderate rivers and streams entering directly into the Bay are tied to local precipitation events
436 and peak during the winter (rainy) months. The larger inflows from the Delta are tied to Sierra
437 snowmelt and the management of reservoirs, leading to a peak in the spring and moderate flows
438 during the summer, decreasing into the fall (Figure 5.3). Finally, wastewater returns are much
439 more uniform throughout the year. Spatially, the North Bay is dominated by the Delta flows,
440 while the South Bay is influenced by a mix of local freshwater flows, wastewater returns and
441 even Delta flows in the late Spring and early Summer months.

442 **5.3.4 Coastal ocean exchange**

443 In addition to providing tidal forcing, the oceanic boundary is also the source of salt water for the
444 Bay. The interplay of freshwater flows and the tides leads to the intrusion of salt into the Bay,
445 with the extent of salt intrusion, which is frequently characterized by X2⁶ in the North Bay, being
446 highly seasonally variable. Briefly, during high flow periods, the salt field is compressed down-
447 estuary (Figure 4.2); when the flows relax, the salt field disperses back up-estuary. There is an
448 asymmetry in the process for down-estuary and up-estuary movement of the salt field that is
449 important to characterize. The down-estuary movement is advective and relatively rapid,
450 whereas the up-estuary movement is dispersive and more gradual. In South Bay, the seasonal
451 variation of salinity is more complex: during winter, runoff events reduce the salinity locally, but
452 it is not until late spring or early summer that the effects of Delta flows are felt south of the Bay
453 Bridge. During winter and spring, it is possible for South Bay to have low salinities at both ends:
454 reduced salinity in both Central Bay due to Delta flows and Lower South Bay and southern
455 South Bay due to local flows. Finally, in the late summer and fall, evaporation in Lower South
456 Bay can lead to hypersaline conditions and a reversed estuarine density gradient.

457 **5.4 Estuarine circulation, flushing and residence times**

458 The flushing (or, inversely, the residence time; see Monsen et al. REF for detailed discussion) of
459 an estuary, or an embayment within an estuary, is driven by a combination of factors, including
460 tidal forcing, density-driven circulation and, potentially, wind forcing. The combination of these
461 influences define the “estuarine circulation”. Typical estuarine circulation has up-estuary flow in
462 the subsurface waters due to denser saltier waters moving underneath freshwater. Less-dense
463 fresher waters move down-estuary along the surface. These up-estuary salty and down-estuary
464 exchanges occur along the axis of an estuary as well as laterally between deeper and shallower
465 water regions. This circulation is defined both by direct forcing by the density gradient

⁵ <http://www.water.ca.gov/dayflow/>

⁶ 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.

466 (gravitational circulation; REFs) and asymmetries in the tidal flows (REFs). The influence of
467 wind is less established, and is likely to depend on the specific details of an estuary's geometry
468 and a particular wind event. Supplementing the estuarine circulation, tidal dispersion processes,
469 including tidal pumping (REF), tidal trapping (REF) and shear dispersion (REF) will create
470 exchanges between regions of an estuary. In many cases, these tidal processes will overwhelm
471 the estuarine circulation and dominate flushing (REFs).

472
473 At the transition between embayments, or between the ocean and the estuary, the interplay of the
474 tides, density-driven exchange and the topography determines the exchange. In one limiting
475 case, pure density-driven (or gravitational) exchange determines transport between basins. In
476 this hydraulic limit, there is no mixing in the strait and the waters of the two adjoining basins
477 exchange under the influence of their density difference. The maximum exchange has been
478 analyzed by Farmer and Armi (REFs), and is set by the geometry of the strait and the density
479 difference. The other limiting case is pure diffusive exchange, which results from tidal forcing
480 interacting with the topography (see Ivey REF for detailed discussion). The distinction between
481 these two cases is important to the net transport: In hydraulic exchange, waters from each
482 embayment are transported into the other in distinct layers; in diffusive exchange, net transport is
483 directed down gradient.

484
485 At the mouth of San Francisco Bay, evidence suggests that tidal (diffusive) processes dominate
486 the exchange, with density-driven circulation providing only about 10-15% of the total exchange
487 (Fram et al. REF). The implication is that the magnitude of flushing will primarily vary with the
488 strength of the tides, which vary on the spring-neap and seasonal cycle. The Fram et al. estimate
489 that approximately 80% of the exchange at the Bay's mouth is tidal is based on data spanning a
490 spring-neap cycle, so spring-neap variability is aggregated in this estimate. Seasonal variability
491 of this result, however, is expected, with minima occurring during the spring and fall (just after
492 the equinoxes) and maxima in the summer and winter (around the solstices). This variability was
493 evident in the Fram et al. results, with fall dispersion coefficients reduced by about 45% relative
494 to summer conditions. The dispersive nature of this exchange means that flushing is driven by
495 the interaction of the tidal motions with the ocean-estuary gradient of the quantity being
496 analyzed. In fact, the bi-directional nature of dispersive exchange means that net fluxes of
497 individual species may be completely different from aggregate fluxes or exchanges, if their
498 gradients are reversed (Martin et al. REF). Similar results are to be expected at other narrow
499 straits connecting embayments throughout San Francisco Bay.

500
501 Within individual subembayments, the residence time of subhabitats will be determined by the
502 flushing and exchange flows along the perimeter of the subhabitat. An important distinction in
503 much of San Francisco Bay is separating the deep channels from the broad shoals that
504 characterize much of the Bay. In the channel, tidal and freshwater flows dominate along-channel
505 transport, but the shoals are more strongly influenced by the interplay of tides and winds. The
506 residence time of the shoals will be determined by the net exchange between the shoal and the
507 adjoining channel, which has been recently examined in South Bay in a series of papers
508 (Collignon and Stacey REFs). In this work, the authors found that shoal waters were exchanged
509 into the channel late in each ebb tide, but the nature of the exchange was a strong function of the
510 local density gradients. Frequently, at the end of ebb the shoals are more saline than the channel
511 (due to differential advection of the salinity gradient during the ebb), so the shoal waters that are

512 pulled towards the channel by the tides late in the ebb tend to plunge down the slope and intrude
513 into the channel at an intermediate depth. Although the net exchange from this transport process
514 is not yet determined, the fact that shoal waters enter the channel at variable depths is likely to
515 have important implications for the ecosystem through the effects on productivity. Although
516 reversed salinity gradients were not analyzed at this site, they could develop in the early summer
517 (due to the influence of Delta flows in northern South bay) or in the fall (due to evaporation in
518 the Far South Bay). If the salinity gradient were reversed, then the late ebb flow of shoal waters
519 towards the channel would lead to a surface flow in the channel, due to the shoal waters, in this
520 case, being less saline than the channel.

521
522 At a much smaller scale, and considering local effects, recent analyses have looked at flushing of
523 small perimeter habitats around the edge of the estuary (Hsu et al. REF). Using a combination of
524 numerical and observational analyses, the authors found that tidal exchanges dominate the
525 flushing of small slough-marsh complexes, but the net exchange is likely to be strongly affected
526 by wind forcing, which is currently being analyzed. In the absence of wind, the Hsu et al. (REF)
527 found that approximately half of the waters in a small slough-marsh complex in South San
528 Francisco Bay was exchanged each tidal cycle.

529
530 Finally, small-scale features can result from local retention or convergence. The presence and
531 maintenance of convergent fronts can lead to locally high residence times in relatively small
532 regions. Simplified analyses of convergences and mixing (which must be in balance for the front
533 to be maintained) can define representative timescales for retention and exchange (Stacey REFs).
534 Examples of these convergences are frequently associated with the channel-shoal transition
535 (Collignon REF) or other lateral density-driven flows (Lacy REF).

536 **5.5 Stratification**

537 As outlined in the introduction, the Bay is characterized by large-scale salinity gradients along
538 the Bay axes (Figure 5.4). At a large scale, the North Bay gradient is the most prominent in the
539 estuary, defined by a transition from fresh to oceanic conditions over the length of the Bay; the
540 gradient in South Bay is more variable and tends to be weaker than its North Bay counterpart.
541 Moving away from the primary axis of the estuary, in other parts of the Bay salinity gradients
542 may be comparable to or stronger than those along the North Bay axis. Specifically, the gradient
543 along North Bay is approximately 0.5 psu/km, but salinity gradients in perimeter habitats may be
544 10 times that (Ralson REF, MacVean REF). The presence of a horizontal salinity gradient
545 makes the estuary susceptible to vertical stratification due to the tendency of the horizontal
546 gradient to relax, or “lay down”, into a vertical gradient. The interaction of horizontal salinity
547 gradients and tidal forcing, which can both create and destroy vertical stratification, leads to
548 dynamic density stratification with important implications for vertical mixing.

549
550 In the estuarine water column, velocity shear (or vertical mixing energy) and density
551 stratification are in competition in defining the state of the turbulence. Sheared velocity profiles
552 act to increase the turbulent energy (and mixing), while stable density stratification acts to reduce
553 the same (REF). The competition between shear and stratification plays a critical role in
554 determining whether phytoplankton blooms develop (see Section 7).

555
556 The potential for stratification to develop depends on both longitudinal and lateral salinity
557 gradients, related to the concepts of the Richardson number and Strain Induced Periodic

558 Stratification (SIPS), whose discussion is beyond the scope of this overview. The magnitudes of
559 these salinity gradients vary seasonally (Figure 5.4).

560
561 More recent studies of San Francisco Bay stratification dynamics (as well as other estuaries)
562 have demonstrated the importance of lateral dynamics. If there is a lateral density gradient, as
563 develops at the channel-shoal transition, and a lateral velocity, then lateral straining can
564 contribute to the vertical stratification in the same way as the longitudinal does in the SIPS
565 equation above. Examples of lateral straining's influence on stratification come from South Bay
566 (Collignon et al. REF); Suisun Bay (Lacy et al. REF) as well as other estuaries (St. Lawrence
567 REF).

568
569 Taken together, we expect an estuarine water column to stratify and destratify on a wide range of
570 timescales that represent the variation of the density and tidal forcing as captured in the Simpson
571 number. At seasonal timescales, the strength of the longitudinal density gradient varies; but just
572 as importantly, its position changes so that the strongest density gradients may move between
573 deep and shallow portions of the Bay (e.g., between Suisun Bay and Carquinez Strait, e.g.). As
574 the density gradient strengthens, or moves into deeper regions, its effectiveness at creating
575 stratification is increased and a stratified water column becomes more likely. Variations in tidal
576 energy at the seasonal and spring-neap timescales can cause density stratification to adjust, and
577 the strongest salinity stratification should occur during neap tides when the salinity gradient is
578 compressed (following large freshwater flow events, e.g.). The ability of stratification to persist
579 varies on multiple time scales due to changes in the vertical mixing energy of the tides with the
580 spring-neap cycle: during neap tides, stratification is more persistent, but becomes periodic
581 during the springs (REF). The straining effects of the tidal flows lead to stratification that
582 strengthens and weakens within the tidal cycle.

583
584 Beyond the spring-neap cycle, SFB experiences two annual minima periods in tidal energy
585 (March/April, September/October). The green vertical bars in Figure 5.3 illustrate the periods of
586 minimum tidal mixing energy. In March/April, freshwater inputs and relatively low mixing
587 energy allow the water column to stratify for ~10-14 days. In September/October, lower
588 freshwater inputs limit the potential for salinity stratification. However, it is also possible to
589 have density stratification induced by temperature variations, although temperature induced
590 stratification is not as commonly analyzed in estuaries (because of the dominance of salinity
591 stratification) as in lakes or the deep ocean where it is an important factor. There are times,
592 however, when temperature stratification may be an important factor for estuarine mixing: they
593 result from a confluence of events involving warm, sunny days, neap (low energy) tides and low
594 wind energy. Throughout much of the year in San Francisco Bay, this combination is unlikely,
595 except perhaps during the fall, when the diurnal sea breeze is reduced, fog is less present, and
596 tidal energy is at its annual minimum (Figure 5.3).

597 **5.6 Suspended Sediment**

598 The common paradigm for San Francisco Bay is that it is quite turbid due to high suspended
599 sediment concentrations, or suspended particulate matter (SPM). Recent analyses (Schoellhamer
600 2011) have indicated that the Bay may be clearing, with Bay-wide decreases of ~35% since 1998
601 (Figure 5.5.a), and up to 50% since 1975 in Suisun Bay (Figure 5.6). Within the Bay itself, the
602 dynamics of the inorganic fraction of turbidity, suspended sediment concentration, is governed
603 by its upstream supply, resuspension and deposition in the Bay, and transport throughout the

604 Bay. The explanation for the decreased concentrations is that both external loads of suspended
605 sediment and resuspension of material from the bed have decreased (because of a depleted
606 erodible sediment pool; see Figure 5.5.b).

607
608 The circulation that governs transport is largely the same as what governs salinity, flushing times
609 and even stratification. The effects of supply have been considered elsewhere {Schoellhamer
610 REF}, and we will focus here on resuspension and deposition and vertical transport.

611 For sediment to be resuspended from the bed, the flow-induced bed stress, i.e., the frictional
612 force at the sediment:water interface, must exceed a critical threshold (Sanford REF; Friedrichs
613 REF). The magnitude of the critical stress will vary with the type of sediment and the degree of
614 consolidation of the bed (Sanford REF; Wiberg REF). Newly deposited sediments are more
615 readily resuspended; after some time (approximately 3 days, Wiberg REF), the bed consolidates
616 considerably and becomes more resistant to resuspension.

617
618 Both wind waves and tidal flows create stresses at the estuary bed that can act to resuspend
619 sediments. In the deep channels, the effects of wind waves do not extend to the bed (Kundu
620 REF), so only tidal forcing needs to be considered when analyzing resuspension. Although the
621 tides are nearly symmetric, because of the threshold nature of sediment resuspension, even subtle
622 asymmetries could have large impacts on the timing of sediment resuspension and net transport.
623 The superposition of density forcing (flow in at the bed, out at the surface) with tidal flows adds
624 to the bed stress on flood tides and reduces it on ebbs. If this asymmetry crosses the
625 resuspension threshold, then sediment concentrations may be higher on floods than ebbs, leading
626 to a net upstream transport of sediment. This effect is counteracted by large freshwater flow
627 events, which add to the bed stress on ebbs and reduce it on floods. The net effect is expected to
628 be a downstream push of sediments due to large freshwater flows events followed by tidally-
629 driven up-estuary sediment transport once the flows reduce (Ralston REF).

630
631 In the shallows, windwaves are able to reach the bed and create large oscillatory bed stresses that
632 can resuspend sediments. The resuspended sediment from windwaves is largely contained in the
633 wave boundary layer, which may only be a few centimeters thick, but if tidal flows coincide with
634 this resuspension, then they can mix sediments further up into the water column. This
635 combination of factors was found to be important to the sediment dynamics on South Bay shoals
636 by Brand et al. (REF), who found that the highest sediment fluxes into the water column
637 occurred on flood tides that followed wavy low water periods. The explanation was that wind
638 waves were able to resuspend sediments into the wave boundary layer, and then the following
639 flood tide mixed the sediments into the water column. The importance of windwaves to
640 resuspension mean that summer months, characterized by strong diurnal sea breezes, are likely to
641 have the highest sediment concentrations in the shallows, even though the watershed supply is at
642 its lowest during that period.

643
644 In the water column, settling and turbulent mixing define the evolution of the suspended
645 sediment concentration profile. The settling velocity for the sediment depends on the particle size
646 and density, which may be poorly defined for fine particles that form flocs. For large, dense
647 particles, or during low energy periods, the suspended sediment is largely constrained to the
648 near-bed region; for smaller particles, or less dense flocs, or during high energy periods, the
649 suspended sediment is more widely distributed throughout the water column.

650
651 Together, the suspended sediment concentrations in the waters of San Francisco Bay will vary
652 tidally and diurnally (or in response to wind events), will vary between embayments due to
653 supply, and will vary within embayments due to spatially variably resuspension in response to
654 the local depth. Seasonally, supply has a strong variation, with more turbid waters being brought
655 into the Bay with winter rains, but the shoals may actually be more turbid during summer months
656 due to resuspension of sediments from the bed (Figure 5. .

657 **5.7 Summary**

658 This review is not meant as a comprehensive description of the hydrodynamics of San Francisco
659 Bay, but is instead focused on the basics of flushing, stratification and suspended sediment. The
660 key factors driving all three of these processes are tidal, wind and freshwater forcing. The
661 variability of those factors, and their interactions, define the dynamics of the processes.
662

663 Looking ahead several decades, the prospects for change in the Bay are extensive. Climate
664 change and variability will bring with it warmer air temperatures and more frequent heat waves,
665 creating the risk of more anomalous temperature stratification events. Precipitation may shift
666 towards rain from snow, altering the timing of freshwater flows entering the Bay and the
667 associated response in the salt field. Sea level rise will alter the tidal dynamics of the Bay,
668 perhaps increasing the dissipation of energy due to extra inundation, or decreasing it if the Bay is
669 made deeper (i.e. sediment accumulation does not keep pace with sea level rise).
670

671 The changes the Bay faces are not limited to climate forcing, however, and anthropogenic
672 changes may be just as pronounced. Along the Bay's shorelines, marsh restoration will alter the
673 tidal dynamics by increasing tidal dissipation locally and, for large restoration projections, could
674 potentially alter the tidal dynamics more broadly. The management of California's water
675 resources through reservoir operations alters the timing and amount of freshwater flows that
676 enter the Bay, perhaps in a more profound way than a shift in the type of precipitation would.
677 Finally, land use practices, as well as the operation of reservoirs, alter the sediment supply that
678 watersheds provide to the Bay.
679

680 While these scenarios are all plausible, the potential magnitudes of their effects on nutrient
681 cycling and ecosystem response remain highly uncertain.

682 **6 Nutrients**

683 **6.1 Introduction**

684 The nutrient module of the conceptual model focuses on the macro-nutrients N, P, and Si, with a
685 greater emphasis on N and P because their loads and concentrations have been most altered by
686 anthropogenic activities. N, P, and Si are essential for primary production in all aquatic
687 environments, including SFB. Requirements for N, P, and Si differ among phytoplankton
688 species, as do uptake rates. In addition, some species show a relative preference for certain forms
689 of N. These requirements and preferences, along with the relative nutrient abundances, can
690 influence the growth rate of phytoplankton and the magnitude (concentration) of phytoplankton
691 blooms (Section 7); they may also influence the types of phytoplankton species that prosper
692 (Section 9).

693
694 The observed nutrient concentration at any given point in space and time in SFB represents a
695 balance of multiple processes, including: input, export, water mixing (vertical, lateral,
696 longitudinal), uptake by phytoplankton, transformations, and losses. The summary discussion
697 below covers the major environmental processes that are relevant to management issues in SFB.

698 **6.2 N, P, and Si cycling**

699 **6.2.1 N cycling**

700 Nitrogen exists in numerous environmentally-relevant forms and undergoes complex
701 biologically-mediated transformations between these forms (Figure 7.1). The major dissolved
702 forms of N include the ions: nitrate (NO_3^-), ammonium (NH_4^+), and nitrite (NO_2^-). Dissolved
703 and particulate organic nitrogen (DON and PON) are major forms of N in some aquatic systems,
704 but more often in relatively pristine systems having low anthropogenic nutrient loads. The
705 relative importances of DON and PON to the N budget as a function of space in time in SFB are
706 not well known. Dissolved gaseous forms of N include di-nitrogen (N_2) and nitrous oxide
707 (N_2O). The “bio-accessible” or “fixed” forms of N include all the ions and organic forms, and
708 N_2O , which is an important intermediary in some N transformation processes but is typically
709 present at only low concentrations. N_2 is both an end-product of denitrification and a potential N
710 source for a limited set of phytoplankton that perform nitrogen fixation, an energy-intensive
711 process through which they convert N_2 into an usable organic form. The remainder of the N
712 cycling description focuses primarily on NO_3^- and NH_4^+ , since they are the dominant N forms.

713
714 Figure 7.1 illustrates processes that affect N forms and abundance in subembayments of SFB.
715 Nitrogen inputs include: riverine inputs via the Sacramento-San Joaquin Delta; other freshwater
716 inputs at the Bay margins (smaller perennial streams, along with stormwater inputs and
717 ephemeral wet season streams); inputs from point-sources, primarily POTWs; and other sources
718 that are less readily quantified but expected to be relatively small (e.g., direct atmospheric
719 deposition, groundwater). While N fixation can be an important source of N to some aquatic
720 systems, it is likely unimportant at present in SFB relative to other sources; however increased
721 nitrogen fixation is a possible ecosystem-level response to nitrogen limitation, should inputs of
722 fixed nitrogen from other sources decrease substantially. Exchange with the Pacific Ocean at the
723 Golden Gate can be either a net source or sink of N depending on coastal processes (i.e.,
724 upwelling or non-upwelling time period) and conditions within SFB. Similarly, hydrodynamic
725 exchange processes (tidal, gravitational, advective) can result in net N exchange between
726 subembayments. N is supplied to subembayments primarily in the form of NO_3^- , NH_4^+ , DON,
727 and PON. The relative proportion of each of these forms varies by source.

728
729 Nitrogen transformations take place within the oxic water column, within the (typically) anoxic
730 sediments, and within the narrow - but geochemically important - transition zone at the
731 sediment:water interface. NH_4^+ and NO_3^- (and some forms of DON) can be readily taken up and
732 assimilated into biomass by primary producers. When dead phytoplankton undergo degradation
733 or mineralization by microbes, much of the organic N is regenerated as NH_4^+ . Some of the
734 ammonia released is oxidized to nitrate in the water column via the process of nitrification. This
735 process requires oxygen, but can proceed in environments with reduced oxygen concentrations,
736 including at the sediment-water interface. Denitrification is a form of respiration used by some
737 heterotrophic microbes. In denitrification, NO_3^- is used instead of oxygen to oxidize organic

738 matter, producing N_2 and carbon dioxide. Denitrification requires organic matter to proceed, and
739 its rate can be limited by the availability of sufficient organic matter. Denitrification only
740 proceeds in anoxic environments, primarily within sediments, or biofilms, after NO_3^- diffuses
741 from the water column into the anoxic conditions. Some portion of the organic nitrogen
742 produced in the Bay is buried in the sediments where it decomposes slowly to release
743 ammonium. Burial can take place anywhere in the bay, but is more likely in locations where
744 there is net accumulation of sediments. Newly restored tidal salt marshes are likely to be
745 particularly important in this regard; because of the anoxic conditions and abundance of organic
746 matter in the sediments, these marshes are likely also important sites of denitrification. Some of
747 the buried material continues to decompose, releasing ammonium into the sediment pore water,
748 which eventually diffuses back to the water column. A small fraction of the PON is buried
749 permanently, unless it is resuspended by erosion, dredging, etc. The coupled process of ammonia
750 oxidation-denitrification at the sediment water interface is important and can be responsible for
751 most of the denitrification in some estuarine systems.

752
753 Nitrification and denitrification are expected to be quantitatively important processes that
754 influence N form and fate at the subembayment and Bay scales, and quantifying these processes
755 will be one key component for determining the N loads that SFB subembayments can assimilate
756 without beneficial use impairment. The importance of nitrification in SFB is evident, given that
757 in some subembayments (e.g, South Bay) N is loaded as primarily NH_4^+ but is measured in the
758 water column as primarily NO_3^- . Denitrification likely represents a substantial loss route for
759 bioavailable N within SFB. However the magnitudes and importance of nitrification and
760 denitrification relative to other processes (uptake by phytoplankton or Microphytobenthos,
761 transport out of the system) are poorly known. The importance of denitrification and nitrification
762 could be readily constrained through a combination of relatively straightforward
763 biogeochemical/hydrodynamic models for individual subembayments and field studies using
764 well-established methods to measure these rates. The field data and lessons learned from small-
765 scale models could then be effectively applied in highly-resolved full-Bay models.

766 6.2.2 P cycling

767 A schematic of the phosphorous cycle is shown in Figure 7.2. P cycling is relatively
768 straightforward compared to N, since P does not commonly occur in multiple dissolved inorganic
769 redox states or undergo numerous transformations. P occurs as dissolved orthophosphate (o-
770 PO_4), particle-complexed o- PO_4 , other solid mineral phases of P, and dissolved and particulate
771 organic P (DOP and POP). o- PO_4 would be expected to comprise most of dissolved P in the
772 water column. However, particle- or colloiddally-complexed P can also be important in the water
773 column. A substantial fraction of o- PO_4 can be bound to iron(III)-oxide particles in both the
774 sediments and water column, a form in which it is essentially unavailable for uptake by primary
775 producers. Other particulate mineral phases of P occur, but they tend to be relatively refractory.

776
777 P sources to SFB subembayments are similar to those for N, and include: riverine inputs of
778 naturally-derived P (from dissolution of P-rich mineral phases) or anthropogenically-sourced P
779 (fertilizer, livestock excrement, treated wastewater) via the Sacramento-San Joaquin Delta; other
780 freshwater inputs at the Bay margins - perennial streams or rivers, stormwater inputs, and
781 ephemeral wet-season streams; direct inputs to subembayments from point-sources, primarily
782 POTWs; and other sources that are less readily quantified but believed to be relatively
783 unimportant (ground water, atmospheric deposition, etc.). P has no analogous process to N-

784 fixation. Similar to N, exchange with the Pacific Ocean at the Golden Gate can be either a net
785 source or sink of P depending on coastal processes (i.e., upwelling or non-upwelling time period)
786 and conditions within SFB. Similarly, hydrodynamic exchange processes (tidal, gravitational,
787 advective) can result in net P exchange between subembayments.

788
789 P form and abundance are influenced by uptake and assimilation, surface reactions with
790 particles, settling, and microbial mineralization and recycling. Within the water column, o-PO₄
791 can be readily taken up and assimilated by phytoplankton. During grazing on phytoplankton (by
792 zooplankton) or mineralization of dead phytoplankton in the water column or sediments, DOP
793 and POP are released and converted to o-PO₄ by microbes. Particle-complexed o-PO₄ and POP
794 settle in the water column and eventually reach the bed sediments. Respiration using iron(III) is
795 an important anaerobic reaction in sediments, which dissolves iron(III)-oxides and releases
796 dissolved o-PO₄ to porewater. Similar to N, burial of particulate P can take place anywhere in
797 the bay, but is more likely in locations where there is net accumulation of sediments, like
798 wetlands. Some of the o-PO₄ produced in sediments returns to the water column and re-enters
799 the cycle of organic matter production and degradation.

800 **6.2.3 Si cycling**

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

810
811 Si is supplied to subembayments primarily as dissolved silicate (SiO₄), solid mineral phase
812 silicates, and reactive or refractory biogenic silicates. In the absence of biological uptake and
813 assimilation, Si should behave conservatively in SFB, with no relevant geochemical
814 transformations or sinks that are decoupled from uptake/assimilation by organisms reliant on Si
815 for growth. While N and P requirements (C:N:P) vary substantially among phytoplankton
816 groups, all phytoplankton require N and P for growth. This is not the case for Si: only diatoms
817 and several other species require silicate in substantial amounts. Thus, only the growth of these
818 types of phytoplankton, will have a substantial effect on Si concentrations.

819
820 The recycling of Si is slow relative to P and N. Si taken up and assimilated by diatoms is less
821 readily regenerated during grazing or microbial degradation of cells. Instead, the silicate-rich
822 frustules settle and accumulate as biogenic Si in the sediments where they are only slowly
823 remineralized, or they are transported out of the subembayments. Compared to N and P, a larger
824 proportion of biogenic Si that reaches the sediments is ultimately buried.

825 **6.3 Sources of N and P**

826 N and P sources to SFB include anthropogenic and natural external inputs, while Si sources are
827 predominantly natural. Figure 6.3 presents an overview of DIN and DIP loads to SFB, divided
828 among by the five main subembayments. A separate report on N and P nutrient loads, available

829 in draft form, explores loads, data gaps, and uncertainties in more detail (Novick and Senn,
830 2013). Groundwater and direct atmospheric deposition loads are expected to be small and are not
831 discussed here.

832
833 Discharge of treated wastewater effluent by publicly owned treatment works (POTWs) to SFB's
834 subembayments is a major source of N and P. The San Francisco Bay Area has 42 POTWs
835 (Figure 2.1.A) that service the regions 7.2 million people and discharge either directly to the Bay
836 or to receiving waters in adjacent watersheds that drain to the Bay (not including discharges east
837 of Suisun Bay that enter through the Delta). While several of these POTWs conduct nitrification
838 or nitrification plus some forms of advanced treatment that remove a portion of nutrients prior to
839 discharge, most POTWs carry out only secondary treatment, which transforms nutrients from
840 organic to inorganic forms, but generally does not remove much N or P. Bay-wide, POTWs
841 discharged (annual average) $34400 \text{ kg d}^{-1} \text{ NH}_4^+$, $11800 \text{ kg d}^{-1} \text{ NO}_3^-$, and $4000 \text{ kg d}^{-1} \text{ PO}_4$.
842 Detailed effluent characterization work that began in July 2012 suggests ~90% of total N
843 discharged was in the form of DIN and ~80% of total P discharged was in the form of o-PO₄.
844 Refineries also contribute loads in Suisun Bay and San Pablo, but they appear to be relatively
845 minor sources.

846
847 The dominant sources of N and P loads, and the form of N, vary substantially among
848 subembayments (Figure 6.3). In LSB, South Bay, and Central Bay, POTWs are the dominant
849 source of N and P. In LSB, NO_3^- is the dominant N form discharged because POTWs there carry
850 out nitrification. In South Bay and Central Bay, NH_4^+ is the dominant N form released by
851 POTWs. In San Pablo Bay, direct POTWs are relatively low and primary release NH_4^+ . In
852 Suisun Bay, NH_4^+ is the primary form of N discharged, and the important of these direct loads
853 relative to other inputs vary seasonally (discussed more below).

854
855 Stormwater flows deliver seasonally-varying N and P loads to SFB. Only coarse estimates of
856 those loads have been made thus far due to data limitations. In most subembayments during most
857 of the year, these estimates suggest that stormwater DIN and o-PO₄ loads are substantially less
858 than POTW loads (Figure 6.3), with potential exceptions being loads to San Pablo Bay and
859 Suisun Bay. Rain is generally limited to October-April; N and P loads from runoff are highest
860 during this period and generally insignificant (at least at the subembayment scale) during the dry
861 season. The relative uncertainty in the magnitude of stormwater-derived N and P loads is high,
862 Furthermore, it is likely that estimates thus far poorly represent loads from perennial rivers and
863 streams (other than the Delta). While more work is necessary if better constraining stormwater N
864 and P loads is a priority, it seems unlikely that these loads will rival POTW loads at the
865 subcatchment scale in LSB, South Bay, and Central Bay. However, while stormwater loads may
866 not play a dominant role at the subembayment scale in these subembayments, the importance of
867 stormwater N and P loads at smaller spatial scales (e.g., along the Bay's margins, including
868 wetlands) should not be ruled out.

869
870 Loads entering SFB from the Sacramento/San Joaquin Delta have the potential to be large and
871 seasonally-dominant sources of N and P to Suisun and San Pablo Bays (Figure 6.3). Delta DIN
872 loads far exceed those from Suisun direct POTWs for half the year, and Delta NO_3^- loads exceed
873 NO_3^- loads from direct POTW loads to Suisun Bay year-round. For NH_4^+ , however, direct
874 POTW loads are comparable to or exceed Delta loads during late spring through fall. Most of

875 the NH_4^+ entering Suisun Bay from the Delta likely comes from the Sacramento wastewater
876 treatment plant, which currently does not nitrify and discharges ~70 km upstream of Suisun Bay.
877 Although the Delta load estimates to Suisun Bay are believed to be reasonable approximations,
878 their accuracy and uncertainty need to be further evaluated and refined using hydrodynamic and
879 biogeochemical models for the Delta.

880
881 Hydrodynamic exchange between subembayments may comprise a large proportion of loads to
882 some subembayments. This is particularly true for San Pablo Bay, which has relatively low
883 POTW direct loads but receives loads from Suisun Bay and the Delta. The loads entering San
884 Pablo Bay from Suisun Bay (including loads from the Delta) were only roughly estimated and
885 need to be refined with hydrodynamic/reactive-transport models. Nonetheless, these calculations
886 suggest they could be the dominant source to San Pablo Bay for most of the year. Similarly, the
887 southern reaches of South Bay are likely highly influenced by direct loads to LSB.

888
889 Whether or not exchange of water across the Golden Gate acts as a substantial net source of
890 nutrients to the Bay during certain times of the year remains highly uncertain. Freshly-upwelled
891 coastal water contains up to $30 \mu\text{mol L}^{-1} \text{NO}_3^-$; however, the extent to which that NO_3^- -rich coastal
892 water enters SFB depends on a complex set of hydrodynamic and climatological factors. Under
893 maximal conditions, daily NO_3^- loads into the Bay through the GG could be of similar magnitude
894 as all POTW DIN loads combined (J. Largier, pers. comm.). That said, the frequency with
895 which the hydrodynamic and climatological drivers align is unknown, and needs to be further
896 explored. The fate of the nutrient plume that leaves SFB, and its potential impacts on biological
897 response in coastal waters also needs to be considered.

898 **6.4 Seasonal variation in N and P among subembayments**

899 The fundamental processes that determine the ambient forms and concentrations of N and P are
900 the same throughout SFB. However, the relative importances of processes vary considerably
901 within and between subembayments, as well as over a range of time scales (tidal, diurnal,
902 seasonal). The differences in the magnitudes of these processes cause the spatial and seasonal
903 differences in forms and concentrations of N and P.

904
905 The importance of the variations in the magnitudes of the major drivers is evident when viewing
906 how NH_4^+ concentrations vary among subembayments and seasonally. Maximum NH_4^+ levels in
907 Suisun Bay are the highest of anywhere in the SFB; however NH_4^+ levels exhibit strong seasonal
908 variability, with winter concentrations being 3-5 times greater than those in spring and summer
909 (Figure 6.4). Mass balance estimates suggest that, during spring and summer, ~75% of NH_4^+ that
910 enters Suisun Bay is “lost”, presumably through either nitrification to NO_3^- or uptake by
911 phytoplankton (Novick and Senn, 2013). This seasonality is likely due to longer residence times
912 in Suisun Bay in spring/summer and warmer water temperatures, favoring processes like
913 nitrification; longer days could also contribute to greater primary production and related uptake
914 of NH_4^+ .

915
916 LSB represents an interesting counter example (Figure 6.4). Strong seasonality in NH_4^+
917 concentrations is also evident in LSB. Although LSB has one of the highest areal N loads of all
918 SFB subembayments (Figure 3.1), the vast majority of N loaded directly to LSB is in the form of
919 NO_3^- . Therefore, much of the NH_4^+ observed in LSB may in fact be NH_4^+ regenerated from the
920 sediments. Sediment sources of NH_4^+ may be so pronounced in LSB (even if they are not larger)

921 because of LSB's morphology: LSB is quite shallow, and has a low ratio of water volume to
922 sediment area compared to other subembayments. Thus, any flux from LSB sediments would be
923 mixed over a relatively smaller volume of water, causing a larger increase in concentration. The
924 NH_4^+ concentration minima in April and September coincide with periods of highest
925 phytoplankton biomass (see below), and may indicate NH_4^+ uptake by phytoplankton. The
926 relative maximum in June-July may be due in part to higher rates of mineralization of organic
927 matter in the sediments (due to higher water temperatures).

928
929 NO_3^- concentrations also vary considerably between subembayments (Figure 6.5). NO_3^-
930 concentrations are highest in LSB (40-80 $\mu\text{mol L}^{-1}$), due in part to the fact that all POTWs in
931 LSB nitrify before discharging effluent, and also because of the high areal loads to LSB. The
932 lower NO_3^- concentrations in spring and fall are likely partially due to higher uptake rates by
933 phytoplankton. The continued low concentrations during summer in LSB may also be due to
934 higher rates of denitrification during this time period resulting from warmer temperatures, and
935 perhaps a higher abundance of labile organic matter in the sediments (after spring phytoplankton
936 blooms) to fuel anaerobic respiration (i.e., denitrification). The next highest concentrations
937 occur in Suisun Bay and South Bay. In Suisun Bay, the substantial NO_3^- loads entering from the
938 Delta likely contribute to these elevated NO_3^- concentrations. In South Bay the predominance of
939 N in the form of NO_3^- likely results from in situ nitrification of NH_4^+ from POTW loads. The
940 lowest concentrations ($\sim 20 \mu\text{mol L}^{-1}$) are observed Central, San Pablo, and northern South Bay,
941 all of which have greater exchange with coastal waters entering through the Golden Gate.

942
943 In South Bay and Central Bay, although the vast majority of N loaded to the system occurs in the
944 form of NH_4^+ (Figure 6.3), ambient N is present primarily as NO_3^- (Figure 6.5), arguing that
945 nitrification plays an important role in shaping ambient N speciation. Benthic or pelagic
946 nitrification rates have not been measured in South Bay, and no published values exist yet for
947 elsewhere in the Bay. These rates could also be readily estimated through basic modeling and
948 budgets at subembayment scales.

949
950 Nitrification and denitrification are likely quantitatively important processes in the N budget for
951 SFB subembayments. Estimating these rates will be important for determining subembayments'
952 ability to assimilate or transform nutrients, which is essential information for determining
953 allowable loads should load reductions be necessary. The ability to estimate DIN budgets and
954 transformation rates are currently hampered by lack of a water quality / biogeochemical models,
955 and by field studies aimed at estimating rates.

956
957 LSB had the highest o-PO4 concentrations, which were ~ 4 -fold higher than most other
958 subembayments. In Suisun Bay, o-PO4 does not exhibit the same strong seasonality as did NH_4^+
959 or NO_3^- . In the other subembayments, o-PO4 concentrations exhibit more defined seasonality.
960 Minimum o-PO4 concentrations occur in April and May in San Pablo Bay, Central Bay, South
961 Bay, and LSB, consistent with modest o-PO4 drawdown occurring during spring phytoplankton
962 blooms. o-PO4 concentrations then increase to relatively constant concentrations over summer
963 and fall, before dropping to lower levels in wet season winter months (Nov-Feb) levels.

964 **6.5 Current state of knowledge**

965 Table 6.1 summarizes critical information gaps related to N and P in SFB.

966

967 Nitrification (water column or sediment:water interface) and denitrification (sediment:water
968 interface) likely play important roles in regulating ambient concentrations of NH_4^+ and NO_3^- in
969 the Bay, and thereby in determining what loads subembayments can assimilate without
970 beneficial use impairment. Developing basic models for initial quantification of these processes
971 is an essential early step that will inform decisions about allowable N loads to individual
972 subembayments. If mass balance estimates from modeling suggest that nitrification and
973 denitrification play an important role in N cycling in SFB, field studies should be conducted to
974 quantify rates and their spatial/seasonal variability.

975
976 Limited data exists on nutrient concentrations at time scales shorter than ~1 month. Finer
977 temporal resolution data will be needed to improve understanding about nutrient transformation
978 rates. There is also limited information on nutrient concentrations along the shoals and in
979 shallow margin habitats. Also little information on time-scales shorter than 1 month.

980 **7 Primary Production and biomass accumulation**

981 **7.1 Introduction**

982 Primary production in SFB is carried out by phytoplankton, benthic algae (microphytobenthos,
983 MPB), macrophytes, and macroalgae. At this point, the conceptual model focuses primarily on
984 phytoplankton, and to a lesser degree on MPB, and does not consider macrophytes and
985 macroalgae. For more on those topics, the reader is to the SFB NNE Literature Review and Data
986 Gaps Analysis (McKee et al., 2011).

987
988 Phytoplankton biomass is highly relevant as an indicator of ecosystem health and nutrient-related
989 beneficial use impairment. Phytoplankton reside at the base of the food web, and are the
990 predominant food resource for most pelagic and benthic primary consumers in San Francisco
991 Bay. Phytoplankton require nutrients for growth, and there is often a direct link between
992 phytoplankton biomass and nutrient loads, with nutrient abundance being one of several factors
993 that regulate primary production rates and biomass accumulation. As noted in Section 3,
994 excessive phytoplankton biomass is one plausible impaired state in SFB. Excessive
995 phytoplankton biomass can be a direct beneficial use impairment (odor, aesthetics). More
996 commonly high rates of primary production and accumulation of high levels of phytoplankton
997 biomass are of concern because they lead to low dissolved oxygen levels in the water column
998 and sediments when phytoplankton die, settle, and are undergo degradation by microbes
999 (Section 8). High phytoplankton biomass can also lead to impairment through shading of
1000 submerged aquatic macrophyte production (valuable habitat) and benthic primary production
1001 (benthic food resource); however, these are not likely impairment pathways in SFB because of
1002 the system's already high turbidity due primarily to inorganic particles.

1003
1004 Phytoplankton biomass is actually comprised of multiple species, with complex community
1005 responses to natural and anthropogenic drivers. Both the biomass and the types of organisms
1006 present (community composition) are important for adequately supporting food webs. This
1007 section focuses on phytoplankton biomass; Section 9 addresses community composition.

1008
1009 Microphytobenthos are discussed in Section 7.3.

1010 **7.2 Phytoplankton**

1011 Phytoplankton biomass is the concentration of living phytoplankton material in the water
1012 column. Biomass is probably most accurately quantified in units of $\mu\text{g C L}^{-1}$, but is commonly
1013 presented in units of mg chl-a m^{-3} or $\mu\text{g chl-a L}^{-1}$. Biomass measured at any given point in space
1014 and time is the net result of multiple processes (Figure 7.1): growth; settling; pelagic and benthic
1015 grazing; sinking and degradation or burial; and exchange or mixing between areas through water
1016 movement (lateral, longitudinal, vertical). The magnitudes of these processes vary in space and
1017 time, and this variation leads to spatial and temporal differences in biomass concentrations.

1018 **7.2.1 Transport and Loads**

1019 Loads of externally-produced (i.e., allochthonous) phytoplankton biomass to a subembayment's
1020 water column can occur through fluvial transport of freshwater into the subembayment, carrying
1021 phytoplankton produced in adjacent systems; hydrodynamic exchange between subembayments
1022 or habitats within subembayments (e.g., exchange between shoals and channel); and exchange
1023 with the coastal ocean. In general, the majority of phytoplankton biomass observed in SFB is
1024 produced within the Bay (Jassby et al., 1993). However, Suisun Bay may serve as a notable
1025 exception. Jassby et al. (1993) estimated loads of phytoplankton-derived particulate organic
1026 carbon (POC) produced within the Delta and found that they could account for 20-80% (median
1027 ~ 50%) of total POC loads to Suisun Bay (including that produced in situ phytoplankton
1028 primary production). Those estimates were based on data from 1975-1989. Considering the
1029 substantial ecosystem changes observed since the late 1980s, these estimates likely need to be
1030 updated.

1031 **7.2.2 Production and accumulation**

1032 The processes that control biomass can be divided into those that influence the rate of growth
1033 and those that influence the rate of accumulation. The common modes of phytoplankton
1034 production rates and biomass accumulation in SFB are presented in Figure 7.2. The most
1035 common condition is low phytoplankton productivity and low biomass (Figure 7.2.a). Blooms
1036 develop when the water column becomes periodically stratified (Figure 7.2.b) or when
1037 appropriate conditions prevail in shallow areas (Figure 7.2.c and 7.2.d). Major processes and
1038 drivers are described below.

1039 **7.2.2 Factors that influence production rates**

1040 Several factors influence phytoplankton production rates, including temperature; light
1041 availability; nutrient concentrations; and inhibition of production by elevated NH_4^+ .

1042
1043 *Temperature*

1044 Phytoplankton maximum growth rates are highly sensitive to temperature (e.g., Eppley 1972;
1045 Behrenfield and Falkowski, 1997). Bay-wide average temperatures vary seasonally from 10°C
1046 to $>20^\circ\text{C}$, with as much as a 7°C difference in maximum temperatures between subembayments.
1047 As a result, maximum growth rates may vary by 200% and 25% due to seasonal and spatial
1048 temperature differences, respectively.

1049
1050 *Light levels*

1051 Throughout much of SFB and during most of the year, light availability acts as the main
1052 limitation on phytoplankton production rates, and phytoplankton growth rates depend primarily
1053 on the amount of time cells spend in light-rich zones (Figure 7.3). The amount of light reaching

1054 the water column surface (incident light or insolation) varies seasonally due to length of day, and
1055 over shorter time scales due to cloud cover (Figure 5.3). From the surface, light levels decrease
1056 exponentially with depth, primarily due to light scattering and absorption by suspended
1057 sediments.

1058
1059 While in some nutrient-rich systems phytoplankton abundance can contribute substantially to
1060 light attenuation, light attenuation in SFB is primarily due to non-phytoplankton SPM (Cloern,
1061 19xx). SFB is a highly turbid system. As a result, the photic zone (the area above the depth at
1062 which light levels are 1% of incident light) is typically only 1-2 m thick. SPM concentrations,
1063 and photic zone depth, vary substantially between subembayments, within subembayments, and
1064 as a function of season (Figure 5.7). SPM and light attenuation are often higher along shallow
1065 shoals than in deeper areas. This is due to turbulent energy (from winds, tides) more readily
1066 resuspending particles from the bottom, and mixing that material over a smaller volume of water.
1067 SPM concentrations have decreased significantly in some areas of SFB over the past several
1068 decades. For example, SPM concentrations have dropped by on-average 50% in Suisun Bay
1069 since 1975 (e.g., Figure 5.6), due to decreasing loads and gradual loss of erodible bed sediments
1070 already in the Bay (Schoellhamer, 2011). This 50% decrease in SPM translates to roughly a
1071 doubling of the photic zone depth. The Bay-wide average decrease is ~35% (Schoellhamer,
1072 2011).

1073
1074 *Hydrodynamic controls over phytoplankton's access to light and production rates*

1075 The vertical and lateral movements of water masses - and the phytoplankton they contain -
1076 within SFB play an important role in regulating overall system productivity by controlling the
1077 average amount of time phytoplankton remain within the light-rich photic zone. Variability in
1078 the magnitude of vertical and lateral mixing also plays a role in determining if, when, and where
1079 phytoplankton blooms develop and terminate. Thus, understanding hydrodynamics in the Bay is
1080 essential for understanding productivity and the accumulation of phytoplankton biomass.

1081
1082 The presence or absence of vertical stratification in the water column strongly influences
1083 productivity (Figure 7.2.a and 7.2.b). When the water column is unstratified or vertically well-
1084 mixed (7.2.a), the amount of time phytoplankton spend in the photic zone decreases in
1085 proportion to water column depth, since they are mixed over that entire depth. Vertical
1086 stratification develops due to density differences in water layers. Density differences are created
1087 by fresher (less dense) water overlaying salty water, or warmer water overlaying colder water.
1088 The density gradient inhibits vertical mixing and allows phytoplankton to reside in the relatively
1089 thin (e.g., 1-3 m) and light-rich surface layer, as opposed to being moved over the entire water
1090 column depth. Under these conditions phytoplankton harvest more light, resulting in higher
1091 productivity (Figure 7.2.b and 7.3.a).

1092
1093 Factors that influence the duration of stratification therefore have an important influence on
1094 productivity and biomass accumulation. SFB experiences strong tidal mixing (Cloern, 1991),
1095 which acts to break down stratification and vertically mix the water column. Tidal energy has
1096 two minimum periods each year, in March/April and September/October (Figure 5.3). During
1097 these low-energy periods, stratification will develop if there are sufficient freshwater inputs
1098 (salinity stratification, typically in spring in LSB and South Bay; may also happen in Fall in
1099 Suisun Bay) or calm clear days (temperature stratification, more typically in fall). Under these

1100 conditions, phytoplankton remain in the light-rich photic zone and grow rapidly. Typically these
1101 blooms are short-lived, lasting 10-14 days, with bloom termination occurring when increased
1102 tidal energy re-mixes the water column.

1103
1104 Spring blooms have typically been the most pronounced blooms throughout SFB. However, fall
1105 blooms have been occurring with increased If winds are calm and skies are clear, the water
1106 column may become stratified as surface waters warm, permitting higher growth rates and a fall
1107 bloom to develop. The reason for the increased recent frequency of fall blooms in LSB and
1108 South Bay is unknown, but could be the result of lower SPM and lower grazing pressure (Section
1109 7.2.3). One particularly striking example occurred in September 2004, when calm winds and
1110 weak tides occurred coincident with record temperatures clear days, allowing a warm surface
1111 layer to establish (Figure 3.10). A bloom of the red tide organism *Akashiwo sanguinea*
1112 developed, with biomass levels reaching nearly 200 mg chl-a m⁻³, the highest levels ever
1113 observed in this region of SFB over the 40-year period of record. The bloom terminated after
1114 only 1 week, once mixing conditions returned to more typical intensity.

1115
1116 SFB's expansive shallow shoals are an important zone for phytoplankton productivity. Large
1117 proportions of Suisun Bay, San Pablo Bay, South Bay, and Lower South Bay have water depths
1118 of <2 m. Several field and modeling studies in South Bay have demonstrated that phytoplankton
1119 blooms often originate on the shallow shoals (Figure 7.2.c and 7.2.d), capitalizing on the
1120 relatively light-rich conditions of the shallow water column (Cloern et al., 1989; Huzzey et al.,
1121 1990; Lucas et al, 1999; Lucas et al., 2009 ; Thompson et al., 2008). This is well illustrated in
1122 South Bay in Figure 7.4. Under appropriate lateral mixing conditions, production on the shoals
1123 can lead to appreciable biomass accumulation in the relatively unproductive channel (Lucas et
1124 al., 2009). However, higher turbidity resulting from tidally- or wind-driven local resuspension of
1125 sediments can decrease productivity on the shoals (Lucas et al., 2009). Furthermore, suspension
1126 feeding by clams can more efficiently clear the shallow shoal water column than the channel, and
1127 reign in shoal blooms (see Section 7.2.3; and Lucas and Thompson 2013). Despite the
1128 importance of productivity in shoals, there is very limited data available from these areas.
1129 Increased monitoring (and in particular continuous monitoring with moored sensors, e.g,
1130 turbidity, chlorophyll, etc.) is needed to understand when shoal induced blooms (Figure 7.2.c and
1131 7.2.d) drive production in subembayments when

1132
1133 Cole and Cloern (1984) demonstrated that primary production rates in SFB could be reliably
1134 quantified by knowing incident light intensity, depth of the photic zone, and the concentration of
1135 phytoplankton biomass (as µg chl-a L⁻¹). This predictive relationship was calibrated using an
1136 “efficiency factor”, ψ , for new biomass production per unit light energy (expressed in units mg
1137 chl-a [Einstein m⁻²]⁻¹), which is specific to the phytoplankton community of the system (Cole
1138 and Cloern, 1987; Jassby et al., 2002). This relationship is valid as long as ψ remains constant
1139 over space and time (Jassby et al., 2002 ; Kimmerer et al. 2012 ; Parker et al., 2012), and C:chl-a
1140 is reasonable well-known and constant. Recent studies focused in northern SFB have suggested
1141 that both ψ and C:chl-a may have changed considerably over the past 20 years, potentially due to
1142 large changes in phytoplankton community composition (Kimmerer et al., 2012; Parker et al.,
1143 2012).

1144

1145 *Nutrients and phytoplankton production rates*

1146 While nutrient concentrations play an important role in initiating or terminating phytoplankton
1147 blooms in many estuaries, nutrients tend to be replete year-round in SFB, and thus they seldom
1148 control production rates (Figure 7.5 and 7.3.b). Nutrient concentrations do exhibit periodic
1149 drawdowns in SFB, owing at least in part to phytoplankton growth (Thompson et al., 2008).
1150 However, concentrations infrequently dip to levels that are low enough to cause production to
1151 proceed more slowly (Figure 7.5 and 7.3.b). Instead, field and modeling studies in SFB suggest
1152 that phytoplankton bloom termination at the subembayment scale generally occurs due to other
1153 factors, especially break-down in stratification (Cloern 1991), and sometimes increase in grazing
1154 pressure (Thompson et al., 2008).

1155
1156 *Low production rates due to elevated ammonium in Suisun Bay*

1157 Recent studies in SFB and the Delta have argued that the influence of nutrients on biomass
1158 production rate may be more complex than the generally accepted idea of nutrient limitation on
1159 growth. Studies by Dugdale and colleagues suggest that elevated NH_4^+ levels in Suisun Bay and
1160 the Delta slow primary production rates and can prevent blooms from developing (Dugdale et al.
1161 2007, 2012; Parker et al., 2012a,b). These studies refer to the phenomenon as the “ NH_4^+
1162 paradox”: the crux of the hypothesis is that when NH_4^+ concentrations exceed 2-4 μM ,
1163 phytoplankton can not access the relatively large NO_3^- pool on which they studies suggest they
1164 can grow more rapidly than NH_4^+ . The NH_4^+ paradox studies acknowledges that other factors
1165 such as light limitation, clam grazing, and residence time also exert influence over phytoplankton
1166 production or biomass accumulation; However they hypothesize that NH_4^+ -inhibition of
1167 productivity could be a quantitatively important mechanism during critical periods, such as
1168 spring, when clam grazing may in fact be low due to seasonal variations in clam abundance
1169 (Dugdale et al., 2007).

1170
1171 There remains a lack of consensus among the regional scientific community about the
1172 mechanistic interpretations of the NH_4^+ -paradox studies, and about the potential ecosystem-scale
1173 importance of the mechanism relative to other factors limiting phytoplankton biomass
1174 accumulation. A detailed review of these studies was recently completed, and the reader is
1175 referred to that report for more information (Senn et al. 2012). Experiments to explore the
1176 mechanisms are continuing. Studies evaluating the relative importance of key processes that
1177 regulate biomass accumulation in Suisun and other subembayments, including NH_4^+ -inhibition,
1178 also need to be conducted, and could be readily carried out with basic biogeochemical models
1179 using currently available data.

1180 **7.2.3 Top-down biological processes that influence biomass accumulation**

1181 *Benthic grazing*

1182 Benthic grazing plays an important and sometimes dominant role in regulating the accumulation
1183 of phytoplankton biomass in some SFB subembayments or habitats within those embayments.
1184 (e.g., Thompson et al. 2008; Kimmerer and Thompson, in prep; Cloern et al., 2007). The effect
1185 of benthic grazing rates on phytoplankton biomass is dependent on the filtration rates ($\text{m}^3 \text{g}^{-1} \text{d}^{-1}$)
1186 of the species present and the abundance of grazers (g m^{-2}). Grazer abundance varies seasonally
1187 and spatially based on individual species’ life histories, predation, and habitat preference
1188 (salinity, sediment type, etc.). Grazer abundance is also tightly coupled to their food supply (i.e.,
1189 grazer growth requires phytoplankton or other planktonic food, such as bacteria and to a lesser
1190 degree particulate organic matter). The influence of a particular filtration rate on concentration of

1191 phytoplankton also depends on water column depth: a given abundance can filter the entirety of a
1192 shallow water column faster than they can filter a deep water column. Other factors such as
1193 benthic boundary layer thickness and stratification can also be important.

1194
1195 Clam filtration efficiency is high on relatively large phytoplankton (>5 μm = 100%; Kimmerer
1196 and Thompson, in prep) and lower for smaller phytoplankton (<5 μm = 75%; Kimmerer and
1197 Thompson, in prep; Werner and Hollibaugh, 1993). This size-dependent filtration efficiency
1198 may play be the reason behind observed shifts in the proportions of phytoplankton biomass
1199 toward smaller size-classes in Suisun Bay since the 1980s (Kimmerer et al., 2012), and may have
1200 similarly contributed to shifts in phytoplankton community composition, as discussed in Section
1201 9.

1202
1203 Three examples offer insights into the strong influence that benthic suspension feeders can have
1204 on phytoplankton biomass.

1205
1206 In 1987, the Asian overbite clam (*Corbula amurensis*) was first detected in Suisun Bay, and its
1207 effect on phytoplankton biomass was almost immediate (Figure 3.7.a). Baseline biomass values
1208 dropped off considerably, and peak biomass levels decreased by a factor of 5-10. While
1209 substantial phytoplankton blooms had been observed during most years prior to 1987, post-1987
1210 blooms have been a rare occurrence. *Corbula* biomass exhibits pronounced seasonality, and
1211 large interannual variability (Figure 7.6), as well as considerable spatial variability (Figure 7.7).
1212 This seasonality may allow windows for blooms to develop before clam grazing rates are high
1213 enough to draw down phytoplankton biomass. Occasional spring blooms have been observed
1214 over the last several years (Dugdale et al, 2012; R Dugdale, pers. comm.) . A large fall bloom
1215 was also observed in September 2011. *Corbula* tolerate salinities that are commonly
1216 encountered in Suisun (Low Salinity Zone; LSZ), and are well-established at all depths
1217 throughout Suisun and at locations in San Pablo Bay (Figure 7.6). *Corbula* do, however, have a
1218 fairly clear up-estuary boundary, apparently dictated by salinity, and researchers are exploring
1219 the potential for higher freshwater flows in the Delta to drive *Corbula* out of Suisun (Greene et
1220 al., 2011). *Corbula* are voracious filter feeders, and, at their current densities in the LSZ, grazing
1221 rates typically exceed phytoplankton growth rates in the LSZ (Figure 7.8).

1222
1223 Through the mid-1990s, benthic filter feeding was among the dominant controls on
1224 phytoplankton biomass accumulation and productivity in the South Bay (Thompson et al., 2008 ;
1225 Lucas et al., 2009). Clams were heavily preyed upon by migrating birds in the fall. Thompson
1226 et al. (2008) observed that interannual variations in abundance and timing of spring
1227 reestablishment of benthic suspension feeders along the shoals dictated whether or not blooms
1228 could form on the shoals, and propagate from the shoals to the channel (Figure 7.4.b).

1229
1230 Cloern et al (2007) observed sharp increases in chl-a and in gross primary production in the
1231 South Bay beginning in the late 1990s (Figure 7.9). After ruling out several potential drivers
1232 (e.g., changes in nutrient loads, SPM), they determined that the increase in phytoplankton
1233 biomass was due to pronounced loss of benthic suspension feeders, and that the decline of
1234 benthos abundance was due to an increase in benthivorous predators (sole, Bay shrimp,
1235 Dungeness crab; Figure 7.10). The increase in predator abundance was attributed to large scale
1236 climate forcings (a change in the Pacific Decadal Oscillation) that brought colder waters to SFB

1237 and allowed these predators to prey heavily over multiple years on benthic suspension feeders in
1238 SFB.

1239
1240 Grazing by benthic filter feeders is considered to be one of the main controls on phytoplankton
1241 biomass accumulation. In recent years there has been ample benthos monitoring in Suisun Bay
1242 and the Delta (and some in San Pablo Bay), although the fate of this program is not known.
1243 There are no sustained programs in the other subembayments. However, there are some years
1244 during which intensive benthic sampling has taken place (e.g., Thompson et al. 2008; see Figure
1245 7.X), and other opportunistic sampling efforts after which samples have been archived but not
1246 yet analyzed for biomass (J Thompson, personal communication). A consistent benthos
1247 monitoring program is needed in these other subembayments, most importantly Lower South
1248 Bay, South Bay, San Pablo Bay, and Suisun Bay.

1249 *Pelagic grazing*

1250
1251 Pelagic grazing rates on phytoplankton by zooplankton are dependent on the types of
1252 zooplankton present, their abundance, and their biomass-normalized grazing rates. Relevant
1253 zooplankton grazers in SFB can be roughly divided into two broad classes: mesozooplankton and
1254 microzooplankton. Results presented in Kimmerer and Thompson (in review) indicate that
1255 grazing by mesozooplankton, such as copepods, has only a limited effect on phytoplankton
1256 biomass in Suisun Bay. However, microzooplankton do have the potential to substantially
1257 influence phytoplankton biomass (Figure 7.8). Outside of Suisun Bay there are limited data on
1258 mesozooplankton and microzooplankton biomass and feeding rates. While, the effect of
1259 mesozooplankton grazing on phytoplankton biomass may be expected to be small, it is
1260 reasonable to expect that microzooplankton may also play a substantial role in other
1261 subembayments. Additional zooplankton monitoring in other subembayments is needed to better
1262 constrain pelagic grazing rates.

1263 **7.2.4 Spatial and temporal variations in phytoplankton biomass**

1264 Figure 7.11 presents monthly averages of phytoplankton biomass (2006-2011) broken down by
1265 subembayment; Figure 7.12 shows time series from 1975-2012. The highest phytoplankton
1266 biomass concentrations are generally observed in LSB. Bay-wide, the largest blooms typically
1267 occur in spring. Over the last ten years, however, pronounced fall blooms have also been
1268 occurring in LSB and SouthBay (Figures 7.11 and 3.6). Recent increases in baseline chl-a
1269 concentrations are also evident in all subembayments (Figure 7.12).

1270 **7.3 Conceptual Model: Microphytobenthos**

1271 Microphytobenthos (MPB) primary production has received little attention in SFB relative
1272 phytoplankton production. However, given the broad shallow shoals in several of SFB's
1273 subembayments, the primary production by benthic microalgae – or microphytobenthos (MPB) –
1274 could be important. Although only coarsely quantified due to limited data, Jassby et al. (1993)
1275 suggested that MPB production could account for as much as 30% of overall primary production.
1276 Thus, MPB production could have a substantial influence on food web structure (by favoring
1277 organisms and pathways that utilize benthic microalgae), dissolved oxygen budgets, and nutrient
1278 cycling. Most of this production would be concentrated in shallow areas of the estuary where the
1279 water column depth is less than the photic zone depth (<2 m, including the intertidal area)

1280

1281 Many of the same factors that influence phytoplankton growth rates of phytoplankton will
1282 similarly influence MPB growth. These include: light availability, temperature, and nutrients
1283 (Figure 7.1). While MPB primarily occur attached to bed sediments, they are also commonly
1284 found in the water column due to physical resuspension. Benthic diatoms (mainly pennate but
1285 some centric) have been the major taxa of MPB in limited studies in SFB (Guarini et al. 2002).
1286

1287 Accumulation of MPB biomass (often reported as $\text{mg chl-}a \text{ m}^{-2}$) is a function of productivity
1288 rates ($\text{mg chl-}a \text{ m}^{-2} \text{ d}^{-1}$), predation/grazing, and exchange with the water column. Light
1289 availability strongly influences MPB productivity and is a function of water column depth and
1290 light attenuation (i.e., SPM concentration), and of variations in depth due to tides. The amount
1291 of MPB resuspension depends on sediment type and consolidation, biofilm production in the
1292 sediment, and the magnitude of shear stresses (Macintyre, 1996; Underwood and Kromkamp
1293 1999). Sediment resuspension reduces light penetration for MPB remaining in sediment, but
1294 MPB in the water column could experience increased light availability. MPB residing on
1295 intertidal mudflats experience unattenuated incident light levels during low tide, and productivity
1296 would be greatest then. Nutrient limitation is unlikely to be an important constraint on MPB
1297 growth, because MPB can readily access NH_4^+ and PO_4 diffusing out of the sediments, provided
1298 there is sufficient organic matter remineralization and nutrient release. In sandy sediments with
1299 low organic matter content, MPB can be nutrient limited (Underwood and Kromkamp, 1999).
1300 MPB concentrations have been shown to be lower in sandy silts and sands than in finer, cohesive
1301 sediment ((Cammen, 1982; Montagna et al, 1983; Cammen 1991; de Jong and de Jonge, 1995;
1302 Underwood and Smith, 1998a). Temperature and CO_2 availability are thought to also influence
1303 MPB productivity, but are minor factors compared to light availability. Zoobenthos, some
1304 bottom-feeding fish, and birds would be the prime grazers on MPB. MPB biomass would be,
1305 however, generally unaffected by filter-feeding clams. Thus, MPB production may constitute
1306 larger portions of overall production in shallow areas with high abundance of filter-feeding
1307 clams.
1308

1309 While MPB production is potentially important in terms of its overall contribution to primary
1310 production, and some estimates of its magnitude have been made, little is known about how
1311 much it contributes to or shapes the food web, the net effect it has on dissolved oxygen budgets,
1312 or how it might respond to system perturbations (e.g, decreases in SPM). As noted above, Jassby
1313 (1993) estimated that MPB production could account for approximately 30% of overall primary
1314 production in both southern and northern SFB subembayments. Similar studies in other estuaries
1315 suggest that MPB could account for up to 50% of total primary production, but estimates vary
1316 widely due to different assemblages, sediment type and light availability in individual estuaries
1317 (Underwood and Kromkamp, 1999). Guarini et al (2002) estimated that MPB productivity (mg C
1318 ($\text{mg chl-}a$) $^{-1} \text{ d}^{-1}$) could be nearly 4x as large in South Bay as in Suisun Bay, possibly due to
1319 spatial differences in MPB assemblage or bathymetry-induced differences in light exposure to
1320 intertidal areas. In a more recent study, direct measurements of sediment chl-*a* ($\text{mg chl-}a \text{ m}^{-2}$)
1321 were made in September 2011 and March 2012 at sites in the Delta and open Bay (Cornwell and
1322 Glibert, in progress). Benthic chl-*a* abundance was roughly 30% larger in September than in
1323 March at both locations, and about 4x larger in the Delta than in the open Bay at both time
1324 points, with the latter difference likely due in part differences in depth and light availability.

1325 **7.4 Current state of knowledge**
1326 Tables 7.1 and 7.2 summarize critical information gaps related to phytoplankton biomass and
1327 MPB in SFB.

1328 **8 Dissolved Oxygen**

1329 **8.1 Introduction**

1330 Dissolved oxygen concentration can serve as a highly relevant indicator of nutrient-related
1331 impairment, both because maintaining sufficient dissolved oxygen levels is critical for sustaining
1332 aquatic life, and because low dissolved oxygen is a common ecosystem response to high nutrient
1333 loads. Oxygen is both produced and consumed within the estuary, and transported into the water
1334 column across the air:water interface and by water inputs and outputs. If the oxygen loss rate
1335 exceeds the oxygen production or input rate, hypoxia or anoxia can develop. Persistent hypoxia
1336 or anoxia leads to stress among or death of aquatic organisms, and also leads to sulfide gas
1337 production, which can be toxic to aquatic organisms and causes both odor and infrastructure
1338 damage (corrosion, discoloration of painted exteriors).

1339
1340 Prior to the 1970s areas of SFB (specifically LSB) did experience impairment due to persistent
1341 low DO (e.g., Cloern and Jassby, 2012). Implementation of secondary wastewater treatment
1342 addressed the issue of large-scale and persistent anoxia in deep subtidal areas. However, limited
1343 information is available about DO levels in shallow subtidal (sloughs, tidal wetlands) and
1344 managed ponds, and the extent to which low DO that occurs there may be problematic.

1345 **8.1 General DO conceptual model**

1346 Dissolved oxygen, measured at a given point in space and time in the water column, represents
1347 the concentration that results from multiple competing production and loss processes, as well as
1348 inputs, outputs, and mixing (Figure 8.1).

1349 **8.1.1 DO transport**

1350 O₂ is readily exchanged across the air:water interface, and has high solubility in water (Figure
1351 2.1). DO saturation concentration varies in direct proportional to the O₂ concentration in the
1352 overlying air (atmospheric pressure). The saturation concentration also decreases with
1353 increasing temperature and salinity. If DO concentrations in the water column are undersaturated
1354 relative to O₂ in the overlying air, atmospheric exchange will occur, with O₂ flux from the
1355 atmosphere into the water column. If DO concentration exceeds saturation (e.g., after periods of
1356 intense photosynthesis), DO flux will occur from water to the atmosphere. In both cases, flux
1357 occurs at a rate proportional to the magnitude of DO under- or over-saturation, and to the amount
1358 of turbulence at the water surface (determined largely by wind speed).

1359
1360 DO also enters (and leaves) the water column through fluvial transport (from the Delta, perennial
1361 ephemeral streams, stormwater inputs, and treated wastewater effluent), water exchange between
1362 subembayments (advective, tidal, gravitational), and mixing between zones within a
1363 subembayment. Exchange with an adjacent subembayment can result in net increases or
1364 decreases in DO depending on whether the prevailing conditions differ substantially between the
1365 two subembayments. During coastal upwelling events, gravitational circulation (i.e., intrusions
1366 of denser (colder, more saline) water) has the potential to transport substantial volumes of

1367 relatively low DO water far up-estuary (and displace an equal volume of relatively DO-rich
1368 water down-estuary), and measurably influence DO concentrations. Tidal exchange between a
1369 subembayment and wetlands, salt ponds, and sloughs along its margins could be a net source or
1370 sink of DO, depending on the balance of O₂ production and consumption in those systems. This
1371 is discussed further below.

1372 **8.1.2 O₂ production and consumption**

1373 Primary production - by phytoplankton, MPB, and macrophytes – produces O₂ during daylight
1374 hours. The O₂ production rate varies in proportion to the primary production rate, which, for
1375 phytoplankton and MPB, is light-limited in most SFB habitats. Thus, analogous to primary
1376 production rates (Section 7), O₂ production rates exhibit large variability on hourly and seasonal
1377 time scales, respond to weather conditions that influence incident light (cloud cover or fog), and
1378 may vary substantially between shallow and deep habitats or in response to stratification.

1379
1380 Respiration by aquatic and benthic organisms consumes dissolved DO. Viable phytoplankton
1381 respire throughout the entire day, and consume oxygen in the process. During daylight hours,
1382 their O₂ production exceeds respiration, resulting in net O₂ production; however, during dark
1383 periods only respiration occurs, with net DO consumption. As a result DO levels exhibit a daily
1384 sinusoidal-like cycle, with mid-day maxima and minima near mid-afternoon and sunrise,
1385 respectively.

1386
1387 Nitrification of NH₄⁺ to NO₃⁻ by nitrifying microbes also consumes O₂ (Figure . Treated
1388 wastewater effluent from POTWs is a major NH₄⁺ source to some subembayments. OM
1389 respiration also releases N in the form of NH₄⁺. Nitrification of NH₄⁺ from both sources occurs in
1390 the water column (pelagic nitrification) and at the sediment:water interface (benthic
1391 nitrification).

1392
1393 The balance between O₂ production and consumption is also influenced by microbial respiration
1394 of dead organic matter (OM). Microbes respire or degrade OM, both from phytoplankton and
1395 MPB biomass produced within SFB (autochthonous OM) and terrestrial organic matter
1396 (allochthonous OM) carried to the Bay by freshwater inputs and treated wastewater effluent (i.e.,
1397 commonly referred to as biochemical oxygen demand, BOD), and consume O₂ in the process.
1398 While BOD loads from POTWs used to be high, those loads decreased substantially once
1399 secondary treatment was implemented in the 1970s. Some of the respiration of OM occurs in the
1400 water column (pelagic respiration), but much of it happens in the sediments and at the
1401 sediment:water interface (benthic respiration) where particulate OM accumulates. Aerobic
1402 microbial respiration occurs continuously and its rate is strongly influenced by temperature, the
1403 abundance of fresh or readily-degradable OM, and DO concentrations. In the sediments, when
1404 the DO supply is exhausted (often by within a few millimeters or centimeters into the sediments),
1405 anaerobic respiration occurs using alternate electron acceptors (nitrate, manganese(IV), iron(III),
1406 sulfate). Although anaerobic respiration does not directly consume O₂, the reduced compounds
1407 produced (Fe(II), Mn(II), sulfide) can diffuse upward through the sediments and react with and
1408 consume O₂ (benthic oxidation).

1409
1410 Sediment oxygen demand (SOD), which includes benthic aerobic respiration, benthic
1411 nitrification, and benthic oxidation of reduced compounds, can play a dominant role influencing
1412 the O₂ budget of a habitat. This is particularly true in shallow habitats, where the ratio of

1413 overlying water volume to sediment area is relatively small compared to deeper areas. While
1414 SOD is comprised of several types of reactions, its rate is ultimately driven by the rate of OM
1415 loading, which can be allochthonous or autochthonous in origin. SOD can be gradually
1416 exhausted through oxidation; however, it is continuously replenished by new OM reaching the
1417 sediments. A substantial fraction of SOD likely traces directly back to internal production by
1418 phytoplankton and MPB, and therefore to nutrient loads, although allochthonous inputs may also
1419 contribute in margin habitats.

1420 **8.1.3 Spatial differences in O₂ budgets and DO concentrations**

1421 An aquatic ecosystem's O₂ budget can be characterized in terms of whether it acts as a net
1422 producer or consumer of O₂, referred to as net ecosystem metabolism (NEM). If a system
1423 produces more (NEM > 0) or less (NEM < 0) oxygen than it consumes it is considered net
1424 autotrophic or net heterotrophic, respectively. NEM will vary considerably based on the time
1425 scale and location considered, because of temporal (e.g., diurnal variability in O₂ production
1426 rate) and spatial variability in the relative magnitude of O₂ sources and sinks.

1427 Past studies have shown that SFB shallow shoals and intertidal areas are likely to have NEM > 1
1428 (Caffrey et al. 2003). Atmospheric exchange, along with high rates of phytoplankton and MPB
1429 primary production (due to the shallow water column and higher average light levels), maintain
1430 high DO concentrations. While SOD and pelagic respiration also occur in these areas, the DO
1431 inputs more than offset these O₂ sinks.

1432
1433 SFB's deep subtidal habitats more frequently have negative NEM (Caffrey et al. 1998), and, as a
1434 result, DO is often undersaturated in these areas. Due to light limitation, deep areas generally
1435 experience lower rates of pelagic primary production than shallow habitats, and little or no MPB
1436 primary production occurs due to insufficient light. As a result, O₂ production rates are lower. At
1437 the same time, deep channel areas receive both viable and dead/decaying phytoplankton inputs
1438 through lateral exchange with shallow subtidal areas, which exert O₂ demand. Although
1439 atmospheric flux of O₂ may occur at similar rates in shallow and deep habitats, the same O₂ flux
1440 entering the deep water column is diluted over deep subtidal areas larger volume; thus this
1441 exchange may not keep pace with respiration losses. Primary production rates in deep channel
1442 areas can be higher when the water column stratifies (Figure 7.2.b). However, eventually this
1443 OM settles to the bottom where it is respired. During stratified periods, DO concentrations
1444 decrease in bottom waters due to respiration, since DO cannot be replenished through vertical
1445 mixing or atmospheric exchange at the surface. Due to the relatively short duration of
1446 stratification events in SFB, deep subtidal DO levels seldom dip below 80% saturation (Figure
1447 8.2). Low DO can also be observed in SFB bottom waters when plumes or "intrusions" of
1448 recently-upwelled and relatively dense (colder, more saline) coastal water containing low-DO
1449 enter through the Golden Gate and occupy the bottom layer of some subembayments.

1450
1451 While measurements indicate that DO levels in deep subtidal areas are typically within an
1452 acceptable range, continuous monitoring data at Dumbarton bridge illustrate that DO
1453 concentrations do vary substantially. Oscillations of 1-2 mg L⁻¹ were observed during a 3-week
1454 time series from June 2011 (Schoellhamer et al., pers. communication). The variability in DO
1455 appeared to have both strong tidal and diurnal components, as well as a spring-neap component
1456 (Schoellhamer, 2011). The large variability indicates that oxygen demand within LSB can be
1457 quite substantial at the subembayment scale

1458
1459 SFB's shallow margin habitats – e.g., sloughs, tidal wetlands, and restored salt ponds -
1460 experience large DO swings due to both temporal variability in DO production rates and tidal
1461 exchange. Higher average light levels (due to the shallow water column) allow for high primary
1462 production – and O₂ production – rates during daylight hours (Figure 8.3, 8.4, 3.11.b). The
1463 greater abundance of phytoplankton and MPB biomass, and the higher loads of dead organic
1464 matter to the sediments, tend to cause higher pelagic and benthic respiration rates. SOD exerts
1465 more influence on DO concentrations than pelagic respiration in these systems, because of the
1466 relatively high ratio of sediment area to water column volume. At night, net O₂ production is
1467 negative leading to early morning DO minima. This diurnal cycle in the balance of O₂
1468 production and consumption is superposed upon semi-diurnal tidal exchange. During flood tide,
1469 relatively DO-rich water from the larger subembayment moves into the margins and supplements
1470 the O₂ budget. During slack and ebb tide, the tidal DO supplement is consumed by SOD (Figure
1471 8.4). DO undersaturation will thus be most pronounced when ebb tide occurs during nighttime.

1472
1473 To what extent might the low DO levels in SFB's shallow margins be the result of anthropogenic
1474 perturbations, in particular high nutrient loads? And do current conditions constitute an impaired
1475 state? Answering these questions is nontrivial. The processes described above, and the resulting
1476 low DO are common to wetland-like habitats, even in relatively pristine ecosystems, native
1477 organisms are well-adapted to deal with this cycle. Three issues need to be considered: i.
1478 whether or not DO deficits are more severe than natural conditions, i.e., lower DO, longer
1479 duration, or more frequent occurrence; ii. the extent to which anthropogenic nutrients cause or
1480 contribute to the more severe conditions; and ii. whether the conditions cause impairment.

1481
1482 Since anthropogenic loads are the main nutrient sources to SFB, anthropogenically-derived
1483 nutrients undoubtedly contribute to primary production and thereby contribute new OM to the
1484 sediments to maintain SOD. However, because primary production rates in many areas of SFB
1485 are light-limited as opposed to nutrient-limited, the higher nutrient concentrations may not be
1486 efficiently converted into biomass, and may not necessarily translate into substantially higher
1487 SOD in, for example, sloughs in LSB. Some data is available to explore this issue, and detailed
1488 quantitative analysis (e.g., modeling) of primary production rates and OM and DO budgets in
1489 shallow margin habitats is needed to address this question.

1490
1491 Some highly-altered habitats in SFB have delicately balanced O₂ budgets. For example, restored
1492 salt ponds in LSB have extremely high primary production and O₂ production rates, made
1493 possible by relatively high light levels and high nutrient concentrations (Thebault et al., 2008).
1494 Respiration rates are also high due to the reservoir of labile OM in the sediments, and large
1495 fluctuations in DO levels occur (Figure 3.11.a and 8.3). While Figure 8.3 shows a diurnal cycle
1496 of maxima and minima, DO can also crash for longer periods of time. Thebault et al. (2008)
1497 observed that when primary production rates are periodically low (e.g., during a prolonged
1498 period of summer clouds or fog), sustained periods of anoxia can occur (Figure 3.11.a). On the
1499 one hand, the high productivity supports wetland food webs, including those of migratory birds
1500 (Thebault et al. 2008). On the other hand, the extent to which the large diurnal fluctuations in
1501 DO, or the more prolonged periods of anoxia that occur on cloudy days (Thebault et al., 2008),
1502 constitute impairment is not currently known. In sloughs, it is not known whether the DO deficits
1503 or the duration of low DO conditions exceeds what would occur naturally, or, similarly, the

1504 degree to which elevated anthropogenic nutrient loads and any incremental increases primary
1505 productivity. South Bay, San Pablo Bay, and Suisun Bay also have substantial shallow subtidal
1506 margin habitats. Additional DO data exists from margin habitats in LSB and likely other
1507 subembayments and needs to be further evaluated. Well-designed experiments and monitoring
1508 may also be needed.

1509 **8.2 Current state of knowledge**

1510 Table 8.1 summarizes major knowledge and data gaps for dissolved oxygen.

1511 **9. Phytoplankton Community Composition**

1512 **9.1. Introduction and Background**

1513 Phytoplankton community composition is highly relevant to the ecological status and function of
1514 the greater San Francisco Bay. The importance of community composition follows directly from
1515 the general conceptual model for phytoplankton biomass (Section 7), since it is the community at
1516 the level of strains, species, and functional types that in aggregate makes up the “phytoplankton
1517 biomass”. Selection pressure operates on species and has resulted in systematic phylogenetic
1518 differences between the red and green “superfamilies” (Quigg et al., 2003). These evolutionary
1519 differences in turn drive differences in nutrient assimilation, elemental composition, growth
1520 rates, and size (Irigoien et al., 2004; Irwin et al., 2006; Quigg et al., 2003). This has profound
1521 effects on ecosystem function. Phytoplankton photosynthesis drives the metazoan food webs of
1522 San Francisco Bay (Cloern et al., 2005; Jassby et al., 1993; Kimmerer et al., 2012). Changes in
1523 community composition can also alter energy flow from predominantly supporting higher
1524 trophic levels to a microbially-dominated, highly regenerating community which in turn leads to
1525 increased respiration and hypoxia (c.f. Cloern and Dufford 2005).

1526
1527 There are several potential ways to assess community composition (Figure 9.0). One of the
1528 simplest divisions is based on size. As a general rule, increased mean (or median) phytoplankton
1529 size is directly related to increased productivity, increased new production, and increased trophic
1530 transfer (Chisholm, 1991; Wilkerson et al., 2000). Phytoplankton size is particularly important
1531 for SFB because only phytoplankton $> \sim 5 \mu\text{m}$ equivalent spherical diameter (ESD) are available
1532 as a food source for copepods (Berggreen et al., 1988, #271). Size-based classification is
1533 sometimes coupled with nutritional mode to separate the plankton into heterotrophs, mixotrophs,
1534 and Photo-autotrophs (Figure 9.1). While this is convenient conceptually, there is increasing
1535 evidence that many phytoplankton, including perhaps the majority of dinoflagellates, are
1536 facultative mixotrophs, blurring the line between these divisions (Burkholder et al., 2008).

1537
1538 Moving beyond size, a common approach taken when examining community composition is to
1539 group organisms into “phytoplankton functional types” (PFTs) such as diatoms, dinoflagellates,
1540 cryptophytes, etc., and/or based on trait-differentiated groupings such as high-nutrient, high light,
1541 etc. (Reynolds et al., 2002; Smayda et al., 2001). This level of analysis is often convenient for
1542 relating phytoplankton composition to ecological forcing functions (e.g. Cloern and Dufford,
1543 2005). Continuing to a finer level of detail, community composition can also be analyzed at the
1544 species level, the basis for taxonomic classification. Finally, there is increased interest in the
1545 molecular and strain-level variability of phytoplankton. This becomes particularly important
1546 when the organism of interest is considered a harmful algal bloom (HAB) species (Burkholder et

1547 al., 2006{, #277}), in part because many of the coastal HAB organisms do not fit well into
1548 classic paradigms as a function of PFT or size Kudela et al., 2010).

1549
1550 For the purposes of this conceptual model, it is assumed that phytoplankton community
1551 composition can be adequately addressed using a combination of high-level metrics (size, trophic
1552 status, functional category) with the exception of HAB organisms that must be assessed at the
1553 species or strain level.

1554 9.2. General Conceptual Model

1555 In order to use community composition as a metric for ecosystem status it is first necessary to
1556 define the spatial extent of the Bay included in the model. While the physical (geographical)
1557 boundaries are set, with the open ocean as one (external) boundary and the Sacramento/San
1558 Joaquin River and South Bay inputs as the other boundary, there are at least three potential
1559 models for describing San Francisco Bay (Figure 9.2):

- 1560 1) the Bay is a mixture of the ocean and riverine end-members;
- 1561 2) the Bay is a separate and distinct estuarine community, with mixing (source and sink) of
1562 oceanic and freshwater phytoplankton at the boundaries;
- 1563 3) the Bay is composed of a series of basins (e.g. South Bay, Central Bay, etc.) with distinct
1564 community composition.

1565
1566 Under scenario 1, community composition is largely driven by external factors that influence the
1567 oceanic and freshwater end-members. Scenario 2 assumes that the phytoplankton are dominated
1568 by a distinct estuarine community with transient “invasion” by oceanic and riverine inputs.
1569 Scenario 3 is predicated on distinct communities occupying each sub-basin, responding to
1570 location-specific forcing, such that Suisun is under fundamentally different control than South
1571 Bay (for example). These scenarios are not mutually exclusive, and could (for example) vary
1572 seasonally or interannually in response to river flow, residence time, and hydrologic
1573 modifications such as the restoration of the South Bay Salt Ponds.

1574
1575 The community composition data necessary to evaluate these conceptual models do exist, and
1576 distinct patterns have been identified between (e.g. South Bay and North Bay, However, the data
1577 are often aggregated to look at large-scale and long-term patterns (Cloern et al., 2005,
1578 2010;Kimmerer,et al. 2012; Winder et al., 2010) unless there is an obvious end-member
1579 intrusion impacting the community composition (Cloern et al., 2005; Lehman et al., 2010). *A*
1580 *first-order question that should be examined in more detail is whether a sub-basin analysis*
1581 *provides more or less information than the aggregate trends.* For now, it is assumed that a
1582 simple model with oceanic, freshwater, and estuarine components is sufficient for development
1583 of a community composition conceptual model. This forms the basis for the conceptual model
1584 developed by the Phytoplankton Composition working group (Figure 9.3). Specific forcing
1585 functions are discussed in more detail below.

1586 9.2.1. General trends

1587 San Francisco Bay exhibits both a weak seasonal cycle and decadal trends in community
1588 composition that generally follow the trends identified for the Biomass conceptual model. Total
1589 chlorophyll in the Delta is typically high in summer (Jassby et al. 2002) while chlorophyll in
1590 south San Francisco Bay is the highest during (typically) several-week spring blooms and shorter
1591 fall blooms (Cloern et al. 2007). Like many nutrient enriched systems, San Francisco Bay is

1592 characterized by a bloom-bust cycle of larger cell species periodically dominating a more stable
1593 community of small cell species (Cloern and Dufford, 2005; Wilkerson et al., 2006; Kimmerer et
1594 al. 2012). These large-cell blooms are superimposed on a picoplankton background population
1595 composed primarily of cyanobacteria and small eukaryotes (*Nannochloropsis* sp., *Teleaulax*
1596 *amphioxeia*, *Plagioselmis prolonga*) that are found across a wide range of salinities and seasonal
1597 conditions (Ning et al., 2000; Cloern and Dufford, 2005).

1598
1599 San Francisco Bay contains over 500 phytoplankton taxa. Approximately 10-20 phytoplankton
1600 species account for between 77% and >90% of the total biomass (Cloern and Dufford, 2005).
1601 Diatoms (Bacillariophyta) dominate, accounting for ~81%; dinoflagellates and cryptophytes
1602 (Pyrrophyta and Cryptophyta) made up 11% and 5% respectively (Cloern and Dufford, 2005).
1603 Picoplankton make up <15% of the Bay biomass (<2% during blooms; Ning et al., 2000; Cloern
1604 and Dufford, 2005).

1605
1606 At a decadal scale several shifts in community composition are evident. Some phytoplankton
1607 taxa (*Prorocentrum aporum*, *Coscinodiscus marginatus*, *Protoperidinium depressum*, *Eucampia*
1608 *zodiacus*) have not been seen since 1996 while others (*Protoperidinium bipes*, *Pseudo-nitzschia*
1609 *delicatissima*, *Scrippsiella trochoidea*, *Thalassiosira nodulolineata*) have appeared. The benthic
1610 diatom *Entomoneis* sp. Similarly was a minor component of the community from 1992-2001,
1611 comprising 0.1% of the biomass and identified in about 20% of all samples (Cloern and Dufford
1612 2005, as reported in Kimmerer 2012). Kimmerer et al 2012 suggest that, although it is not clear
1613 how much it contributes to productivity in the water column, its sudden appearance at a fairly
1614 substantial portion of phytoplankton biomass could be an indication of change in the system.

1615
1616 There is also evidence for abrupt shifts in community composition from the longer time-series.
1617 Total biomass decreased substantially in 1986 (Figure 9.4) as noted by many others (e.g.
1618 Lehman, 2000; Glibert, 2010; Kimmerer, 2012). Lehman (2000) identified a decrease in diatom
1619 abundance from 1975-1989 linked to the 1977 climate regime shift and El Niño, attributing the
1620 change to community shifts in high stream flow, wet years (low light, high turbulence, favoring
1621 pennate diatoms) and dry years (long residence time, favoring cryptophytes and flagellates).
1622 Using the same data, Glibert (2010) identified a decline in diatoms, cryptophytes, chlorophytes,
1623 and cyanobacteria after 1986, coincident with an abrupt decline in biomass. These shifts were
1624 attributed to changes in nutrient composition and stoichiometry. These abrupt shifts in
1625 community composition are readily apparent from the community composition time-series at
1626 Station D7 in Grizzly Bay (Suisun), collected by DWR/IEP (Figure 9.5), although it should be
1627 noted that the DWR/IEP values are cell counts and should be interpreted with caution since
1628 biovolume is not accounted for. ***A clear goal for this conceptual modeling framework is to***
1629 ***identify the major drivers of these long-term trends in community composition, and to relate***
1630 ***these drivers to metrics of ecosystem health and stability.*** This is a challenging proposition
1631 given that, with the same datasets, multiple authors have proposed several (potentially
1632 conflicting drivers including, but not limited to, basin- and climate-scale variability, river flow,
1633 nutrient composition and stoichiometry, light limitation, and benthic grazing. The main factors
1634 are discussed in more detail below, and are divided (approximately) into bottom-up physical
1635 factors, inherent physiological factors, top-down factors, and interactive or multiplicative factors.

1636 **9.2.2. Bottom-Up Control: Basin-scale oscillations**

1637 There is ample evidence that San Francisco Bay community composition responds more or less
1638 uniformly (i.e. across the estuary) to both basin-scale and climate-scale trends. As described
1639 above, Lehman (2000) identified stream flow as an important indicator of community
1640 composition. Low light, turbulence, and short residence times were associated with pennate and
1641 single-celled centric diatoms. Cryptophytes and flagellates were associated with “critically dry”
1642 periods of increased residence time, light intensity, and water temperature. Cloern et al. (1983)
1643 similarly argued that river flow can regulate community composition by selectively retaining
1644 particles (neritic diatoms) near productive shallow bays under low flow, but promotes loss of
1645 seed populations during both high and very low flow (drought) because of changes in circulation
1646 and the position of the suspended particulate maximum. Within the Delta, low streamflow has
1647 also been associated with enhanced *Microcystis* blooms (Lehman et al. 2010), attributed to
1648 reduced turbulence and prolonged retention. Basin-scale oscillations also profoundly impact the
1649 coastal plankton assemblage. Since the oceanic end-member can serve as a seed population for
1650 the estuary, San Francisco Bay is also indirectly influenced by El Niño, the Pacific Decadal
1651 Oscillation, the North Pacific Gyre Oscillation, and other mesoscale changes (Cloern et al. 2005,
1652 2010).

1653
1654 While these observed patterns suggest that community composition is regulated by (and
1655 therefore can be to some extent predicted; Cloern et al. 2011), a larger analysis of coastal
1656 estuaries suggests that each estuarine system is unique and responds to some combination of
1657 annual forcing, regime shifts and climate trends, and the residual (or stochastic) component
1658 (Cloern and Jassby 2008, 2010), suggesting that the low-frequency basin- or climate-scale
1659 patterns must be interpreted with caution.

1660 **9.2.3 Bottom-Up Control: Temperature**

1661 Phytoplankton species composition is strongly controlled by temperature, since each species and
1662 strain exhibits an optimal growth response to a specific temperature range (Eppley, 1972). In
1663 addition to this species-level response PFTs also exhibit some generalized temperature optima.
1664 Diatoms generally prefer colder temperatures, and are associated with cool periods both annually
1665 and interannually in San Francisco Bay (Lehman 2000). Diatoms also exhibit optimal nitrate
1666 assimilation at lower temperatures and also reduce nitrate under cold temperatures as an electron
1667 sink to maintain optimal energy balance (Lomas and Glibert, 1999). As temperature rises some
1668 PFTs respond positively. *Microcystis* and other cyanobacteria appear to be favored by warmer
1669 conditions (Lehman et al. 2010; Paerl and Huisman 2008, 2009). Less is known about the
1670 temperature-specific response for other PFTs (flagellates, cryptophytes, dinoflagellates) but
1671 community composition generally shifts towards more of these groups coincident with increased
1672 temperature (e.g. Lehman 2000). Because temperature covaries with several other
1673 environmental factors including flow, nutrients, stratification, etc. it is difficult to determine what
1674 the impact of rising temperatures would be. ***Experimental manipulations of temperature or***
1675 ***temperature and CO₂ would provide useful information about potential shifts in***
1676 ***phytoplankton community composition for San Francisco Bay.***

1677 **9.2.4 Bottom-Up Control: Irradiance**

1678 San Francisco Bay productivity is generally considered to be light-limited, and is well described
1679 by a “light utilization” productivity model that uses chlorophyll, PAR, and light attenuation
1680 (Cole and Cloern 1984). Parker et al. (2012) recently re-evaluated this approach and concluded

1681 that while the general model still works, there is considerable variability in the calibration
1682 coefficient, possibly due to a shift in the carbon:chlorophyll ratio of the phytoplankton
1683 assemblage. Parker et al. (2012) noted that concurrent evaluation of the phytoplankton
1684 community composition from 2006-2007 (during their study period) by Lidström (2009) are
1685 consistent with PFT-specific shifts in both the C:CHL ratio and P_m^B (light-saturated
1686 productivity). The authors conclude that seasonal, interannual, and long-term shifts in
1687 community composition from diatoms to flagellates may be linked to changes in the modeled
1688 productivity. ***This suggests that, if bulk productivity estimates are to be used as an index of***
1689 ***ecosystem health, the light-utilization model should be updated to include PFT-specific***
1690 ***response functions.***

1691 **9.2.5 Bottom-Up Control: Mixing/Turbulence**

1692 As summarized in Cloern and Dufford (2005), mixing and turbulence become important for
1693 phytoplankton community composition primarily through alleviation of light limitation due to
1694 runoff-induced salinity stratification, increased light penetration (decreased turbidity), and
1695 separation of phytoplankton and benthic grazers. Classically, it is also assumed that diatoms
1696 respond positively to turbulence while ephemeral dinoflagellate blooms respond to “windows of
1697 opportunity” when environmental conditions, such as reduced grazing, enhanced stratification,
1698 and warm conditions, allow these organisms to respond rapidly (e.g. Stoecker et al. 2008; Cloern
1699 et al. 2005). As noted above, there is also evidence for shifts between diatoms and
1700 flagellates/cyanobacteria linked to changes in retention and mixing (e.g. Lehman et al. 2010). It
1701 should be noted, however, that Cloern and Dufford (2005) noted niche-separation of a small
1702 number of marine and riverine species, but also noted that a large fraction of the phytoplankton
1703 community were “generalists”, doing equally well across a broad range of conditions (Figure
1704 9.6). This suggests that canonical descriptions of PFT response to environmental conditions
1705 such as mixing are potentially useful but should not be over-interpreted.

1706 **9.2.6 Physiological Factors: Nutrients**

1707 San Francisco Bay is generally considered to be nutrient-replete. This has been corroborated
1708 several times (e.g. Mallin et al. 1993), and is supported by the lack of response between
1709 productivity and river flow (Kimmerer 2005, 2012). While this perspective is useful for
1710 examining forcing of phytoplankton biomass, this general nutrient-replete condition can mask
1711 considerable variability at the species or PFT level of community composition. It is generally
1712 assumed that dinoflagellates exhibit low affinity for N-substrates relative to diatoms (Smayda,
1713 1997, 2000) and that nutrient uptake kinetics scale as a function of cell size (larger size equals
1714 lower affinity; e.g. Irwin et al., 2006; Litchman et al., 2007), although Collos et al. (2005) argue
1715 that at high-nutrient concentrations, such as in upwelling systems and estuaries, multiphasic
1716 kinetics may be quite common among a diverse array of phytoplankton species. Kudela et al.
1717 (2010) summarized the measured kinetics responses for N-uptake in several algal groups,
1718 focusing on harmful algal bloom species from upwelling systems (Figure 9.7). While the general
1719 canonical pattern of lower K_s for diatoms and higher for dinoflagellates, there is considerable
1720 overlap and the number of recorded species is quite low. It is particularly striking that there
1721 appear to be no phytoplankton strains isolated from San Francisco Bay in the National Center for
1722 Marine Algae (NCMA). Again, this highlights the need to be cautious when applying canonical
1723 patterns for nutrient utilization derived from global data sets.

1724

1725 Despite the nutrient-replete status of San Francisco Bay, several groups have proposed direct or
1726 indirect nutrient effects on phytoplankton species composition. While not specific to San
1727 Francisco Bay, vitamin B1, B7, and B12 have been implicated in controlling phytoplankton
1728 species composition in both estuarine (Tang et al. 2010) coastal, and HNLC waters (Koch et al.
1729 2011). The response is greatest in large (>2 μm ESD) cells, and in particular for dinoflagellates.
1730 There has been no published evaluation of vitamin B effects in San Francisco Bay.

1731
1732 Other nutrient interactions have also been poorly defined for the estuary. For example, free
1733 copper has a strong, PFT-specific response on algae (Brand et al. 1986; Sunda and Huntsman,
1734 1995), and elevated copper concentrations will become toxic to phytoplankton (Brand et al.
1735 1986; Sunda et al. 1987). Brand et al. (1986) demonstrated that neritic diatoms are least
1736 sensitive, while cyanobacteria and dinoflagellates were most sensitive to copper. Copepods such
1737 as *Acartia tonsa* also exhibit more sensitivity to copper than do diatoms (Sunda et al. 1987),
1738 suggesting that copper could subtly impact both the productivity and loss terms, leading to shifts
1739 in community composition. Buck et al. (2007) recently reviewed copper trends in San Francisco
1740 Bay. They concluded that copper concentrations have declined significantly since 1993, with the
1741 North Bay declining 17% and South Bay declining 29-44%. No data are available prior to 1993,
1742 but copper concentrations were presumably elevated since the Gold Rush of 1848. As copper
1743 concentrations drop, it is at least possible that inhibition of flagellates, cyanobacteria, and
1744 zooplankton has been alleviated, leading to increased competition with diatoms.

1745
1746 Two other nutrient relationships have been proposed as regulators of both total biomass and
1747 community composition. Dugdale et al. (2007) have proposed that elevated ammonium
1748 concentrations from wastewater discharge is suppressing diatom productivity, while Glibert
1749 (2010) and Glibert et al. (2011) have argued that N:P ratios are indirectly controlling community
1750 composition. Dugdale et al. (2007) proposed a modified conceptual model of bloom initiation for
1751 the North Bay as follows: (1) In spring, increased irradiance and increased river flow (diluted
1752 ammonium) promote diatom growth, initially fueled by ammonium; (2) if the ammonium is
1753 drawn down to < ~4 μM , nitrate uptake is initiated; (3) if conditions remain suitable (increased
1754 irradiance, low ammonium, retention) a bloom develops. This hypothesis was developed
1755 primarily with direct field observations, but there are multiple ongoing projects evaluating
1756 several aspects with both field and laboratory experiments.

1757
1758 Elevated external NH_4^+ levels are toxic to photosynthetic organisms because the build-up of a
1759 charged molecule on one side of cell membranes results in the establishment of a high cross-
1760 membrane potential. While NH_4^+ is mostly transported into the cell via active, ATP-dependent
1761 transport (as are nearly all charged molecules) it can also passively diffuse into the cell via
1762 channels (facilitated diffusion). When external concentrations are elevated, these channels will
1763 allow a large influx of NH_4^+ as a consequence of the cross-membrane potential. The influx
1764 initiates active pumping to rid the cytosol of NH_4^+ and to prevent an intracellular pH disturbance
1765 (Bligny et al. 1997). However, the efflux of NH_4^+ maintains the cross-membrane gradient,
1766 thereby the channel influx, and necessitates continued, active efflux pumping at a great energetic
1767 cost to the cell, culminating in the cessation of growth and sometimes death of the organism
1768 (Britto et al. 2001). Some plant species have adapted to high external NH_4^+ concentrations by
1769 preventing the establishment of a cross-membrane potential, eliminating the futile NH_4^+ cycling
1770 and high respiratory cost of efflux pumping (Britto et al. 2001). Because the susceptibility to the

1771 establishment of a cross-membrane potential varies from organism to organism, susceptibility to
1772 NH_4^+ toxicity also varies greatly. For example, susceptibility to NH_4^+ toxicity is known to vary
1773 by orders of magnitude in aquatic plant species and in unicellular algae. Freshwater unicellular
1774 algae such as *Chlorella vulgaris* isolated from wastewater settling ponds can tolerate NH_4^+
1775 concentrations up to 3 mmol/L (Berg et al. unpublished data, Perez-Garcia et al. 2011). Among
1776 marine species, diatoms also tolerate NH_4^+ concentrations in the mmol/L range (Antia et al.
1777 1975, Lomas 2004, Hildebrand 2005, Pahl et al. 2012). In contrast, marine phytoplankton species
1778 with a large variety of NH_4^+ transport proteins encoded in their genomes, and with low half
1779 saturation constants for NH_4^+ uptake, can be susceptible to toxicity at orders of magnitude lower
1780 NH_4^+ .

1781
1782 While NH_4^+ toxicity at the physiological level has a response time on the order of the cell
1783 division time, it can culminate in a much greater, community-level response that builds-up over
1784 longer time scales. The community-level response is manifested through a change in
1785 phytoplankton community composition to species that are more tolerant to high NH_4^+
1786 concentrations and to primary and secondary consumers that can feed on those species (Glibert et
1787 al. 2011). This can also lead to proliferation of Harmful Algal Blooms since many of the noxious
1788 and toxic species found in the California Current show a preference for reduced N compounds
1789 such as NH_4^+ (Kudela et al. 2010). It's this community-level response that is important for
1790 ecosystem function. But, the latter cannot occur if the former, physiological effect is not present.

1791
1792 To date, investigators have used a lack of chlorophyll *a* (Chl *a*) biomass or a lack of nitrate (NO_3^-
1793) uptake as evidence of NH_4^+ stress on the phytoplankton community in Suisun Bay, (Dugdale et
1794 al. 2007). However, both changes in Chl *a* and NO_3^- uptake may be influenced by a multitude of
1795 factors including irradiance, community composition, and season, making it difficult to use these
1796 indirect measures as evidence of NH_4^+ inhibition (e.g. Kimmerer et al. 2012). While the
1797 ammonium-inhibition hypothesis appears to explain the observations from the North Bay, it is
1798 unclear why similar nutrient concentrations do not result in the same phenomenon in the South
1799 Bay, since NH_4^+ occurs at similar concentrations there. ***A direct comparison between the North
1800 and South Bay would likely help to determine whether ammonium concentrations are directly
1801 inhibiting diatoms, are indirectly shifting the community towards organisms with lower K_s , and
1802 higher maximal uptake rates (Figure 9.7), or are covarying or interacting with some other
1803 variable such as irradiance, or size-selective grazing (Section 9.2.7).***

1804
1805 A complementary hypothesis linking nutrients and community composition has been proposed
1806 based on the stoichiometry of N and P (Glibert 2010; Glibert et al. 2011). Glibert (2010)
1807 proposed that decadal changes in phytoplankton community composition altered the food web of
1808 San Francisco Bay by favoring varying groups of organisms. Prior to 1982, the community was
1809 dominated by a nitrate-driven diatom assemblage (Figures 9.5, 9.9). With the increasing
1810 ammonium loads from wastewater treatment plants the community shifted towards flagellates.
1811 As the N:P ratio continued to increase, cyanobacteria were eventually favored. This analysis is
1812 based largely on a statistical metric called cumulative sum analysis, and has been criticized by
1813 others as flawed (Cloern and Jassby et al. 2012; but also see Lancelot et al. 2012). Glibert et al.
1814 (2011) elaborated on this argument by proposing a conceptual model for how estuarine systems
1815 respond to changes in N:P ratios. They argue that even though N and P are in excess for
1816 phytoplankton growth, the ratio impacts higher trophic levels (and thus the ecological

1817 stoichiometry of the system). The authors argue that decadal changes in DIN:DIP ratios correlate
1818 with declines in diatoms and chlorophytes, and increases in dinoflagellates, because diatoms and
1819 dinoflagellates also exhibit different intrinsic N:P ratios. There are two potential issues with this
1820 argument. First, so long as N and P are saturating, the ratio should have no direct impact on
1821 species composition, other than by selecting for the organism with optimal growth (loss).
1822 Second, Chlorophytes have a higher N:P ratio than either diatoms or dinoflagellates, suggesting
1823 that chlorophytes should be dominant under these conditions (Figure 9.10). The authors argue
1824 that this is accounted for due to the stoichiometric adjustments and feedback loops that occur
1825 between primary producers and higher consumers, and that both the Pelagic Organism Decline
1826 and the invasion of organisms such as *Corbula* were triggered by bottom-up control through
1827 nutrient stoichiometry. These assertions are controversial, but the conclusion, that phytoplankton
1828 community composition is an indicator of ecosystem “health”, is consistent with other
1829 hypotheses.

1830 **9.2.7 Top-Down control: *Corbula***

1831 While Glibert et al. (2011) conclude that the invasion of *Corbula* was triggered by gradual shifts
1832 in ecosystem nutrient stoichiometry, others have pointed to the invasion as coincident with the
1833 rapid decline of diatoms in San Francisco Bay (Figure 9.5). The long-term shift in
1834 phytoplankton from diatoms to flagellates and cyanobacteria and the timing of declines in
1835 apparent silica uptake in Suisun Bay (Kimmerer 2005) and in abundance of anchovies in the
1836 Low Salinity Zone (Kimmerer 2006) are consistent with an influence of size-selective grazing by
1837 the clam *C. amurensis*. *Corbula* exhibits lower feeding rates on bacteria (typically <1 µm) than
1838 on phytoplankton (Werner and Hollibaugh 1993). Thus, the phytoplankton biomass available to
1839 many grazers is considerably lower than indicated by bulk chlorophyll values. The combination
1840 of low productivity and a high proportion of small cells offers poor support to the food web of
1841 the upper estuary, likely resulting in shifts in diet and food limitation and contributing to the poor
1842 condition of some fish species (Feyrer et al. 2003; Bennett 2005) and the general pattern of
1843 decline across species and trophic levels (Kimmerer et al., 2012). This direct modulation of
1844 phytoplankton community composition by an introduced benthic predator presents a conceptual
1845 model of trophic interactions that is strikingly different from the bottom-up, stoichiometrically
1846 driven scenario described above. As detailed below, *Corbula* grazing could also have other
1847 indirect impacts on community composition in addition to the size-selective removal of PFTs.

1848 **9.2.8 Top-Down control: other grazers**

1849 Winder and Jassby (2011) document both abrupt and gradual changes in zooplankton
1850 composition, abundance, and occurrence in San Francisco Bay. Major shifts coincide with the
1851 extended drought from 1987-1994 and the invasion by *Corbula*. The calanoid copepod
1852 *Limnoithona tetraspina* increased rapidly in the 1990s to become the numerically abundant
1853 zooplankton, presumably due to predator avoidance, low respiration, and a dietary preference for
1854 bacteria and mixotrophic ciliates, which were in turn stimulated by the shift from diatoms to
1855 flagellates and cyanobacteria (Figure 9. 11). Rollwagen-Bollens et al. (2011) also noted the
1856 importance of microzooplankton as both a consumer of small autotrophs and a link to metazoans.
1857 Microzooplankton grazing is classically assumed to differentially impact small autotrophs,
1858 suggesting that microzooplankton grazing has increased in importance with the shift away from
1859 diatoms. This could also lead to more stochastic bloom events of other organisms as proposed by
1860 Irigoien et al. (2005) and Stoecker et al. (2008), who argued that blooms occur when a particular
1861 species of PFT exploits a “loophole” in grazing pressure. This is also consistent with Greene et

1862 al. (2011) who reported high mortality rates of microzooplankton due to *Corbula* grazing, thus
1863 potentially disrupting trophic transfer and stimulating more nano- and picoplankton by removing
1864 grazing pressure on these smaller organisms, even though the nano- and picoplankton are not
1865 efficiently grazed by *Corbula* directly. This highlights the potential complex interactions
1866 between top-down and bottom effects in relation to the use of phytoplankton community
1867 composition as an index of ecosystem health.

1868 9.2.9 Interactive Effects

1869 Several of the previous sections allude to interactive effects between multiple drivers. For
1870 example, water flow regulates turbidity, water clarity, residence time, nutrient concentrations and
1871 ratios, and benthic-pelagic coupling. Trace metals and vitamins can have subtle influences on
1872 phytoplankton community composition, leading to shifts in trophic efficiency as well as shifts in
1873 dominant phytoplankton assemblages. The ecological stoichiometry hypothesis proposed by
1874 Glibert et al. (2011) assumes a series of interactive effects, ultimately stemming from changes in
1875 nutrient forms and ratios. A conceptual model (or models) of phytoplankton community
1876 composition must be flexible enough to allow for these interactive effects, and for differential
1877 responses spatially and temporally.

1878
1879 A specific example of the potential for interactive effects focuses on light-nutrient-
1880 photosynthesis interactions. There is clear evidence for light limitation of phytoplankton
1881 productivity in San Francisco Bay, while it is generally accepted that macronutrients are not
1882 limiting to productivity. The interactive effects of these processes are rarely examined, but can
1883 have a direct impact on phytoplankton community composition. After carbon assimilation,
1884 nitrogen metabolism is the second largest sink for photosynthetic reductant (ATP, NADPH) in
1885 most photo-autotrophs. Under light limitation (e.g. San Francisco Bay), it is often assumed that
1886 ammonium will be a preferred N source compared to nitrate because of the large differential in
1887 energy required, since nitrate must be reduced first to nitrite and then to ammonium before being
1888 metabolized in the cell (Figure 9.12). As noted above, diatoms will also reduce nitrate as an
1889 electron sink under rapidly changing light environments (such as occurs in a turbulent estuary).
1890 Much of this N is subsequently effluxed as ammonium. This could conceivably lead to a scenario
1891 where (1) diatoms are initially light-limited in a heterogenous, rapidly mixing environment,
1892 leading to (2) efflux of ammonium, nitrite, and DON as an electron sink; as the water column
1893 stabilizes, (3) physiological energy balance is restored, ammonium efflux stops, and N is
1894 assimilated to produce more biomass, leading to (4) depletion of ammonium followed by
1895 depletion of nitrate as a diatom bloom develops. While there is no direct evidence for this
1896 occurring in San Francisco Bay, Kimmerer et al. (2012) noted that productivity was positively
1897 correlated to light availability and negatively correlated with ammonium concentrations, while
1898 Parker et al. (2012) noted a shift towards lower C:N ratios, both of which are consistent with this
1899 scenario.

1900
1901 These potentially complex interactions are not limited to diatoms. A previous field study of a
1902 “red tide” of the dinoflagellate *Lingulodinium polyedrum* in Southern California demonstrated
1903 that to maintain the bloom, the dinoflagellates had to be using urea, possibly in some
1904 combination with other nitrogen sources (Kudela and Cochlan, 2000). This observation would
1905 not be evident from direct measurements of nutrients, photosynthetic carbon fixation, or ¹⁵N-
1906 labeled nitrogen uptake, but could be inferred by comparing the elemental ratio of the algae with
1907 nutrient kinetics curves, nutrient versus irradiance uptake curves, and photosynthesis versus

1908 irradiance curves (Figure 9.13). In contrast to typical paradigms, the bloom could also maintain
1909 balanced growth at very low or very high irradiances using only nitrate, while the classic
1910 Michaelis-Menten kinetics would suggest the bloom was using $\text{NO}_3 > \text{NH}_4 > \text{Urea}$. While these
1911 complex interactions are presumably common in dynamic environments, simultaneous
1912 evaluation of these interactive effects is rarely performed. Since every species (and probably
1913 strain) of algae has a potentially unique combination of light, nutrient, and carbon assimilation
1914 capabilities there is plenty of opportunity for seemingly stochastic selection of species or PFTs in
1915 the real world.

1916 **9.2.10 Harmful Algae**

1917 A special case within the larger framework of phytoplankton community composition are those
1918 organisms classified as harmful algal blooms. This provides perhaps the most direct metric of
1919 ecosystem health since presence of the algae and associated toxins is a clear indication of
1920 impaired ecosystem health. Similarly, HAB organisms are well studied at the species level in
1921 terms of both physiological parameters and ecological patterns. Despite the persistent nutrient
1922 enriched status of San Francisco Bay, few harmful algal blooms have been reported recently for
1923 the estuary. A lack of monitoring may play a role, given the large number of potentially harmful
1924 algae present in San Francisco Bay (Cloern and Dufford, 2005; Table 3.1 and Figure 3.9).
1925 However, there have been historical occurrences (see Cloern et al., 1994 referenced in Cloern,
1926 1996), and recently cyanobacteria and dinoflagellate blooms have been documented. For
1927 example, blooms of the cyanobacteria *Microcystis aeruginosa* have been occurring in the late
1928 summer/autumn in the northern reaches of the Bay since 1999 (Lehman et al., 2005), the
1929 raphidophyte *Heterosigma akashiwo* created a red tide in the Central Bay in summer 2002
1930 (Herndon et al., 2003), and the dinoflagellate *Akashiwo sanguinea* caused a red tide in the
1931 Central and South Bay areas during September 2004 (Cloern et al., 2005).

1932
1933 *Microcystis aeruginosa* blooms have occurred in the Delta and the North Bay during July
1934 through November of each year since 1999. The colonial form of *M. aeruginosa* is the first
1935 recorded toxic phytoplankton bloom in the northern reach of SF Bay and may have been recently
1936 introduced because it was not recorded in historic samples taken between 1975 and 1982
1937 (Lehman et al., 2005). *M. aeruginosa* can form surface scums and is a nuisance to recreational
1938 users; reduce aesthetics and oxygen; and produce microcystin, a hepatatoxin to humans and
1939 wildlife (Lehman et al., 2005; Lehman et al., 2008). Several surveys of *M. aeruginosa* blooms
1940 have documented that the blooms can be widespread, often with microcystin concentrations that
1941 exceed World Health Organization guidelines for risks to humans and wildlife (e.g., Lehman et
1942 al. 2005; Lehman et al., 2008). *M. aeruginosa* may also produce cascading effects on the food
1943 web (Brooks et al. 2012).

1944
1945 The other well-studied HAB organisms within California waters, *Alexandrium catenella* (causes
1946 paralytic shellfish poisoning) and *Pseudo-nitzschia spp.* (causes domoic acid poisoning) are also
1947 present in the estuary. Indeed, sampling in South Bay Salt Pond A18 during 2006 (Thébault et al.
1948 2008) revealed the presence of six phytoplankton taxa that can potentially cause harmful algal
1949 blooms (HABs): dinoflagellates *Alexandrium sp.* And *Karenia mikimotoi*, pelagophyte
1950 *Aureococcus anophagefferens*, raphidophyte *Chattonella marina*, and cyanophytes
1951 *Anabaenopsis sp.* And *Anabaena sp.* Microscopic analysis of samples collected by USGS
1952 monitoring in 2006 and 2008 revealed seven additional species of phytoplankton (e.g., Figure 3.9
1953 and Table 3.1) that, at bloom abundances, have disrupted aquatic food webs, caused mortality of

1954 invertebrates, fish and birds, or human illness in other shallow marine ecosystems. In 2007 and
1955 2008 the USGS water-quality sampling program also found HAB species in South San Francisco
1956 Bay, including *Karlodinium (Gyrodinium galatheanum) veneficum* (November 2007),
1957 *Chattonella marina* (March 2008), and *Heterosigma akashiwo* (September 2007). Appearances
1958 of these taxa are surprising because they were not detected previously in 3 decades of sampling
1959 (Cloern and Dufford 2005). These observations, all made after the first commercial salt ponds
1960 were opened in 2004, suggest that the salt ponds might function as incubator habitats and a
1961 source of toxic phytoplankton to San Francisco Bay as they are opened to tidal exchange.
1962 Dinoflagellates, flagellates, and pelagophytes form HABs in other shallow marine ponds that are
1963 enriched in organic matter and have long hydraulic residence time (e.g. Gobler et al. 2005).
1964 Shallow, semi-isolated systems (such as the salt ponds) can also serve as “biological capacitors”,
1965 providing inocula for large-scale blooms in nearby bay and coastal waters (Vila et al., 2001).
1966 Actions to open these habitats might pose an unanticipated risk to the water quality and living
1967 resources of San Francisco Bay and to tidal-ponds created by the South Bay Salt Pond
1968 Restoration Program, particularly for water birds and fish assemblages.

1970 A common theme emerging from observations of all recent HAB blooms have been there
1971 occurrence in the summer and autumn months, perhaps associated with the decline of the spring
1972 and summer diatom blooms and consumption of regenerated nutrients. ***Given the prevalence of***
1973 ***HAB organisms in the Bay, the dramatic increase in blooms of Microcystis, and the potential***
1974 ***linkages between ecosystem health and HABs (Kudela et al. 2008), it would be prudent to***
1975 ***more closely monitor HAB organisms within San Francisco Bay as an indicator of water***
1976 ***quality.***

1977 **9.3 Summary of Major Conceptual or Data Gaps**

1978 San Francisco Bay is somewhat unique in that it is well studied for both physical/environmental
1979 parameters, and for phytoplankton community composition. Despite this wealth of information,
1980 any attempt to develop a conceptual model of community composition runs into the fundamental
1981 issue identified by Cloern and Dufford (2005): “...the problem is hyperdimensional, whereby
1982 communities are assembled by selective forces operating on variation in algal size, motility,
1983 behavior, life cycles, biochemical specializations, nutritional mode, chemical and physiological
1984 tolerances, and dispersal processes...our knowledge base is therefore insufficient for
1985 constructing reliable numerical models of phytoplankton population dynamics at the species
1986 level, in spite of our recognition that the functions provided by the phytoplankton vary among
1987 species.”

1988
1989 While this issue is not intractable, it is unlikely that we will be able to predict or even understand
1990 the species-level variability in San Francisco Bay in the near future. We can, however, identify
1991 important components of a conceptual model for phytoplankton community composition at the
1992 level of traits and ecosystem function (Figure 9.0). The immediate challenge is to identify the
1993 relative importance of these sometimes conflicting conceptual relationships. A long-term goal
1994 should perhaps be the development of sophisticated numerical-biological models that incorporate
1995 “evolution” and natural selection. This approach is being increasingly applied to oceanic
1996 ecosystems with some success (Follows and Dutkiewicz 2011) and has recently been used to test
1997 fundamental questions about community assembly and stability (Barton et al. 2010a,b).
1998

- 1999 Several gaps in our ability to develop or apply a conceptual model of phytoplankton community
 2000 assembly include the following specific issues:
- 2001 • It is unclear how many spatio-temporal compartments need to be included for San Francisco
 2002 Bay. The estuary could be modeled as single unit, as North Bay versus South Bay, or as a
 2003 series of sub-basins. While many authors recognize that algae are both imported and exported
 2004 from the ocean and riverine end members, it is still very common to describe the mean
 2005 patterns for the estuary or to develop conceptual models based on data from particular
 2006 locations.
 - 2007 • The estuary clearly responds to forcing from the oceanic and riverine end-members; any
 2008 conceptual model of community assemblage for San Francisco Bay must be linked to models
 2009 of the coastal ocean and the watershed.
 - 2010 • The estuary is generally considered to be nutrient-replete, but there is little or no information
 2011 available about vitamins, trace-metals, and the influence of anthropogenic contaminants such
 2012 as pesticides that may be influencing community composition. Several of these factors would
 2013 likely co-vary with more easily measured parameters and could easily be overlooked.
 - 2014 • Very little is known about the species-specific physiological properties of the community,
 2015 nor about the potential interactions between (e.g.) light, nutrients, photosynthesis, etc.
 - 2016 • The presence of HABs and toxins has been largely ignored in San Francisco Bay. The
 2017 prevailing assumption is that the Bay is resilient to these impacts, but this may simply be a
 2018 lack of monitoring and measurement. Large-scale restructuring such as the opening of the
 2019 salt ponds has the potential to suddenly and dramatically alter this perspective.
 - 2020 • Several conceptual models have been proposed that could account for the abrupt and long-
 2021 term trends in community composition, and are diametrically opposed. Similar to the classic
 2022 paradigm of top-down versus bottom-up control in marine systems, reality is probably
 2023 somewhere in between, and may change spatially and temporally (Figure 9.14).

2024 **10 Other proposed impairment pathways and indicators**

2025 There are other possible nutrient-related impairment pathways and indicators that have not been
 2026 considered in detail in this report. These are described briefly below, and may warrant further
 2027 consideration in future versions of the nutrient-response conceptual model.

2028 *Submerged aquatic vegetation (SAV) habitat*

2029 Eelgrass beds provide protective habitats for small or spawning fish, influence the structure of
 2030 benthic communities and enhance resistance of sediment to re-suspension and erosion. Loss of
 2031 SAV habitat has been used in other estuaries as would serve as indicator of impairment. The
 2032 most abundant and most well studied SAV species in SFB is *Zostera marina*, commonly known
 2033 as eelgrass (Zimmerman 1991, 1995; Schaeffer 2007). Eelgrass extent, density and productivity
 2034 appear to be regulated largely by light limitation (Zimmerman 1991, 1995). In SFB, where the
 2035 euphotic zone can be less than 1m in many areas (Alpine and Cloern 1988), eelgrass are found in
 2036 low turbidity near-shore areas of San Pablo Bay, Central Bay and South Bay at depths <2m
 2037 (Zimmerman 1991). The contribution of eelgrass and other SAV to overall ecosystem
 2038 productivity is currently unknown. In other estuaries, where high nutrient concentrations have
 2039 lead to large phytoplankton blooms, that phytoplankton biomass shaded SAV, limiting its access
 2040 to light and causing die-off. In SFB, where the vast majority of the turbidity comes from non-
 2041 phytoplankton SPM, this is not currently an issue.

2043 *Invasive plants*
2044 Non-native submerged and floating aquatic vegetation has become widespread in Suisun Bay
2045 and the Delta, the most common of which are *Egeria densa* (Brazilian elodea, submerged) and
2046 *Eichhornia crassipes* (curly-leaf pondweed, floating) (C Foe, personal communication). *Egeria*
2047 currently occupies thousands of acres in the Delta. Similar to native SAV, *Egeria* abundance is
2048 largely regulated by light availability. Overgrowth of *Egeria* can have multiple effects on light
2049 availability. Dense *Egeria* beds can shade out phytoplankton, MPB or native macrophytes, but
2050 less dense growth can slow local water velocity and cause settling of suspended matter, possibly
2051 then stimulating additional *Egeria* growth. Growth of *Eichhornia* is largely regulated by light,
2052 since nutrients are abundant in the region. *Eichhornia* overgrowth can impair the ecosystem by
2053 shading out phytoplankton, MPB and native macrophytes. Extremely high density *Eichhornia*,
2054 beyond typical density of native macrophytes, can be cause abnormal organic matter loading to
2055 sediment and contribute to low dissolved oxygen. Nutrients are not currently limiting the growth
2056 of these invasives, and the State Water Board is currently evaluating the ability of nutrient load-
2057 reductions to control the spread of these species.

2058
2059 *Direct NH₄⁺ toxicity to copepods*

2060 Changes in the quality and availability of food for pelagic fishes has been identified as one
2061 potential factor that could be contributing to the recent Pelagic Organism Decline (POD) in the
2062 Delta and Suisun Bay. According to Baxter et. al. (2010), overall zooplankton abundance and
2063 size has decreased over the last four decades, which could be exerting bottom-up pressure on the
2064 food web, since zooplankton are the primary prey for Delta smelt and other pelagic fishes. It has
2065 been hypothesized that grazing (e.g., by clams), low prey abundance (i.e., low phytoplankton
2066 biomass), direct toxicity of contaminants, or some combination of these stressors are acting to
2067 maintain low zooplankton populations, or suboptimal quality of zooplankton for supporting the
2068 food web.

2069
2070 In a 2011 study funded by the Central Valley Regional Water Quality Control Board, Teh et. al.
2071 (2011) studied the acute and chronic effects of ammonia + ammonium on *Pseudodiaptomus*
2072 *forbesi*. This species is of particular interest because according to studies by the CA Department
2073 of Fish and Game (CDFG) that examined gut contents of larval fish, during most times of the
2074 year *P. forbesi* is the dominant food source for all fish that have shown declining populations
2075 (delta smelt, longfin smelt, striped bass and threadfin shad), and changes in *P. forbesi* abundance
2076 is likely to have significant effects on the food web.

2077
2078 The concentrations at which acute toxicity was observed far exceed ambient levels of NH₃+NH₄⁺
2079 in SFB. However, in a chronic toxicity 31-day life cycle test, Teh et al. (2011) observed that
2080 gravid females either produced significantly lower numbers of nauplii or survival of nauplii and
2081 juveniles to adulthood was significantly lower when they were exposed to NH₄⁺ at levels as low
2082 as 0.36 mg N L⁻¹ (26 μmol L⁻¹). Even 26 μM is still substantially higher than typical ambient
2083 concentrations in SFB (Figure 6.4). However, the lowest dose used in Teh et al (2011) was 26
2084 μmol L⁻¹, which was also the lowest observed effect level; a no observed effect level was not
2085 established. Discussions are underway about potentially redoing this study, and among other
2086 goals trying to establish a no observed effect level.

2087 **11 Scenario Analysis**

2088 **11.1 Introduction**

2089 The future trajectory of SFB's response to nutrients is uncertain. One plausible trajectory is that
2090 SFB maintains its current level of resistance to high nutrient loads and no further degradation
2091 occurs. A second, equally plausible scenario is that SFB's resilience continues to decline until
2092 moderate to severe impairment occurs along one or more pathways in some subembayments. The
2093 highly elevated DIN and DIP concentrations Bay-wide provide the potential for future
2094 impairment to develop. Any major reductions in loads to SFB would take years-to-decades to
2095 implement. Thus, if future problems are to be averted, potential impairment scenarios need to be
2096 anticipated, evaluated, and, if deemed necessary, managed in advance of their onset.

2097

2098 Section 3 addressed the question

2099 *What would a nutrient-related problem look like in SFB if a problem is currently occurring or if*
2100 *one was to occur in the future?*

2101 Eight plausible impaired states were identified (Table 3.2), based on experiences in other
2102 estuaries, and the current state of knowledge in SFB.

2103

2104 As described in Sections 6-10, factors that limit the conversion of N and P into phytoplankton
2105 biomass are what have historically prevented SFB from experiencing classic symptoms of
2106 nutrient-related impairment, such as exceedingly high phytoplankton biomass and low dissolved
2107 oxygen. Nutrients are abundant in SFB. However, primary production rates are strongly limited
2108 by light availability throughout most of the year due to high turbidity and strong tidal mixing of
2109 the water column. In some subembayments and habitats, filter feeding clams exert a further
2110 strong control that limits phytoplankton biomass accumulation. In addition, algal species that
2111 have formed harmful or nuisance blooms in other estuaries are regularly detected in SFB. There
2112 are ample nutrients to support their proliferation. However, low light levels, strong tidal mixing,
2113 and relatively cold water temperatures limit opportunities for HAB and NAB formation.

2114

2115 To identify future scenarios that need to be considered, we asked the following questions:

- 2116 • *What would have to change to sufficiently relax physical or biological controls and allow*
2117 *current nutrient loads to be more efficiently turned into phytoplankton biomass, HABs and*
2118 *NABs to become common or widespread occurrences, or phytoplankton composition to*
2119 *shift toward suboptimal assemblages?*
- 2120 • *What is the outlook based on current trends alone (no dramatic changes beyond the*
2121 *continuation of those trends)? Based on those, are subembayments on a path toward*
2122 *impairment?*
- 2123 • *What management actions or environmental changes could prevent or mitigate nutrient-*
2124 *related impairment?*

2125

2126 11.1.1 *What would have to change to sufficiently relax physical and biological controls and*
2127 *allow current nutrient loads to be more efficiently turned into phytoplankton biomass, HABs and*
2128 *NABs to become common or widespread occurrences, or phytoplankton composition to shift*
2129 *toward suboptimal assemblages?*

2130 Addressing this question, using the conceptual model as a guide, pointed us toward several
2131 categories of change that have the potential to move areas of SFB toward impairment:

- 2132 • Increased light availability
- 2133 • Increased duration of stratification events
- 2134 • Loss of benthic grazers
- 2135 • Increased seeding rates of undesirable phytoplankton species
- 2136 • Warmer water in margin habitats
- 2137 • Increased residence time in margin habitats

2138 Some of these changes in SFB were identified because of their importance primarily for a single
2139 impairment pathway, while others may act along multiple pathways. We next identified
2140 scenarios that could potentially cause these changes. Scenarios that could lead to these changes
2141 are described in Table 11.1, and the linkages between scenarios and categories of change are
2142 illustrated in Figure 11.1. The effect that individual or multiple changes may have on
2143 impairment indicators are illustrated in Figure 11.2.

2144

2145 11.1.2 *What is the outlook based on current trends?*

2146 We considered current trends in indicators that have generated concern that SFB is on a path
2147 toward nutrient-related impairment. In some cases, observed trends in readily measured
2148 parameters (e.g., phytoplankton biomass) suggest an increased responsiveness to current nutrient
2149 loads, however, the underlying causes are poorly understood and the trajectories uncertain. In
2150 other cases, a well-understood causal link between nutrients and an indicator (e.g., low DO in
2151 shallow margin habitats) may exist but insufficient monitoring and modeling limit the ability to
2152 assess whether impairment is occurring, and whether that impairment is related to anthropogenic
2153 nutrient loads. Finally, recent studies have suggested nutrient-impairment pathways that are
2154 currently poorly understood (e.g., phytoplankton community composition, HABs, NABs) both in
2155 the terms of the mechanistic links and potential magnitude of the effect relative to other factors
2156 that also influence the indicator.

2157

2158 11.1.3 *What management actions or environmental changes could mitigate nutrient-related* 2159 *impairment?*

2160 Finally, we considered scenarios or actions that could be taken to mitigate or prevent
2161 impairment. These are also described in Table 11.1.

2162

2163 To limit the scenarios to a manageable set, basic guidelines for scenario selection were
2164 established. First, only scenarios that had a reasonable likelihood of occurring were considered.
2165 The threshold for likelihood for environmental change was set at a similar change having
2166 occurred previously in SFB or other estuaries (e.g., decreases in suspended sediment
2167 concentrations, climate oscillations causing shifts in biota assemblages, or abrupt loss of species
2168 due to disease) or based on anticipated effects of climate change. Management scenarios were
2169 based on what was considered technologically or economically feasible. For all scenario types, a
2170 time horizon of 20-30 years was considered, compatible with planning horizons for large-capital
2171 management projects. Thus, some scenarios related to sea level rise did not receive major
2172 consideration.

2173

2174 Potential impairments within a subembayment – and the role that individual scenarios could play
2175 in hastening or mitigating impairment – were ranked *LOW*, *MEDIUM*, or *HIGH* based on a
2176 combination of:

- 2177 • the potential effect magnitude of the impairment or mitigation

- 2178 • the current level of understanding about the linkage between the scenario and the
2179 impairment/mitigation pathway, or about probability that the scenario could develop
2180

2181 The ranking approach is illustrated in Figure 11.3. The goal of the ranking approach, employing
2182 these two axes (magnitude of effect, current understanding), was to identify and prioritize
2183 scenarios that require further consideration to: i. Evaluate the likelihood and potential magnitude
2184 of a problem developing; ii. Assess the risk of no action; or iii. Evaluate the potential of a
2185 management action to prevent or mitigate problems.
2186

2187 Figure 11.4 presents a broad overview of the prioritization results for *Current Trends*. Figure
2188 11.5 presents the ranks given to each subembayment-impairment-scenario combination for
2189 *Change Scenarios* and *Mitigation Scenarios*. Since the prioritizations reflect both the potential
2190 magnitude of a problem and the current level of understanding, some *HIGH* ranks were assigned
2191 based on actual field observations of changing ecosystem response, while others owe their rank
2192 in large part to our current limited understanding of present-day conditions, underlying
2193 mechanisms, or potential magnitudes of effect.
2194

2195 These scenarios are not intended as predictions of future conditions, nor are the rankings meant
2196 to imply that a scenario is considered imminent, or, conversely, unimportant. Instead, we used
2197 these scenarios and rankings to guide thinking about how SFB might respond to changes and
2198 mitigation efforts, and identify scenarios that require further consideration.
2199

2200 Sections 11.2-11.3 describe a subset of the subembayment-impairment-scenario combinations.
2201 Section 11.4 narrows the focus to a smaller subset considered the highest priority issues to focus
2202 monitoring and research efforts in the near term (e.g., next 1-5 years).

2203 **11.2 Impairment Scenarios**

2204 **11.2.1 Current Trends**

2205 Figure 11.4 ranks impairment scenarios assuming that recent trends continue, but no major
2206 environmental changes occur and no major management actions are implemented.
2207

2208 *High biomass and low DO in deep subtidal areas:* Based on recent trends (Figure 3.4), the
2209 potential for high biomass and low DO in deep subtidal areas emerge as high priority issues in
2210 LSB and South Bay. While phytoplankton biomass in both subembayments does not appear to
2211 be currently causing pronounced impairment, the rate of change in biomass has been rapid. In
2212 addition, there remains a high degree of uncertainty about the underlying cause(s) of this change
2213 and, therefore, uncertainty around how biomass may change in the future: is the increase
2214 primarily due to loss of clams, as suggested by Cloern et al., (2007), or have other factors (e.g.,
2215 declining suspended sediments) also played a role? This issue can be readily explored through
2216 basic modeling, which, in addition to providing a quantitative evaluation of the importance of
2217 major controlling factors, can identify near-term data collection and monitoring needs. Effort
2218 also needs to be directed toward continuous monitoring of phytoplankton biomass, DO, turbidity,
2219 etc., and the collection of bivalve abundance data to better constrain the magnitude of major
2220 drivers.
2221

2222 *Low DO in margin habitats:* Current conditions of low DO in shallow margin habitats were
2223 identified as a high priority in LSB, South Bay, and Suisun Bay. This high ranking is based on
2224 several considerations: recent observations showing low DO in shallow margin habitats in LSB,
2225 and delicately poised systems (i.e., high DO production rates and high respiration rates, and the
2226 potential for prolonged low DO periods when primary production rates are low); the large areas
2227 of shallow margin habitat in LSB, South Bay, and Suisun Bay with limited monitoring to date, or
2228 limited analysis of data to date; the lack of knowledge about whether the intensity, duration or
2229 frequency of low DO are similar to or exceed natural conditions; and, if impairment is occurring,
2230 the plausibility of a link to high nutrient loads. Analysis of existing data for frequency, duration,
2231 and intensity of low DO, and interpretation of those observations (potentially with the help of
2232 basic models) will provide valuable insights into whether there is currently impairment, and the
2233 extent to which that impairment is due to anthropogenic nutrients. Depending on the outcome of
2234 those analyses targeted monitoring and special studies in these habitat types may be warranted.

2235
2236 *HABs and HAB toxins:* HABs need to be considered a high priority issue in all of SFB's
2237 subembayments. While recent measurements have revealed Bay/Delta-wide detection of HAB
2238 toxins (Figure 3.8), both the ecological significance of these observations and the extent to which
2239 they are a new/emerging phenomena (as opposed to having always been present) are unknown.
2240 HAB-forming species are frequently detected throughout the estuary at low abundances (Table
2241 3.1, Figure 3.9) and have been observed at moderate abundance in salt ponds undergoing
2242 restoration (Thebault et al., 2008). While the current ecological significance, trends, and
2243 potential magnitude of any HAB-related impacts in SFB are unknown, based on evidence in
2244 other nutrient-enriched estuaries, increased frequency of HABs and related toxins may be among
2245 the most likely impairments to occur in SFB. Future monitoring work and special studies need
2246 well-designed HAB and HAB-toxin components to document status and trends and develop
2247 improved understanding around the factors favoring HAB formation and toxin production. That
2248 improved understanding will pave the way toward identifying actions that could be taken, if
2249 necessary, to mitigate current or future impairment from HABs and HAB-toxins.

2250
2251 *NABs:* The red tide bloom in Central Bay and South Bay during Fall 2004 was the first of its
2252 kind in 40 years of study in SFB. It is unknown whether this was a random event, unrelated to
2253 other changes in SFB, or if it was the first in what might be a trend of more frequent NAB
2254 occurrences. For that reason, NABs are considered high priority for all subembayments. If
2255 sufficiently long-term and reliable climate/weather records exist for the Bay area they could be
2256 examined to determine if the conditions that allowed this bloom to develop (multiple clear, calm
2257 days in a row) have been occurring more frequently during periods of low tidal energy in the
2258 Fall.

2259
2260 *Low phytoplankton biomass caused by elevated NH_4^+ :* Low phytoplankton biomass resulting
2261 from elevated NH_4^+ is considered a high priority in Suisun Bay, where biomass levels are
2262 extremely low and blooms occur rarely, and where most recent effort on this topic has been
2263 directed (Dugdale et al., 2007; Parker et al., 2012a,b; Dugdale et al. 2012). There remains a lack
2264 of consensus within the scientific community about both this impairment mechanism and its
2265 importance relative to other processes regulating biomass accumulation. While the process has
2266 been intensively studied in lab and field studies over the past several years, more work is needed
2267 to explore the mechanism and thresholds. Furthermore, the same mechanism should be occurring

2268 in South Bay and LSB given the comparable concentrations of NH_4^+ there, but the regular
2269 phytoplankton blooms in those subembayments mean that either NH_4^+ inhibition of blooms does
2270 not occur there, or it does not play as important a role there (e.g., due to longer water residence
2271 time and lower clam grazing rate).

2272
2273 *Suboptimal phytoplankton composition:* Changes in phytoplankton composition due to elevated
2274 nutrients and altered nutrient ratios (N:P, $\text{NH}_4:\text{NO}_3$) needs to be considered a high priority Bay-
2275 wide. This *HIGH* ranking stems primarily from limited testing to date of the hypothesis that high
2276 nutrient concentrations, or altered N:P or high $[\text{NH}_4^+]$, are adversely affecting phytoplankton
2277 community assemblages within SFB; and the poorly understood mechanistic link between
2278 altered nutrient abundances and phytoplankton composition in SFB, a light-limited system with
2279 an overabundance of all nutrient forms. It was recently hypothesized that elevated nutrients and
2280 altered nutrient ratios (N:P, $\text{NH}_4:\text{NO}_3$) have played an important role in causing the pronounced
2281 changes in phytoplankton community composition in Suisun Bay since the 1980s (Glibert et al.,
2282 2012). The mechanisms underlying this hypothesis need to be rigorously explored through
2283 further detailed conceptual model development based on the scientific literature, statistical
2284 analysis of long time series of composition data from Suisun Bay and the Delta, analysis of
2285 composition data from other subembayments, and potentially through experimentation and
2286 numerical modeling. The analysis in Suisun Bay needs to consider the major role that size-
2287 selective grazing by the invasive *Corbula* clam, which became densely established in 1987, has
2288 played in shaping community composition.

2289
2290 *Other food web effects:* There is currently only limited field and experimental evidence (Teh et
2291 al., 2011; Glibert et al., 2012) that nutrients, at ambient concentrations in SFB, can affect the
2292 food web along pathways other than those explored in Sections 6-9. Other mechanisms should
2293 not be ruled out, and their mechanistic links need to be more firmly established through review
2294 of the scientific literature, and potentially experimentation. However, compared to other
2295 impairment pathways, these other direct and indirect effects were not considered to be among the
2296 highest priorities issues.

2297 **11.2.2 Change scenarios leading to impairment**

2298 Figure 10.5 provides an overview of future impairment scenarios, subembayment, ranking each
2299 subembayment-indicator-scenario combination. This section discusses only a subset of the
2300 impairment scenarios.

2301
2302 *High biomass and Low DO in deep subtidal areas:* The potential for high biomass and low DO
2303 to occur under future scenarios were identified as high priority issues throughout most of SFB.
2304 A diverse set of scenarios could bring about these conditions, including: i. continued decreases in
2305 suspended sediment concentrations; ii. increased frequency and duration of climactic conditions
2306 that allow for fall thermal stratification to develop and persist; iii) changing rainfall patterns that
2307 strengthen and lengthen spring salinity stratification; and iv. wetland or salt pond restoration
2308 dampening turbulent mixing energy, which would allow stratification to persist longer during its
2309 current spring and fall periods, and during other times. Suisun Bay currently has extremely low
2310 phytoplankton biomass. High biomass and low DO would only occur in Suisun if there was an
2311 abrupt loss of the *Corbula* clam (e.g., disease, predator). Prior to the *Corbula*'s establishment,
2312 Suisun was highly productive. With the substantial light level increases in Suisun Bay and
2313 higher nutrient loads, greater biomass accumulation than pre-1987 would be expected now if

2314 *Corubla* disappeared; further declines in suspended sediment or prolonged stratification would
2315 amplify this effect.

2316
2317 *Low DO in margin habitats:* Many of the same scenarios that would lead to high biomass and
2318 low DO in deep subtidal habitats would similarly affect DO in margin habitats. Reconnection of
2319 wetlands and salt ponds would have the added effect of delivering low DO water or high BOD
2320 (in the form of reduced compounds or phytoplankton biomass) to sloughs on ebb tides.

2321
2322 *HABs and NABs:* The scenarios leading to increased light levels and longer periods of
2323 stratification would also tend to favor HABs and NABs. Restored salt ponds have the potential to
2324 be HAB and NAB incubators, due to the relatively long residence times, warm water
2325 temperatures, high light levels, and abundant nutrients. Increased water temperatures in margin
2326 habitats due to climate change or longer water residence time (Suisun Bay: in the Delta due to
2327 flow rerouting or during low flow years) will also favor HABs and NABs.

2328
2329 *Low phytoplankton biomass due to elevated NH_4^+ :* Concerns related to low biomass are limited
2330 to Suisun Bay, and it was included as a future priority mainly because any effect from NH_4^+
2331 inhibition will persist until NH_4^+ levels decrease. Only one of the future scenarios considered
2332 may exacerbate this issue: shifts in rainfall patterns such that flows from the Delta reduce
2333 residence time in Suisun Bay, limiting biomass accumulation.

2334
2335 *Suboptimal phytoplankton community composition:* Many of the same factors and scenarios that
2336 would increase phytoplankton biomass or influence frequency of HAB/NAB occurrence noted
2337 above could exert selective pressure that would alter the types of phytoplankton most likely to
2338 flourish. The high prioritization of this potential impairment Bay-wide and across multiple
2339 scenarios owes in large part to lack of knowledge about fundamental mechanisms and, to date,
2340 lack of analysis of data to test hypotheses related to nutrient-imposed changes in community
2341 composition.

2342
2343 *Other impairment pathways:* Not considered to be among the highest priorities

2344 **11.3 Scenarios that potentially prevent or mitigate impairment**

2345 The potential mitigating effects of environmental scenarios and management scenarios were also
2346 considered (Table 11.X and Figure 10.5) in terms of their ability to address potential current
2347 problems and prevent or mitigate future problems. The mitigation discussion is organized around
2348 the scenarios (as opposed to forms of impairment). Only a subset is discussed here.

2349 **11.3.1 N and P load reductions from POTWs discharging directly to SFB subembayments**

2350 42 POTWs discharge directly to SFB or to watersheds that drain to SFB (Figure 2.1.a). Given
2351 the relative importance of the POTW contribution to nutrient loads throughout SFB (Figure 6.3),
2352 reducing POTW N and P loads is one obvious mitigation scenario to consider. While some
2353 POTWs currently perform nitrification prior to discharge (which converts NH_4^+ to NO_3^- , but does
2354 not remove N), and several carry out advanced treatment that remove some N and P, most SFB
2355 POTWs do not perform nutrient removal. If it was deemed necessary from the standpoint of
2356 beneficial use protection, it is technologically feasible to substantially reduce N and P loads
2357 (Table 11.X), albeit at considerable cost, in particular at higher removal efficiencies.

2358

2359 For ease of discussion, the direct POTW nutrient loads are considered below at the
2360 subembayment scale. It would be a major oversimplification to suggest that these
2361 subembayments are well-mixed water masses. Further these subembayment boundaries were
2362 chosen based on geographic features and not necessarily hydrodynamic features, and one of
2363 several sets of boundaries that could be used (and happen to align with the Water Board's
2364 boundaries). In reality, the complex hydrodynamics in SFB subembayments require that the fate
2365 of POTW effluent plumes be evaluated at much finer spatial resolution to quantify the degree to
2366 which individual POTWs contribute to total nutrient concentrations at a given location, and how
2367 these contributions vary with time. Similarly, NH_4^+ , NO_3^- , and PO_4^{3-} undergo transformation and
2368 losses. In some cases the magnitude of these transformations and losses could make them the
2369 dominant fate pathway and need to be considered alongside transport.

2370
2371 *LSB and South Bay:* Based on estimates of nutrient sources, reducing direct POTW loads would
2372 substantially reduce total subembayment-scale nutrient loads in LSB and South Bay. Direct
2373 POTW loads appear to be the dominant sources of DIN and PO_4^{3-} to LSB and South Bay (Novick
2374 and Senn, 2013b; Figure 6.3). While under current conditions phytoplankton growth and biomass
2375 accumulation are limited much of the time by light, and biomass accumulation is further
2376 controlled by clam grazing, if those constraints on growth were relaxed, higher biomass
2377 production and accumulation would ensue. By limiting the availability of essential nutrients,
2378 POTW load reductions would place an upper bound on the amount of primary production that
2379 could take place and on the amount of biomass that could accumulate. To the extent that HAB
2380 and NAB frequency and shifts toward suboptimal phytoplankton composition are driven by high
2381 nutrients or highly altered nutrient ratios, POTW load reductions would also mitigate these
2382 impairment in LSB and South Bay.

2383
2384 *Suisun and San Pablo Bays:* Assessing the potential effectiveness of direct POTW load
2385 reductions in Suisun Bay and San Pablo Bay is less straightforward. Suisun Bay receives sizable
2386 but seasonally varying NH_4^+ , NO_3^- , and PO_4^{3-} loads from the Delta (Figure 6.3). San Pablo Bay in
2387 turn receives seasonally varying loads from Suisun Bay (which include loads from the Delta;
2388 Figure 6.3). Both Suisun Bay and San Pablo may also have non-trivial stormwater loads. The
2389 effectiveness of direct POTW load reductions in Suisun and San Pablo Bay therefore may
2390 depend to a large extent on whether reductions are made up-estuary and also from stormwater in
2391 the adjacent watersheds.

2392
2393 *Central Bay:* Assessing the effectiveness of load reductions in Central Bay has additional
2394 complexities. Central Bay receives direct POTW loads, along with loads through exchange from
2395 northern and southern subembayments. Loads of NO_3^- and PO_4^{3-} from the coastal ocean to Central
2396 Bay during upwelling periods also occur, and have the potential to be substantial; however, the
2397 magnitude of these loads and the frequency with which they occur is currently poorly
2398 constrained (J Largier, pers. comm.).

2399 **11.3.2 Nitrification of POTW effluent**

2400 Nitrification of POTW effluent alone will not be effective at decreasing phytoplankton
2401 production rates or biomass accumulation, since nitrification does not remove N. However, to the
2402 extent that elevated NH_4^+ concentrations favor HAB or NAB occurrence, or cause shifts in
2403 phytoplankton community composition, nitrification of POTW effluent has the potential to
2404 mitigate these impairment in South Bay and Central Bay, whose N loads are dominated by

2405 POTWs inputs in the form of NH_4^+ . All POTWs in LSB have been performing nitrification since
2406 the 1980s, although nitrification efficiency at one of those POTWs (Sunnyvale) varies
2407 seasonally. Upgrading Suisun POTWs to include nitrification would decrease ambient NH_4^+
2408 concentrations in Suisun Bay and potentially mitigate impairment due to NH_4^+ -inhibition of
2409 primary production. However, Suisun Bay and San Pablo Bay receive substantial seasonally-
2410 varying NH_4^+ loads from the Delta (which is primarily from SacRegional's discharge). In
2411 evaluating the potential environmental effectiveness of upgrading Suisun POTWs to include
2412 nitrification, the seasonally-varying magnitudes of Delta NH_4^+ loads need to be considered.

2413
2414 Nitrification also occurs *in situ* within SFB, and may be particularly important in Suisun Bay
2415 (Novick and Senn, 2013), as well as in other subembayments. In evaluating the benefit of
2416 upgrading POTWs to nitrification alone, the effect achieved relative to *in situ* nitrification should
2417 be considered. The importance of *in situ* nitrification could be quantified reasonably well through
2418 basic modeling (combined with field measurements for model calibration/validation). Along
2419 these lines, it is also worth noting that while all LSB POTWs nitrify prior to discharge, LSB has
2420 the second highest NH_4^+ concentrations Bay-wide (Figure 6.4), much of which likely comes
2421 from organic matter mineralization, suggesting that some nontrivial baseline NH_4 level would
2422 continue even after POTWs upgrade to nitrification (note: this effect may be greatest in LSB
2423 because of its shallow bathymetry and the resulting greater importance of sediment processes on
2424 water column concentrations). NH_4 loads from sediments would gradually decrease after
2425 external nutrient loads decrease (i.e., current source of NH_4^+ is mineralization of OM in
2426 sediments, most of which likely came from phytoplankton production using $\text{NO}_3 + \text{NH}_4^+$).

2427 **11.3.3 Stormwater load reductions**

2428 Stormwater and flow from perennial streams that drain directly to SFB deliver seasonally-
2429 varying N and P loads to the system. Only coarse estimates of those loads are available at this
2430 point (Novick and Senn, 2013b). At the subembayments scale, stormwater N and P loads may be
2431 of substantial importance in Suisun Bay and San Pablo Bay (Figure 6.3; Novick and Senn,
2432 2013b), and lesser importance in other subembayments. Although more work needs to be done to
2433 better constrain estimates, it is unlikely that stormwater N and P loads will rival POTW loads at
2434 the subcatchment scale. However, the importance of stormwater loads in shallow margin
2435 habitats should not be ruled out.

2436 **11.3.4 Increase in grazer abundance due to climate forcings or other factors**

2437 Grazing also places a limit on biomass accumulation. Cloern et al. (2007) argue that loss of
2438 benthic grazers due to a shift in the Pacific Decadal Oscillation (PDO) is responsible for much of
2439 the increase in phytoplankton biomass (Figure 7.10). A shift in the PDO back to pre-1998
2440 conditions would presumably allow benthic grazers to repopulate South Bay and Lower South
2441 Bay.

2442 **11.3.5 Wetland and salt pond restoration**

2443 Wetland and salt pond restoration efforts around the Bay's margins have the potential to reduce
2444 N (and to a lesser degree P) concentrations and potentially play an important role in an integrated
2445 nutrient management strategy. Denitrification converts NO_3^- to N_2 gas, thus serving as a true N
2446 sink, and high denitrification rates can occur in wetlands. However, denitrification rates vary
2447 over a wide range, and strongly depend on temperature and other conditions (e.g., amount of
2448 labile organic matter in the sediments). Furthermore, sufficient hydraulic exchange needs to

2449 occur between the nitrate-replete Bay and the relatively nitrate-poor wetlands to maximize loss
2450 by denitrification. This latter limitation could be overcome by moving deep-channel POTW
2451 outfalls to locations within wetlands so that they directly discharge effluent to wetlands.
2452 However, the issue of seasonally-varying denitrification rates would remain.

2453
2454 Wetlands also retain P. However, unlike N, P has no true sink, although it can be gradually
2455 buried (albeit inefficiently due to recycling).

2456
2457 The largest wetland restoration efforts are currently going forward in LSB and South Bay, and
2458 the scale of planned restoration there is such that those sites could conceivably act as a major N
2459 sink. Restoration in other subembayments may also be important from the standpoint of N
2460 budgets. The potential effectiveness of wetlands as nutrient sinks needs to be initially
2461 estimated with basic modeling work. If initial modeling work suggests that wetlands could be
2462 potentially important sinks, more sophisticated modeling and pilot field studies could be
2463 conducted to further refine estimates.

2464
2465 An additional potential advantage of wetlands is that peat accumulation, sediment trapping, and
2466 land-surface elevation increases around the margins could help mitigate sea level rise effects.
2467 The possible effectiveness along these lines would need to be quantitatively evaluated.

2468 **11.3.6 Cultivating shellfish beds to maintain low biomass**

2469 Cultivation of filter-feeding shellfish beds is an alternative management option that has been
2470 suggested in other estuaries to maintain phytoplankton biomass at acceptable levels. These
2471 shellfish beds could be used exclusively as a phytoplankton biomass management tool, or could
2472 be used as a commercial shellfish opportunity that offsets some their maintenance costs. The
2473 combined filtration rates of the beds would need to be great enough to maintain baseline
2474 phytoplankton levels at acceptable levels (not too low, not too high). The beds would also need
2475 to control phytoplankton blooms, which in SFB tend to occur during relatively short windows of
2476 time. Filtration rate is directly dependent on shellfish biomass, which is in turn dependent on
2477 food that had been previously available to support their growth. Pre-growing enough shellfish
2478 biomass to handle, for example, a spring bloom may require a sophisticated program.

2479
2480 Shellfish beds would need to be placed in appropriate locations and at appropriate densities so
2481 that they could access sufficient phytoplankton. The feasibility of this management approach, in
2482 terms of required grazing rates and distribution to manage conditions under a future scenario,
2483 could be evaluated through basic modeling. If shellfish bed cultivation appears promising as
2484 mitigation measure, more thorough investigations (modeling, pilot field programs) could follow.

2485
2486 Given the large amounts of legacy bioaccumulative pollutants (e.g., methyl-Hg, PCBs) and
2487 contaminants of emerging concern in San Francisco Bay, whether or not shellfish would be
2488 suitable for human consumption needs to receive careful consideration. These shellfish would be
2489 low on the food web (primary consumers) and would tend to accumulate low levels of
2490 contaminants relative to high trophic level organisms (which tend to be of greatest concern for
2491 human exposure to contaminants), especially during early life stages when they are steadily
2492 increasing their own biomass.

2493

2494 **11.3.7 Load decreases from the Central Valley**

2495 Scenarios for load decreases from the Central Valley include changes in plant operations at
2496 SacRegional POTW (located ~70 km upstream of the Sacramento/San Joaquin confluence along
2497 the Sacramento River) and load reductions from agriculture and other POTWs that discharge to
2498 the Delta and the Central Valley. SacRegional's current discharge of ~15000 kg d⁻¹ NH₄⁺ (and
2499 relatively little NO₃) travels along the Sacramento River's main stem, and also moves with the
2500 river into and through the Delta. During certain times of the year considerable nitrification
2501 occurs during transit to Suisun Bay (very little nitrification under high flow conditions, but
2502 upwards of 60% when flows are lower and temperatures are warmer in spring through fall;
2503 Parker et al., 2012; Novick and Senn, in prep.). The Sacramento River, prior to reaching the
2504 SacRegional discharge, also carries a large and seasonally varying NO₃⁻ load, presumably from
2505 upstream agriculture and POTW discharge (Kratzer et al. 2011). The San Joaquin River also
2506 delivers large and seasonally varying NO₃⁻ loads to the Delta (Kratzer et al., 2011), and relatively
2507 little NH₄⁺. Due to complex flow patterns within the Delta, water withdrawals that alter flow
2508 routing, and transformations, losses, and additional loads within the Delta (agricultural, POTWs
2509 discharging to the Delta), determining the ultimate contributions from each of these different
2510 sources to Suisun Bay is non-trivial. That said, it is reasonable to suggest that most of the NH₄⁺
2511 load appears originate from SacRegional, while other sources, including agriculture, contribute a
2512 substantial portion of the NO₃.

2513
2514 Delta nutrient loads to SFB would influence ambient concentrations most in Suisun Bay and San
2515 Pablo Bay. Initial estimates suggest Delta loads could be the dominant nutrient source Suisun
2516 and San Pablo Bays throughout much of the year (Figure 6.3; Novick and Senn, 2013a,b). Delta
2517 loads would also influence Central Bay, but to a lesser extent than in the up-estuary
2518 subembayments. While during very high flows some freshwater from the Delta has been shown
2519 to enter South Bay and, less frequently, LSB, the Delta-derived loads likely have relatively low
2520 influence there.

2521
2522 Based on recent permit requirements, SacRegional will likely be required to both nitrify and
2523 carry out biological nitrate removal before discharge, with upgrades implemented by around
2524 2022. Under this proposed upgraded operation, SacRegional would discharge ~5,000 kg d⁻¹
2525 NO₃⁻ (and little or no NH₄⁺), which amounts to a complete shift from NH₄⁺ to NO₃, and a 2/3
2526 reduction in overall DIN load. The cessation of NH₄⁺ loads will represent a considerable
2527 reduction in overall NH₄⁺ loads to Suisun Bay and San Pablo Bay during much of the year.

2528
2529 To the extent that current ambient NH₄⁺ concentrations encourage HABs, cause shifts in
2530 phytoplankton community composition, and inhibit primary production, nitrification and N
2531 removal at SacRegional would help mitigate these impairments. To determine the extent to
2532 which this changes ambient NH₄⁺ concentrations, and mitigates impairment, internal processing
2533 of NH₄⁺ in Suisun Bay needs to be considered (in situ nitrification estimates suggest that ~75%
2534 of current NH₄⁺ loads to Suisun Bay are nitrified; Novick and Senn, 2013b). Any changes in
2535 N:P entering Suisun Bay, and their effect with Suisun, would also need to be explored.
2536 Hydrodynamic and reactive-transport models for the Delta are needed to explore how changes in
2537 upstream loads would propagate through the Delta to Suisun Bay, both under current and future
2538 flow regimes.

2539

2540 The feasibility and effectiveness of agricultural runoff reductions on loads to and concentrations
2541 in Suisun Bay and San Pablo also need to be considered. Point sources such as POTWs
2542 contributed minimally to total N loads carried by the Sacramento River (upstream of
2543 SacRegional POTW) and San Joaquin River, and agricultural land-uses explained most of the
2544 variance in loads. The contribution of these agricultural loads – along with loads generated with
2545 the Delta by agricultural practices there – to the loads entering Suisun Bay need to be evaluated
2546 through a combination of data analysis and modeling.

2547 **11.4 Further prioritization**

2548 The analysis of scenarios in Sections 11.2-11.3 (summarized in Figures 11.4 and 11.5) served as
2549 an initial screen to identify impairment pathways and mitigation scenarios that warrant further
2550 attention. That assessment was conservative, and minimized ‘false negatives’ (i.e, legitimate
2551 scenarios wrongly excluded from further consideration by receiving a *LOW* rank). At the same
2552 time, this approach leaves a long list of scenarios considered to be *HIGH* priority.

2553
2554 To further narrow this list, we developed an additional ranking layer that identifies
2555 subembayment-impairment-scenario combinations that should be considered among the highest
2556 priorities issues to address through near-term work efforts (e.g., over the next 1-5 years). This
2557 additional ranking considered the following factors:

- 2558 • The combination is among the most plausible or probable issues to develop into a substantial
2559 problem, or among the most feasible mitigation approaches;
- 2560 • Major gaps in knowledge or data exist that limit our current ability to make further
2561 assessments (in terms of determining if there is currently a problem, or high likelihood of a
2562 problem, or whether a management action would mitigate impairment), and severely limit the
2563 confidence with which science-based decisions can currently be made;
- 2564 • Initial steps directed toward exploring these issues (monitoring, special studies, modeling)
2565 would yield a large return on investment in terms of the knowledge/data gaps filled and the
2566 ability to make scientifically-informed decisions. In other words, it is a tractable problem or
2567 question to explore.

2568
2569 Through applying these additional criteria, a refined list of near-term highest priority
2570 combinations emerged, marked in Figures 11.4 and 11.5 with black circles. They include:

2571
2572 *Continuation of current trends (CT) leading to an impaired state*

2573 CT.1 High biomass in LSB and South Bay

2574 CT.2 Low DO in margin habitats in LSB and South Bay (including serving as test cases for
2575 habitats in other subembayments)

2576 CT.3 HABs and NABs in all subembayments

2577 CT.4 Suboptimal phytoplankton composition in all subembayments

2578 CT.5 Low phytoplankton biomass in Suisun Bay

2579

2580 *Change Scenarios (CS) that may lead to impairment*

2581 CS.1 High phytoplankton biomass and low DO in LSB and South Bay due to decreased
2582 sediments and longer stratification (climate change and wetland/salt pond restoration).

2583 CS.2 Increased frequency of HABs or NABs in all subembayments due to longer stratification
2584 and reconnection with salt ponds and wetlands.

2585

2586 *Mitigating scenarios (MS)*
 2587 MS.1 Reductions in nutrient loads from direct POTW discharges, and reduction in nutrient loads
 2588 from the Delta
 2589 MS.2 Reductions in stormwater nutrient loads
 2590 MS.3 Effectiveness of nitrification (at SacRegional and Suisun direct POTWs) on NH_4^+
 2591 inhibition of primary production
 2592 MS.4 Other mitigation strategies: wetland treatment and shellfish bed cultivation
 2593
 2594 For each combination, relevant science questions are presented in Tables 11.3 11.4, and 11.5,
 2595 along with the broad types of investigations that are needed to address these questions. These
 2596 questions are not necessarily intended to be an exhaustive list, but rather to serve as a starting
 2597 point that can be refined as detailed science plans are developed.

2598 **12 Key Observations and Recommendations**

2599 This section summarizes the reports major observations and main recommendations for building
 2600 the necessary scientific understanding to make well-informed science-based decisions about
 2601 nutrient management in SFB.

2602 **12.1 Key observations**

- 2603 1. Changes in the SFB’s response to nutrient loads over the past decade, combined with the
 2604 Bay’s high nutrient loads and concentrations, justify growing concerns about elevated
 2605 nutrients.
 2606
- 2607 2. The future trajectory of SFB’s response to nutrients is uncertain. One plausible trajectory is
 2608 that SFB maintains its current level of resistance to high nutrient loads and no further
 2609 degradation occurs. A second, equally plausible scenario is that SFB’s resilience continues to
 2610 decline until moderate to severe impairment occurs along one or more pathways in some
 2611 subembayments. The highly elevated DIN and DIP concentrations Bay-wide provide the
 2612 potential for future impairment to develop. Any major reductions in loads to SFB would take
 2613 years-to-decades to implement. Thus, if future problems are to be averted, potential
 2614 impairment scenarios need to be anticipated, evaluated, and, if deemed necessary, managed
 2615 in advance of their onset.
 2616
- 2617 3. Although evidence is consistent with conditions in SFB moving toward a critical juncture,
 2618 widespread impairment due to nutrients is not currently occurring. Thus, there is opportunity
 2619 to conduct investigations to improve our understanding of the system, and for well-informed,
 2620 science-based management plans to be developed and implemented. That said, the time
 2621 required to implement any management strategy raises the level of urgency such that work
 2622 should move forward expeditiously.
 2623
- 2624 4. The collaborative approach that regulators, dischargers, and stakeholders have developed in
 2625 the Nutrient Strategy is a forward-thinking and proactive approach, and lays out a logical
 2626 path that will allow managers and regulators to make sound decisions based on the best
 2627 available science.
 2628

- 2629 5. Given the stakes of no action, and the time required for data collection, analysis, and
2630 modeling tools to reach a useable state, work needs to move forward on multiple fronts of the
2631 Nutrient Strategy simultaneously. More specifically, effort should be directed simultaneously
2632 toward
- 2633 a. development and implementation of a sustainably-funded and regionally administered
2634 monitoring program,
 - 2635 b. synthesis and interpretation of existing data to inform the development of an
2636 assessment framework and to improve understanding of the system
 - 2637 c. development and use of nutrient/phytoplankton models,
 - 2638 d. undertaking high-priority special studies
- 2639
- 2640 6. Implementation and coordination of these efforts will significantly improve the knowledge
2641 base from which decision-makers can:
- 2642 - Base decisions on the changing status of water quality and living resources in SFB as
2643 their responses to nutrient pollution continue to evolve;
 - 2644 - Establish and revise approaches and criteria for assessing impairments based on latest
2645 understanding of the contributing factors;
 - 2646 - Further develop and understand future scenarios within which SFB subembayments may
2647 proceed down one or more pathways toward impairment, including assessing the
2648 probability of occurrence;
 - 2649 - Where necessary, improve scientific understanding of the underlying mechanisms to
2650 better assess the potential for impairment, and the linkages between loads and response;
 - 2651 - Identify management strategies that will mitigate or prevent impairment.
- 2652
- 2653 7. The Delta/Suisun boundary, while an important regulatory boundary, is not especially
2654 meaningful from ecological, watershed, and loading standpoints. Nutrient loads to and
2655 transformations within the Delta exert considerable influence over nutrient loads and ambient
2656 concentrations within Suisun, San Pablo, and Central Bays. Furthermore, ecology and
2657 habitat quality of the Delta and Suisun (the Low Salinity Zone) are tightly coupled. A unified
2658 approach for considering nutrients and beneficial use impairment across the Delta-Suisun
2659 continuum would best serve both management needs and ecological needs.
- 2660

2661 **12.2 Recommendations for Addressing Priority Knowledge Gaps**

2662 Section 12.2.1 provides an overview of the recommended highest priority work efforts over the
2663 next 1-5 years to address knowledge gaps and inform nutrient management decisions in SFB.

2664 The process we followed (outlined in Figure 1.1) consisted of

- 2665 • Identifying the highest priority scenarios (Section 11, and Tables 11.3-11.5) for potential
2666 impairment along one or more pathways, and the outstanding science questions that need to
2667 be addressed related to those scenarios;
- 2668 • Prioritizing data or knowledge gaps related to key processes that control ecosystem response
2669 to nutrients along the pathways of the near-term highest priority scenarios, developed within
2670 conceptual module descriptions in Sections 6-10 and identified in Tables 6.1, 7.1, 8.1, and
2671 9.1.

2672
2673 Recommendations presented in Section 12.2.1 are organized around several major themes or
2674 types of work. Not all high priority data gaps are discussed below, and the reader is also referred
2675 to Tables 6.1, 7.1, 8.1, and 9.1 and Tables 11.3-11.5. Section 12.2.2 takes a broader view, and
2676 describes knowledge gaps and data needs in terms of a set of ecological and management
2677 challenges that lie ahead.

2678 **12.2.1 Recommendations**

2679 **R.1 Develop a regionally-administered and sustainably-funded nutrient monitoring**
2680 **program**

2681 On-going monitoring efforts include the USGS research program⁷ and the IEP Environmental
2682 Monitoring Program (Figure 5.3).⁸ The data generated through these programs, and the related
2683 discoveries, form much of the foundation for current understanding of SFB's response to
2684 nutrients. However, the focus and mandates of these programs are not necessarily aligned with
2685 those of a nutrient monitoring program to inform management decisions. Furthermore, future
2686 funding of the USGS program is highly uncertain.

2687
2688 Developing a regionally-administered and sustainably-funded nutrient monitoring program needs
2689 to be a major priority over the next 1-2 years. Effort needs to be directed toward both developing
2690 the institutional and funding framework and the scientific program. Several initial
2691 recommendations are presented below.

2692
2693 ***R.1.1 Program development***

2694 ***R.1.1.1 Develop institutional and funding agreements***

2695 Developing and implementing a regional nutrient monitoring program will be a major
2696 undertaking in terms of logistics and cost, and long-term institutional support will be needed.
2697 There are several entities currently involved in ship-based and continuous (moored sensors)
2698 monitoring (e.g., USGS, IEP, CA Department of Water Resources, CA Department of Fish and
2699 Game). To avoid unnecessary duplication of effort and maximize resources, when developing
2700 the future nutrient monitoring program there may considerable advantage to achieving some
2701 monitoring program goals through fostering close coordination among on-going programs, and

⁷ <http://sfbay.wr.usgs.gov/access/wqdata/>

⁸ <http://www.water.ca.gov/iep/activities/emp.cfm>

2702 augmenting those efforts with additional monitoring. The efforts need to be well-coordinated, in
2703 particular in terms of methods, data QA/QC, and data sharing, synthesis, and reporting.

2704 *R.1.1.2 Develop monitoring program science plan: management questions, goals, priorities, and*
2705 *approaches*

2706 A monitoring program science plan needs to be developed that lays out the management
2707 questions, and the program's goals and priorities relative to those management questions.
2708 Detailed plans for achieving those goals also need to be developed. A number of the future
2709 nutrient monitoring program's specific goals and data needs of the future may differ
2710 considerably from those of the current research and monitoring activities. When evaluating
2711 future program's needs relative to current efforts, particular attention needs to be given to the
2712 following issues:

- 2713 • The necessary degree of emphasis among broad monitoring categories for monitoring
2714 (water column, benthos, physical/hydrodynamic, biological, chemical)
- 2715 • Key parameters or processes to be measured within these categories;
- 2716 • Spatial and temporal resolution of sampling; and
- 2717 • The distribution of monitoring effort between ship-based sampling and moored sensors for
2718 continuous monitoring.

2719 For some of these issues, considerable data resources exist from long-term monitoring in SFB. a
2720 major component of the monitoring program design effort should include analyzing this data to
2721 inform decisions (e.g., about spatial and temporal density of sampling). Pilot studies should also
2722 be part of planning, to inform which parameters provide important additional information (e.g.,
2723 should TN and TP be measured?), test methods that provide less expensive approaches for
2724 essential data collection, and select moored sensor sites and parameters.

2725

2726 ***R.1.2. Initial monitoring program science recommendations***

2727 Several clear monitoring program recommendations emerged through developing the conceptual
2728 modules, and identifying data/conceptual gaps in light of the priority impairment scenarios
2729 (Tables 6.1, 7.1, 8.1, and 9.1). They are described briefly below.

2730

2731 *R.1.2.1 Continue ship-based monitoring along SFB's deep channel*

2732 The long-term record provided by the USGS research program has yielded insights into the
2733 mechanisms of SFB's response to nutrients and other stressors, and how the response (and the
2734 underlying stressors) have changed over time. Continuing this program will be critical for
2735 anticipating future changes, and in assessing the effectiveness of any management actions.
2736 Adding new parameters may be highly informative, such as size-fractionated chl-a and C:chl-a,
2737 as well as others noted below.

2738

2739 *R.1.2.2 Develop a moored sensor sub-program for high temporal resolution data*

2740 Data collection at higher temporal resolution for chl-a, DO, nutrients, turbidity, and other
2741 parameters is needed at multiple locations to identify the onset of events (e.g., large blooms) and
2742 to: improve understanding about the processes that influence phytoplankton blooms; assess
2743 oxygen budgets; and quantify nutrient fate. High temporal resolution data will also be essential
2744 for accurately calibrating water quality models. Continuous monitoring with moored sensor
2745 systems is feasible for a wide range of water quality parameters. Techniques for some parameters
2746 are becoming increasingly well-established and reliable (e.g., salinity, T, turbidity, chl-a, DO,
2747 and more recently nitrate), while others are advancing (e.g., phosphate, ammonium,

2748 phytoplankton composition using flow-through digital imaging). Moored sensor systems can
2749 telemeter data, allowing for near real-time assessment of conditions.

2750
2751 Although moored sensors may address some questions better than ship-based sampling, they are
2752 not a substitute for ship-based sampling, but rather a strong complement that provides important
2753 additional information about processes operating on shorter time-scales. While there are
2754 currently multiple stations in Suisun Bay and the Delta that measure some of these parameters
2755 (e.g., DO, salinity, T, chl-a), there are no stations south of the Bay Bridge for measuring chl-a or
2756 nutrients.

2757
2758 *R.1.2.3 In addition to monitoring along the channel, monitoring is needed in shoal*

2759 *environments, including lateral transects*

2760 Sampling along the shoals is needed for improved understanding of phytoplankton and nutrient
2761 processes, and for model calibration. Most of the water quality data available in SFB is from
2762 stations along the deep channel. The shoals are important areas for phytoplankton and MPB
2763 production, and large lateral heterogeneities in phytoplankton biomass (and SPM, which
2764 influences light availability and growth rates) are common in SFB (Thompson et al., 2008;
2765 Cloern, 1995). In addition, a substantial proportion of nutrient transformations likely take place
2766 along the shoals (benthic nitrification and denitrification). Shoal monitoring can be accomplished
2767 both through ship-based transects or using moored sensors, and the best approach will vary
2768 depending on the question being addressed. Using autonomous underwater vehicles (AUVs)
2769 outfitted with sensors may also be a possibility. AUVs are commonly employed in research
2770 studies, and some AUV-sensor systems are already commercially-available. Pilot studies that test
2771 the utility of AUVs would be useful to assess feasibility and cost effectiveness, and to inform
2772 planning.

2773
2774 *R.1.2.4 Coordinated monitoring in shallow subtidal habitats.*

2775 Some agencies (e.g., stormwater, wastewater) carry out monitoring in shallow habitats, and
2776 several studies have been conducted in Lower South Bay systems (Thebault et al., 2008;
2777 Shellenbarger et al. 2008; Topping et al., 2009). However, there is currently no Bay-wide
2778 systematic approach to monitoring in shallow subtidal habitats. Data collection on productivity
2779 and DO concentrations in select systems may help inform whether impairment is occurring in
2780 these systems due to low DO, and to help ascertain the causes of any impairment. Before
2781 embarking on this effort, it may be helpful to examine existing data from current or recent
2782 studies (e.g., studies in LSB) to assess the need for monitoring and identify the best approaches
2783 to pursue.

2784
2785 *R.1.2.5 Increased focus on phytoplankton community composition, including HAB/NAB-forming*
2786 *species, and algal toxins*

2787 Given the prevalence of HAB-forming organisms in the Bay, the dramatic increase in blooms of
2788 *Microcystis*, and other hypothesized nutrient-related shifts in phytoplankton community
2789 composition, it would be prudent to more closely monitor phytoplankton composition,
2790 occurrence of HAB-forming organisms, and algal toxins within San Francisco Bay.

2791
2792 The relative importance of factors that regulate phytoplankton community composition in SFB
2793 are poorly understood, in particular those that may shift assemblages toward compositions that

2794 inadequately support food webs. More frequent (in space and time) analysis of phytoplankton
2795 composition, in combination with special studies, (see Recommendation 4.1) will be needed to
2796 better understand these mechanisms and assess potential linkages to nutrients. Determining
2797 taxonomy and biomass by microscopy is expensive and time consuming, which limits the
2798 amount of data that can be collected. Some amount of manual microscopy ground-truthing will
2799 always be needed. However, other techniques, in combination with microscopy, may allow for
2800 increased data collection of at lower costs.

2801
2802 Carrying out pilot studies will help inform which techniques provide valuable and cost-effective
2803 information. Measuring phytoplankton-derived pigments is one such approach. Different classes
2804 of phytoplankton have distinct pigment fingerprints. It is possible, with sufficient calibration
2805 (relative to microscopy) and training of software to quantify phytoplankton biomass within
2806 specific classes

2807
2808 Digital imaging tools are also available. These systems, which are essentially flow-through
2809 microscopes with digital cameras, can be deployed at moored stations for continuous monitoring,
2810 used on a monitoring vessel as it cruises along a transect, or used in the laboratory. After
2811 “training” the software, the system can continuously sample the water column, count individual
2812 cells, and enumerate species. Moored applications can telemeter data, allowing for near real-time
2813 information. One such system provided early warning of a toxic algal bloom in the Gulf of
2814 Mexico.⁹ An additional advantage of digital imaging approaches is that an archive of
2815 phytoplankton image data would be developed: if a phytoplankton species eventually becomes
2816 important, the digital archive could be mined to determine when that species first appeared.

2817
2818 Pilot projects have begun to measure algal toxins in SFB (Figure 3.8). Continuation of similar
2819 pilot studies, and testing a variety of methods, will help identify the most informative and cost-
2820 effective options, all the while establishing baseline concentration data against which future data
2821 can be compared. The feasibility of measuring algal toxins in archived benthos samples should
2822 also be considered in order to generate longer time series of algal toxins and look for changes
2823 over the past decade or more (if well preserved samples exist).

2824
2825 *R.1.2.6 Benthos monitoring to quantify spatial, seasonal, and interannual variability in grazer*
2826 *abundance*

2827 Grazing by benthic filter feeders is considered to be one of the main controls on phytoplankton
2828 biomass accumulation in several subembayments. To estimate the influence of the benthic
2829 grazing, and track its changes in space and time, benthos surveys are needed on a regular basis in
2830 some subembayments, most importantly Lower South Bay, South Bay, San Pablo Bay, and
2831 Suisun Bay.

2832
2833 In recent years there has been ample benthos monitoring in Suisun Bay and the Delta (and some
2834 in San Pablo Bay), although the fate of this program is not known. There are currently no
2835 sustained programs in the other subembayments. However, there are some years during which
2836 intensive benthic sampling has taken place (e.g., Thompson et al. 2008; see Figure 7.4.b), and

⁹ <http://www.whoi.edu/oceanus/viewArticle.do?id=46486>

2837 along with opportunistic sampling efforts (in some cases, samples have been archived but not yet
2838 analyzed for biomass; J Thompson, personal communication).

2839
2840 Benthos monitoring could occur less frequent than water quality monitoring, e.g., three times per
2841 year (spring, summer, fall). Sorting, counting, and weighing benthos samples is time consuming
2842 and thus costly. In designing a benthos sampling program, the use of benthic cameras could be
2843 considered (alongside some traditional sample collection for calibration/validation), and be the
2844 focus of a pilot study, since its use could potentially allow for more cost-effective benthos
2845 surveys.

2846
2847 *R.1.2.7 Zooplankton abundance/composition*

2848 Monitoring data on zooplankton are needed to quantify pelagic grazing rates. Zooplankton
2849 abundance and composition may also serve as an important indicator of food supply and quality
2850 for higher trophic levels. Long term zooplankton monitoring has been carried out in Suisun Bay
2851 and the Delta. However, zooplankton abundance and composition are not currently measured in
2852 other subembayments.

2853
2854 *R.1.2.8 Allocate sufficient funding for data interpretation and synthesis*

2855 Data analysis and data synthesis are essential components of a monitoring program. Allocating
2856 sufficient funds for these activities will allow field results to be efficiently translated into
2857 management-relevant observations that inform decisions, and allow the monitoring program to
2858 nimbly evolve to address emerging data requirements. Annual reports will be needed that not
2859 only compile and present data, but that also evaluate and interpret trends. More detailed special
2860 studies will also be needed periodically to generate scientific synthesis reports on complex data
2861 sets (e.g., spatial and seasonal trends in phytoplankton community composition).

2862
2863 **R.2. Develop and implement science plans for SFB that target the highest priority**
2864 **management and science questions**

2865 The size of SFB, and the complexity of nutrient-response issues in this system, create a situation
2866 in which there are numerous relevant science questions that need to be addressed to improve our
2867 understanding of the system. Addressing the management and science questions will require a
2868 combination of field studies, controlled experiments, monitoring, and modeling across the topics
2869 of nutrient cycling, phytoplankton response (biomass and community composition), and
2870 hydrodynamics.

2871
2872 It will not be feasible to explore all the relevant science questions – that would take longer than
2873 management decisions can wait, and would outstrip any reasonable budget. To best target
2874 science efforts, there would be considerable benefit to developing and implementing science
2875 plans that

- 2876 • Identify the highest priority management issues, and associated science questions
- 2877 • Identify sets of studies and data collection/monitoring needs that efficiently target those
2878 questions

2879
2880 For some management issues and science questions, a Bay-wide science plan may be
2881 appropriate. Other questions, related to geographically specific issues, may be best addressed

2882 with subembayment-specific modules. The science questions listed in Tables 11.3-11.5 could
2883 serve as an early step in what would be an iterative refinement process.

2884
2885 Analysis of existing data from SFB, combined with broader critical literature review, would be
2886 useful early steps in science plan development, to articulate what is well-understood (in other
2887 estuaries and SFB) and focus on critical knowledge gaps.

2888
2889 **R.3. Develop hydrodynamic, nutrient cycling, and ecosystem response models**

2890 Tables 11.3-11.4 illustrate that modeling will play an important and central role in addressing a
2891 diverse set of science questions. Modeling can also help prioritize data collection needs. While
2892 there are numerous hydrodynamic models available for SFB, and several phytoplankton growth
2893 models (that are decoupled from nutrients), there are currently no coupled hydrodynamic-
2894 phytoplankton-nutrient models.

2895
2896 Considerable progress could be made toward addressing several sets of science questions
2897 through using relatively “basic” models that are built upon simplified (aggregated), but still
2898 accurate, hydrodynamics. Recommended model applications include (not an exhaustive list):

2899 *R.3.1* Quantitative analysis of nutrient budgets (including losses/transformations of nutrients) to
2900 determine the Bay’s natural assimilative capacity;

2901 *R.3.2* Assessing the relative importance of major processes that control primary production
2902 (light, clams, flushing, NH_4^+ inhibition);

2903 *R.3.3* Forecasting ecosystem response under future scenarios, and narrowing the list of high
2904 priority scenarios;

2905 *R.3.4* Performing sensitivity/uncertainty analysis, and identifying highest priority monitoring
2906 activities, process level studies, or rate measurements to minimize model uncertainty.

2907 *R.3.5* Determine the amount of turbulent energy dampening (due to salt pond restoration) that
2908 would be required to prolong stratification for a period of time that could potentially lead
2909 to impairment in South Bay or LSB.

2910
2911 In developing such models, there is a benefit to “starting simple”, and adding complexity as
2912 needed. Suisun Bay and LSB/South Bay could serve as good focus areas for basic model
2913 development and application, both because of the abundance of data and the fact that these areas
2914 are among those where concerns about impairment are greatest. Lessons learned through
2915 applying basic models will be useful for informing larger-scale or more complex model
2916 development.

2917
2918 Higher spatial resolution models, or larger spatial scale models (e.g., full Bay as opposed to
2919 individual subembayments) will be needed to evaluate some important questions. Many of these
2920 are related to the management scenarios identified in Table 11.5:

2921 *R.3.6* Assess the hydrodynamic changes that would result from salt pond and wetland
2922 restoration around the margins of LSB, and determine if the altered physics could amplify
2923 nutrient-related impacts (related to *R.3.5*).

2924 *R.3.7* Determine the zones of influence of individual POTWs under a range of hydrodynamic
2925 forcings and estimated transformations/losses

- 2926 R.3.8 Quantify loads from the Delta to Suisun Bay under seasonally- and interannually-varying
 2927 hydrological conditions, and the influence of these loads in Suisun and down-estuary
 2928 subembayments under a range of forcings.
- 2929 R.3.9 Evaluate the effectiveness of different nutrient control strategies for achieving desired
 2930 reductions in ambient concentrations as a function of space and time.
- 2931 R.3.10 Quantify the importance of net nutrient loads from the coastal ocean to SFB under a
 2932 range of commonly-occurring forcing scenarios.
- 2933 R.3.11 Explore the fate of the nutrient-rich SFB plume leaving the Golden Gate, and the
 2934 potential influence of those nutrients on coastal ecosystems.

2935

2936 **R.4. Carry out special studies to address key knowledge gaps about mechanisms that**
 2937 **regulate ecosystem response, and inform whether or not impairment is occurring**

2938 The draft list of priority science questions in Tables 11.3-11.5, viewed alongside the
 2939 data/knowledge gap priorities in Tables 6.1, 7.1, 8.1, and 9.1, present an initial picture of the
 2940 types of data collection and studies that are the most important in the near term. A number of
 2941 priorities have been discussed above in the context of monitoring program development (*R.1.2.1-*
 2942 *1.2.8*) and modeling (*R.3.1-R.3.11*). An overview of special study priorities is provided below;
 2943 however, the reader is also referred to the tables noted above.

2944

2945 *Nutrient cycling*

- 2946 R.4.1 Controlled field/lab experiments to measure pelagic nutrient transformations (pelagic
 2947 nitrification, nutrient uptake rates)
- 2948 R.4.2 Controlled field/lab experiments to measure benthic nutrient transformations (benthic
 2949 nitrification, denitrification, mineralization and N and P fluxes from sediments)
- 2950 R.4.3 Quantify the importance of internal nutrient transformations using models.

2951

2952 *Phytoplankton and MPB productivity*

- 2953 R.4.4 Controlled experiments that further test the proposed “NH₄⁺-paradox” mechanism of
 2954 lower productivity when NH₄⁺ is elevated, determine relevant thresholds, and allow its
 2955 effect to be better parameterized and compared to other regulating factors in models
 2956 (*R.3.2*).
- 2957 R.4.5 Through analysis of existing data or through field studies, test whether the Cole and
 2958 Cloern (1987) productivity relationship continues to hold, or if changes to the “efficiency
 2959 factor”, ψ , or C:chl-a necessitate additional field surveys of productivity.
- 2960 R.4.6 Field measurements to quantify MPB primary production rates and biomass.
- 2961 R.4.7 Compare MPB production and biomass with phytoplankton production and biomass,
 2962 consider how MPB’s relative importance would change (or already has changed) due to
 2963 ecosystem change (lower suspended sediments, benthic grazers), and explore how those
 2964 changes influence nutrient cycling, oxygen budgets, and food webs.

2965

2966 *Dissolved O₂*

- 2967 R.4.8 Controlled field experiments to quantify sediment oxygen demand in a range of
 2968 depositional environments. These can be carried out in conjunction with the benthic
 2969 nutrient transformation special studies as part of the same experimental protocol (*R.4.2*).
- 2970 R.4.9 Analysis of DO data in shallow margin habitats and development of criteria for
 2971 determining whether or not impairment is occurring

2972 R.4.10 Through field experiments and modeling, quantify the contribution of anthropogenic
2973 nutrients to current sediment oxygen demand (through production of new phytoplankton
2974 biomass or MPB biomass that undergoes mineralization in the sediments).
2975

2976 *Phytoplankton community composition and HABs*

2977 R.4.12 Rigorous analysis of existing phytoplankton community composition data to test
2978 qualitative and quantitative agreement with various conceptual models

2979 R.4.13 Field studies (collecting phytoplankton composition data at higher temporal or spatial
2980 resolution) to test mechanisms of phytoplankton community succession in response to
2981 physical, chemical, and biological drivers.

2982 R.4.14 Field studies to evaluate the potential importance of salt ponds as incubators of HAB-
2983 forming species.

2984 R.4.15 Controlled experiments, using phytoplankton assemblages and monocultures from SFB,
2985 that mechanistically explore the interactive effects of nutrient availability (including
2986 variability in concentrations and forms), light, and temperature. The goals of such studies
2987 would be to identify conditions that favor some classes or species of phytoplankton over
2988 others under the prevailing conditions in SFB (light limitation, excess nutrients), and
2989 enable predictions about assemblage response;

2990 R.4.16 Apply the information from R.4.1.5 using basic models to, among other issues, evaluate
2991 the magnitude of the nutrient component of stress, and explore potential composition
2992 responses to changing conditions, including those due to potential management actions
2993 (e.g., nutrient load reductions).

2994 **12.2.2 Grand Challenges**

2995 During the conceptual model development and identification of knowledge gaps, data gaps, and
2996 monitoring needs, four so-called “Grand Challenges” related to understanding and managing
2997 SFB ecosystem health. There is considerable overlap between the underlying issues motivating
2998 the overarching Grand Challenges and those underlying management decisions and science
2999 questions identified while looking through a nutrient lens. These Grand Challenges represent a
3000 helpful and somewhat different perspective or framework for considering science and data
3001 collection needs. In so doing they highlight connections between nutrient issues and other
3002 ecosystem health concerns, and provide an additional impetus for addressing those data
3003 collection needs.

3004 **12.2.2.1 Grand Challenge 1:**

3005 What do we need to know in 10-20 yrs to make improved decisions water quality management or
3006 ecosystem health issues, including those related to nutrients?
3007

3008 1-2 decades is approximately the time scale over which large capital improvement projects are
3009 planned and implemented. 10-20 years is also a long enough time period for trends to become
3010 evident, e.g, the changes in phytoplankton biomass in South Bay and LSB since the late 1990s
3011 (Figure 3.4).
3012

3013 What information needs to be collected now, to serve as baseline condition data, so that changes
3014 in important indicators can be confidently identified and attributed to the correct causal agent(s),
3015 whether those changes show improved or worsened condition?

3016 *12.2.2.1 Grand Challenge #2*

3017 The northern estuary is poised to experience major changes due to management actions and
3018 environmental change. Anticipated changes include:

- 3019 • Nitrification and nutrient load reductions at Sac Regional wastewater treatment plant.
- 3020 • Numerous large scale restoration projects in the Delta
- 3021 • Changes in water withdrawals and flow routing
- 3022 • Changing climate patterns altering the timing, residence time, and amount of water passing
3023 through the Delta.

3024

3025 What do we need to be measuring now in order to determine if these changes have positive,
3026 negative, or no impacts on ecological health in SFB and the Delta? How will phytoplankton
3027 respond to changes in nutrient loads/speciation? How will the food web respond?

3028 *12.2.2.1 Grand Challenge #3*

3029 Large areas along the margins of South Bay and LSB are slated to undergo restoration. Given the
3030 size of these areas compared to the adjacent water surface area (Figure 5.2), it is reasonable to
3031 expect that effects will extend to the open water. Some of these effects may be positive,
3032 including increased habitat for fish, birds and other organisms. It will be desirable to document
3033 those changes; in order to do so, baseline data is needed for indicators of ecosystem health.
3034 Those changes may also encourage much higher rates of denitrification, which should be
3035 considered as part of an integrated nutrient management plan.

3036

3037 As discussed earlier, there may also be unintended and undesirable consequences, including salt
3038 ponds acting incubators for HAB-forming phytoplankton species, exceedingly high primary
3039 production and low DO environments in light-rich, long-residence time habitats, and increased
3040 duration of stratification due to dampening of tidal mixing energy. What hypotheses of adverse
3041 impacts need to be tested so that the risks of severe unintended consequences are minimized?

3042 *12.2.2.1 Grand Challenge #4*

3043 While the exact ways that climate change will manifest itself in SFB habitats are unknown, the
3044 scientific consensus is that some of those changes have already started arriving, and that
3045 combinations of others are on the way. Changes to multiple climate-related drivers are feasible,
3046 and the combined effects are uncertain. Similar to Grand Challenges 1-3, what baseline
3047 observational data is needed in order to see these changes and disentangle them from other
3048 anthropogenic drivers? What types of modeling simulations should be done to anticipate
3049 effects?

3050

3051 The CASCaDE II project is exploring these issues, largely focused in the Delta.¹⁰ Similar
3052 approaches may be worth considering for the Bay.

3053

3054

¹⁰ <http://cascade.wr.usgs.gov/>

3055 **References**

3056
3057 Antia, N. J., B. R. Berland, et al. (1975). "COMPARATIVE EVALUATION OF CERTAIN ORGANIC
3058 AND INORGANIC SOURCES OF NITROGEN FOR PHOTOTROPIC GROWTH OF
3059 MARINE MICROALGAE." Journal of the Marine Biological Association of the United
3060 Kingdom **55**(3): 519-539.

3061 Barton, A. D., S. Dutkiewicz, et al. (2010a). "Patterns of Diversity in Marine Phytoplankton." Science
3062 **327**(5972): 1509-1511.

3063 Barton, A. D., S. Dutkiewicz, et al. (2010b). "Response to Comment on "Patterns of Diversity in Marine
3064 Phytoplankton"." Science **329**(5991).

3065 Behrenfeld, M. J. and P. G. Falkowski (1997). "A consumer's guide to phytoplankton primary
3066 productivity models." Limnology and Oceanography **42**(7): 1479-1491.

3067 Bennett, W. A. (2005). "Critical assessment of the delta smelt population in the San Francisco Estuary,
3068 California." San Francisco Estuary and Watershed Science **3 no. 2**.

3069 Bligny, R., E. Gout, et al. (1997). "pH regulation in acid-stressed leaves of pea plants grown in the
3070 presence of nitrate or ammonium salts: Studies involving P-31-NMR spectroscopy and
3071 chlorophyll fluorescence." Biochimica Et Biophysica Acta-Bioenergetics **1320**(2): 142-152.

3072 Brand, L. E., W. G. Sunda, et al. (1986). "REDUCTION OF MARINE-PHYTOPLANKTON
3073 REPRODUCTION RATES BY COPPER AND CADMIUM." Journal of Experimental Marine
3074 Biology and Ecology **96**(3): 225-250.

3075 Bricker, S. L., B., Dennison, W., Jones, A., Boicourt, K., Wicks, C., and Worner, J. (2007). "Effects of
3076 Nutrient Enrichment in the Nation's Estuaries: A Decade of Change." NOAA coastal Ocean
3077 Program Decision Analysis Series **No. 26**.

3078 Britto, D. T., M. Y. Siddiqi, et al. (2001). "Futile transmembrane NH₄⁺ cycling: A cellular hypothesis to
3079 explain ammonium toxicity in plants." Proceedings of the National Academy of Sciences of the
3080 United States of America **98**(7): 4255-4258.

3081 Brooks, M. L., E. Fleishman, et al. (2012). "Life Histories, Salinity Zones, and Sublethal Contributions of
3082 Contaminants to Pelagic Fish Declines Illustrated with a Case Study of San Francisco Estuary,
3083 California, USA." Estuaries and Coasts **35**(2): 603-621.

3084 Burkholder, J. M., P. M. Glibert, et al. (2008). "Mixotrophy, a major mode of nutrition for harmful algal
3085 species in eutrophic waters." Harmful Algae **8**(1): 77-93.

3086 Caffrey, J. M. (2003). "Production, respiration and net ecosystem metabolism in US estuaries."
3087 Environmental Monitoring and Assessment **81**(1-3): 207-219.

3088 Caffrey, J. M., Cloern, J.E., Grenz, C. (1998). "Changes in production and respiration during a spring
3089 phytoplankton bloom in San Francisco Bay, California, USA: implications for net ecosystem
3090 metabolism." MARINE ECOLOGY PROGRESS SERIES **172**: 1-12.

3091 Cammen, L. M. (1982). "EFFECT OF PARTICLE-SIZE ON ORGANIC CONTENT AND MICROBIAL
3092 ABUNDANCE WITHIN 4 MARINE-SEDIMENTS." Marine Ecology Progress Series **9**(3): 273-
3093 280.

3094 Cammen, L. M. (1991). "ANNUAL BACTERIAL PRODUCTION IN RELATION TO BENTHIC
3095 MICROALGAL PRODUCTION AND SEDIMENT OXYGEN-UPTAKE IN AN INTERTIDAL
3096 SANDFLAT AND AN INTERTIDAL MUDFLAT." Marine Ecology Progress Series **71**(1): 13-
3097 25.

3098 Chisholm, S. W. (1992). "Phytoplankton size." Primary Productivity and Biogeochemical Cycles in the
3099 Sea PG Falkowski and AD Woodhead (eds). Plenum Press, New York.

3100 Cloern, J. E. (1991). "Tidal stirring and phytoplankton bloom dynamics in an estuary." Journal of Marine
3101 Research **49**: 203-221.

- 3102 Cloern, J. E. (1996). "Phytoplankton bloom dynamics in coastal ecosystems: a review with some general
3103 lessons from sustained investigation of San Francisco Bay, California." Reviews of Geophysics
3104 **34**(2): 127-168.
- 3105 Cloern, J. E., A. E. Alpine, et al. (1983). "River discharge controls phytoplankton dynamics in the
3106 Northern San Francisco Bay Estuary." Estuarine, Coastal and Shelf Science **16**: 415-429.
- 3107 Cloern, J. E., B. E. Cole, et al. (1994). "Notes on a *Mesodinium rubrum* red tide in San Francisco Bay
3108 (California, USA)." Journal of Plankton Research **16**(9): 1269-1276.
- 3109 Cloern, J. E. and R. Dufford (2005). "Phytoplankton community ecology: principles applied in San
3110 Francisco Bay." Marine Ecology Progress Series **285**: 11-28.
- 3111 Cloern, J. E., K. A. Hieb, et al. (2010). "Biological communities in San Francisco Bay track large-scale
3112 climate forcing over the North Pacific." Geophysical Research Letters **37**.
- 3113 Cloern, J. E. and A. D. Jassby (2008). "Complex seasonal patterns of primary producers at the land-sea
3114 interface." Ecology Letters **11**(12): 1294-1303.
- 3115 Cloern, J. E. and A. D. Jassby (2012). "DRIVERS OF CHANGE IN ESTUARINE-COASTAL
3116 ECOSYSTEMS: DISCOVERIES FROM FOUR DECADES OF STUDY IN SAN FRANCISCO
3117 BAY." Reviews of Geophysics **50**.
- 3118 Cloern, J. E., A. D. Jassby, et al. (2007). "A cold phase of the East Pacific triggers new phytoplankton
3119 blooms in San Francisco Bay." Proceedings of the National Academy of Sciences **104**(47):
3120 18561-18565.
- 3121 Cloern, J. E., N. Knowles, et al. (2011). "Projected Evolution of California's San Francisco Bay-Delta-
3122 River System in a Century of Climate Change." Plos One **6**(9).
- 3123 Cloern, J. E., T. M. Powell, et al. (1989). "Spatial and temporal variability in South San Francisco Bay
3124 (USA). II. Temporal changes in salinity, suspended sediments, and phytoplankton biomass and
3125 productivity over tidal time scales." Estuarine, Coastal and Shelf Science **28**: 599-613.
- 3126 Cloern, J. E., T. S. Schraga, et al. (2005). "Heat wave brings an unprecedented red tide to San Francisco
3127 Bay." Eos Transactions of the American Geophysical Union **86**(7): 66.
- 3128 Cloern, J.E. and Dugdale, R., 2010, San Francisco Bay, in Glibert, P.M. et al., eds, *Nutrients in Estuaries:*
3129 *A Summary Report of the National Estuarine Experts Workgroup 2005-2007*, p. 117-126.
- 3130 Cloern, J. E., T. S. Schraga, et al. (2005). "Climate anomalies generate an exceptional dinoflagellate
3131 bloom in San Francisco Bay." Geophysical Research Letters **32**: 5 pp. .
- 3132 Cole, B. E. and J. E. Cloern (1984). "Significance of biomass and light availability to phytoplankton
3133 productivity in San Francisco Bay." Marine Ecology Progress Series **17**: 15-24.
- 3134 Cole, B. E. and J. E. Cloern (1987). "An empirical model for estimating phytoplankton productivity in
3135 estuaries." Marine Ecology Progress Series **36**: 299-305.
- 3136 Collos, Y., A. Vaquer, et al. (2005). "Acclimation of nitrate uptake by phytoplankton to high substrate
3137 levels." Journal of Phycology **41**(3): 466-478.
- 3138 Dejong, D. J. and V. N. Dejong (1995). "DYNAMICS AND DISTRIBUTION OF
3139 MICROPHYTOBENTHIC CHLOROPHYLL-A IN THE WESTERN SCHELDT ESTUARY
3140 (SW NETHERLANDS)." Hydrobiologia **311**(1-3): 21-30.
- 3141 Dugdale, R., F. Wilkerson, et al. (2012). "River flow and ammonium discharge determine spring
3142 phytoplankton blooms in an urbanized estuary." Estuarine Coastal and Shelf Science **115**: 187-
3143 199.
- 3144 Dugdale, R. C., F. P. Wilkerson, et al. (2007). "The role of ammonium and nitrate in spring bloom
3145 development in San Francisco Bay." Estuarine, Coastal and Shelf Science **73**: 17-29.
- 3146 Eppley, R. W. (1972). "TEMPERATURE AND PHYTOPLANKTON GROWTH IN SEA." Fishery
3147 Bulletin **70**(4): 1063-1085.
- 3148 Feyrer, F., B. Herbold, et al. (2003). "Dietary shifts in a stressed fish assemblage: Consequences of a
3149 bivalve invasion in the San Francisco Estuary." Environmental Biology of Fishes **67**(3): 277-288.
- 3150 Follows, M. J. and S. Dutkiewicz (2011). Modeling Diverse Communities of Marine Microbes. Annual
3151 Review of Marine Science, Vol 3. C. A. Carlson and S. J. Giovannoni. **3**: 427-451.

- 3152 Glibert, P. M. (2010). "Long-Term Changes in Nutrient Loading and Stoichiometry and Their
3153 Relationships with Changes in the Food Web and Dominant Pelagic Fish Species in the San
3154 Francisco Estuary, California." Reviews in Fisheries Science **18**(2): 211-232.
- 3155 Glibert, P. M. (2012). "Ecological stoichiometry and its implications for aquatic ecosystem
3156 sustainability." Current Opinion in Environmental Sustainability **4**(3): 272-277.
- 3157 Glibert, P. M., D. Fullerton, et al. (2011). "Ecological Stoichiometry, Biogeochemical Cycling, Invasive
3158 Species, and Aquatic Food Webs: San Francisco Estuary and Comparative Systems." Reviews in
3159 Fisheries Science **19**(4): 358-417.
- 3160 Gobler, C. J., D. J. Lonsdale, et al. (2005). "A review of the causes, effects, and potential management of
3161 harmful brown tide blooms caused by *Aureococcus anophagefferens* (Hargraves et Sieburth)."
3162 Estuaries **28**(5): 726-749.
- 3163 Greene, V. E., L. J. Sullivan, et al. (2011). "Grazing impact of the invasive clam *Corbula amurensis* on
3164 the microplankton assemblage of the northern San Francisco Estuary." Marine Ecology Progress
3165 Series **431**: 183-193.
- 3166 Gross, E.S. (2010). Three-dimension modeling of tidal hydrodynamics in San Francisco Estuary. San
3167 Francisco Estuary and Watershed Science, 7(2)
- 3168 Guarini, J. M., J. E. Cloern, et al. (2002). "Microphytobenthic potential productivity estimated in three
3169 tidal embayments of the San Francisco Bay: A comparative study." Estuaries **25**(3): 409-417.
- 3170 Herndon, J., W. P. Cochlan, et al. (2003). "*Heterosigma akashiwo* blooms in San Francisco Bay " IEP
3171 Newsletter **16**(2): 46-48.
- 3172 Hildebrand, M. (2005). "Cloning and functional characterization of ammonium transporters from the
3173 marine diatom *Cylindrotheca fusiformis* (Bacillariophyceae)." Journal of Phycology **41**(1): 105-
3174 113.
- 3175 Huzzey, L. M., J. E. Cloern, et al. (1990). "Episodic changes in lateral transport and phytoplankton
3176 distribution in South San Francisco Bay." Limnology and Oceanography **35**(2): 472-478.
- 3177 Irigoien, X., K. J. Flynn, et al. (2005). "Phytoplankton blooms: a 'loophole' in microzooplankton grazing
3178 impact?" JOURNAL OF PLANKTON RESEARCH **27**(4): 313-321.
- 3179 Irigoien, X., J. Huisman, et al. (2004). "Global biodiversity patterns of marine phytoplankton and
3180 zooplankton." Nature **429**(6994): 863-867.
- 3181 Irwin, A. J., Z. V. Finkel, et al. (2006). "Scaling-up from nutrient physiology to the size-structure of
3182 phytoplankton communities." JOURNAL OF PLANKTON RESEARCH **28**(5): 459-471.
- 3183 Jassby, A. D., J. E. Cloern, et al. (2002). "Annual primary production: patterns and mechanisms of change
3184 in a nutrient-rich tidal ecosystem." Limnology and Oceanography **47**(3): 698-712.
- 3185 Jassby, A. D., J. E. Cloern, et al. (1993). "Organic carbon sources and sinks in San Francisco Bay:
3186 variability induced by river flow." Marine Ecology Progress Series **95**: 39-54.
- 3187 Kimmerer and J. W (2006). Response of anchovies dampens effects of the invasive bivalve *Corbula
3188 amurensis* on the San Francisco Estuary foodweb. Oldendorf, ALLEMAGNE, Inter-Research.
- 3189 Kimmerer, W. (2005). "Long-term changes in apparent uptake of silica in the San Francisco estuary."
3190 Limnology and Oceanography **50**(3): 793-798.
- 3191 Kimmerer, W. J., A. E. Parker, et al. (2012). "Short-Term and Interannual Variability in Primary
3192 Production in the Low-Salinity Zone of the San Francisco Estuary." Estuaries and Coasts **35**(4):
3193 913-929.
- 3194 Koch, F., M. A. Marcoval, et al. (2011). "The effect of vitamin B-12 on phytoplankton growth and
3195 community structure in the Gulf of Alaska." Limnology and Oceanography **56**(3): 1023-1034.
- 3196 Kudela, R. M. and W. P. Cochlan (2000). "Nitrogen and carbon uptake kinetics and the influence of
3197 irradiance for a red tide bloom off southern California." Aquatic Microbial Ecology **21**(1): 31-47.
- 3198 Kudela, R. M., J. Q. Lane, et al. (2008). "The potential role of anthropogenically derived nitrogen in the
3199 growth of harmful algae in California, USA." Harmful Algae **8**(1): 103-110.
- 3200 Kudela, R. M., S. Seeyave, et al. (2010). "The role of nutrients in regulation and promotion of harmful
3201 algal blooms in upwelling systems." Progress in Oceanography **85**(1-2): 122-135.

3202 Lancelot, C., P. Grosjean, et al. (2012). "Rejoinder to "Perils of correlating CUSUM-transformed
3203 variables to infer ecological relationships (Breton et al. 2006; Glibert 2010)". Limnology and
3204 Oceanography **57**(2): 669-670.

3205 Lehman, P. W. (1992). "ENVIRONMENTAL-FACTORS ASSOCIATED WITH LONG-TERM
3206 CHANGES IN CHLOROPHYLL CONCENTRATION IN THE SACRAMENTO-SAN-
3207 JOAQUIN DELTA AND SUISUN BAY, CALIFORNIA." Estuaries **15**(3): 335-348.

3208 Lehman, P. W. (2000). "The influence of climate on phytoplankton community biomass in San Francisco
3209 Bay Estuary." Limnology and Oceanography **45**(3): 580-590.

3210 Lehman, P. W., G. Boyer, et al. (2005). "Distribution and toxicity of a new colonial *Microcystis*
3211 *aeruginosa* bloom in the San Francisco Bay Estuary, California." Hydrobiologia **541**: 87-99.

3212 Lehman, P. W., G. Boyer, et al. (2008). "The influence of environmental conditions on the seasonal
3213 variation of *Microcystis* cell density and microcystins concentration in San Francisco Estuary."
3214 Hydrobiologia **600**: 187-204.

3215 Lehman, P. W., S. J. Teh, et al. (2010). "Initial impacts of *Microcystis aeruginosa* blooms on the aquatic
3216 food web in the San Francisco Estuary." Hydrobiologia **637**(1): 229-248.

3217 Lidström, U. (2009). "Primary production, biomass and species composition of phytoplankton in the low
3218 salinity zone of the northern San Francisco Estuary." MS thesis, San Francisco State University.

3219 Litchman, E., C. A. Klausmeier, et al. (2007). "The role of functional traits and trade-offs in structuring
3220 phytoplankton communities: scaling from cellular to ecosystem level." Ecology Letters **10**(12):
3221 1170-1181.

3222 Litchman, E., and C.A. Klausmeier. 2008. Trait-based community ecology of phytoplankton. Annual
3223 Review of Ecology, Evolution, and Systematics **39**: 615-639

3224 Lomas, M. W. (2004). "Nitrate reductase and urease enzyme activity in the marine diatom *Thalassiosira*
3225 *weissflogii* (Bacillariophyceae): interactions among nitrogen substrates." Marine Biology **144**(1):
3226 37-44.

3227 Lucas, L. V., J. R. Koseff, et al. (1999). "Processes governing phytoplankton blooms in estuaries. II: The
3228 role of horizontal transport." Marine Ecology Progress Series **187**: 17-30.

3229 Lucas, L. V., J. R. Koseff, et al. (2009). "Shallow water processes govern system-wide phytoplankton
3230 bloom dynamics: A modeling study." Journal of Marine Systems **75**(1-2): 70-86.

3231 Lucas, L. V. a. T., J.K. (2013). "Changing restoration rules: Exotic bivalves interact with residence time
3232 and depth to control phytoplankton productivity." Ecosphere, in press.

3233 MacIntyre, H. L., R. J. Geider, et al. (1996). "Microphytobenthos: The ecological role of the "secret
3234 garden" of unvegetated, shallow-water marine habitats .1. Distribution, abundance and primary
3235 production." Estuaries **19**(2A): 186-201.

3236 Mallin, M. A., H. W. Paerl, et al. (1993). "REGULATION OF ESTUARINE PRIMARY PRODUCTION
3237 BY WATERSHED RAINFALL AND RIVER FLOW." Marine Ecology Progress Series **93**(1-2):
3238 199-203.

3239 McKee, L. J., Sutula, M., Gilbreath, A.N., Beagle, J., Gluchowski, D., and Hunt, J. (2011). "Nutrient
3240 Numeric Endpoint Development for San Francisco Bay - Literature Review and Data Gaps
3241 Analysis." Southern California Coastal Water Research Project Technical Report No. 644. June
3242 2011.

3243 Montagna, P. A., B. C. Coull, et al. (1983). "THE RELATIONSHIP BETWEEN ABUNDANCES OF
3244 MEIOFAUNA AND THEIR SUSPECTED MICROBIAL FOOD (DIATOMS AND
3245 BACTERIA)." Estuarine Coastal and Shelf Science **17**(4): 381-394.

3246 Ning, X., J. E. Cloern, et al. (2000). "Spatial and temporal variability of picocyanobacteria *Synechococcus*
3247 sp. in San Francisco Bay." Limnology and Oceanography **45**(3): 695-702.

3248 Nixon, S., B. Buckley, et al. (2001). "Responses of very shallow marine ecosystems to nutrient
3249 enrichment." Human and Ecological Risk Assessment **7**(5): 1457-1481.

3250 Novick, E. a. S., D.B. (2013). "External nutrient loads to San Francisco Bay." A report prepared for the
3251 Regional Monitoring Program for San Francisco Bay. San Francisco Estuary Institute, Richmond,
3252 CA.

3253 Paerl, H. W. and J. Huisman (2008). "Climate - Blooms like it hot." *Science* **320**(5872): 57-58.

3254 Paerl, H. W. and J. Huisman (2009). "Climate change: a catalyst for global expansion of harmful
3255 cyanobacterial blooms." *Environmental Microbiology Reports* **1**(1): 27-37.

3256 Pahl, S. L., D. M. Lewis, et al. (2012). "Heterotrophic growth and nutritional aspects of the diatom
3257 *Cyclotella cryptica* (Bacillariophyceae): effect of nitrogen source and concentration." *Journal of*
3258 *Applied Phycology* **24**(2): 301-307.

3259 Parker, A. E., R. C. Dugdale, et al. (2012a). "Elevated ammonium concentrations from wastewater
3260 discharge depress primary productivity in the Sacramento River and the Northern San Francisco
3261 Estuary." *Marine Pollution Bulletin* **64**(3): 574-586.

3262 Parker, A. E., V. E. Hogue, et al. (2012b). "The effect of inorganic nitrogen speciation on primary
3263 production in the San Francisco Estuary." *Estuarine Coastal and Shelf Science* **104**: 91-101.

3264 Parker, A. E., Kimmerer, W.J., Lidstrom, U. (2012). "Re-evaluating the generality of empirical models
3265 for light-limited primary production in the San Francisco Estuary." *Estuaries and Coasts* **35**(4):
3266 930-942.

3267 Perez-Garcia, O., Y. Bashan, et al. (2011). "ORGANIC CARBON SUPPLEMENTATION OF
3268 STERILIZED MUNICIPAL WASTEWATER IS ESSENTIAL FOR HETEROTROPHIC
3269 GROWTH AND REMOVING AMMONIUM BY THE MICROALGA *CHLORELLA*
3270 *VULGARIS*." *Journal of Phycology* **47**(1): 190-199.

3271 Quigg, A., Z. V. Finkel, et al. (2003). "The evolutionary inheritance of elemental stoichiometry in marine
3272 phytoplankton." *Nature* **425**(6955): 291-294.

3273 Reynolds, C. S., V. Huszar, et al. (2002). "Towards a functional classification of the freshwater
3274 phytoplankton." *JOURNAL OF PLANKTON RESEARCH* **24**(5): 417-428.

3275 Rollwagen-Bollens, G., S. Gifford, et al. (2011). "The Role of Protistan Microzooplankton in the Upper
3276 San Francisco Estuary Planktonic Food Web: Source or Sink?" *Estuaries and Coasts* **34**(5): 1026-
3277 1038.

3278 Schoellhamer, D. H. (2011). "USGS Suspended Sediment Monitoring Program." *A presentation at the*
3279 *Nutrient Strategy Session to Outline a Bay Monitoring Program. 30 June 2011, Richmond, CA.*

3280 Senn, D. B., Novick, E., Jabusch, T.W., Berg, G.M., Kimmerer, W.J. (2012). "Suisun Bay Ammonium
3281 Synthesis Report." *A report prepared for the Bay Area Clean Water Agencies (BACWA). San*
3282 *Francisco Estuary Institute, Richmond, CA.*

3283 SFBRWQCB (1975). "San Francisco Bay Basin (Region 2) Water Quality Control Plan." *As amended*
3284 *December 2011, available at http://www.waterboards.ca.gov/rwqcb2/basin_planning.shtml.*

3285 Shellenbarger, G. G., Schoellhamer, D.H., Morgan, T.L., Takekawa, J.Y., Athearn, N.D., and Henderson,
3286 K.D. (2008). "Dissolved oxygen in Guadalupe Slough and Pond A3W, South San Francisco Bay,
3287 California, August and September 2007." *U.S. Geological Survey Open-File Report 2008–1097,*
3288 *26 p.*

3289 Smayda, T. J. (1997). "Harmful algal blooms: Their ecophysiology and general relevance to
3290 phytoplankton blooms in the sea." *Limnology and Oceanography* **42**(5): 1137-1153.

3291 Smayda, T. J. (2000). "Ecological features of harmful algal blooms in coastal upwelling ecosystems."
3292 *South African Journal of Marine Science-Suid-Afrikaanse Tydskrif Vir Seewetenskap* **22**: 219-
3293 253.

3294 Smayda, T. J. and C. S. Reynolds (2001). "Community assembly in marine phytoplankton: application of
3295 recent models to harmful dinoflagellate blooms." *JOURNAL OF PLANKTON RESEARCH*
3296 **23**(5): 447-461.

3297 Stoecker, D. K., A. E. Thessen, et al. (2008). ""Windows of opportunity" for dinoflagellate blooms:
3298 Reduced microzooplankton net growth coupled to eutrophication." *Harmful Algae* **8**(1): 158-166.

3299 Sunda, W. G. and S. A. Huntsman (1995). "REGULATION OF COPPER CONCENTRATION IN THE
3300 OCEANIC NUTRICLINE BY PHYTOPLANKTON UPTAKE AND REGENERATION
3301 CYCLES." *Limnology and Oceanography* **40**(1): 132-137.

3302 Sunda, W. G., P. A. Tester, et al. (1987). "EFFECTS OF CUPRIC AND ZINC ION ACTIVITIES ON
3303 THE SURVIVAL AND REPRODUCTION OF MARINE COPEPODS." Marine Biology **94**(2):
3304 203-210.

3305 Tang, Y. Z., F. Koch, et al. (2010). "Most harmful algal bloom species are vitamin B-1 and B-12
3306 auxotrophs." Proceedings of the National Academy of Sciences of the United States of America
3307 **107**(48): 20756-20761.

3308 Teh, S., I. Flores, M. Kawaguchi, S. Lesmeister, and C. Teh. (2011). "Full Life-Cycle Bioassay
3309 Approach to Assess Chronic Exposure of Pseudodiaptomus forbesi to Ammonia/Ammonium."
3310 Unpublished report submitted to State Water Resources Control Board.

3311 Thebault, J., T. S. Schraga, et al. (2008). "Primary production and carrying capacity of former salt ponds
3312 after reconnection to San Francisco Bay." Wetlands **28**(3): 841-851.

3313 Thompson, J. K., J. R. Koseff, et al. (2008). "Shallow water processes govern system-wide phytoplankton
3314 bloom dynamics: A field study." Journal of Marine Systems **74**(1-2): 153-166.

3315 Topping, B. R., Kuwabara, J.S., Athearn, N.D., Takekawa, J.Y., Parchaso, F., Henderson, K.D., and
3316 Piotter, S. (2009). "Benthic oxygen demand in three former salt ponds adjacent to south San
3317 Francisco Bay, California." U.S. Geological Survey Open-File Report 2009-1180, 21 p.

3318 Underwood, G. J. C. and J. Kromkamp (1999). Primary production by phytoplankton and
3319 microphytobenthos in estuaries. Advances in Ecological Research, Vol 29: Estuaries. D. B.
3320 Nedwell and D. G. Raffaelli. **29**: 93-153.

3321 Underwood, G. J. C. and D. J. Smith (1998). "Predicting epipelagic diatom exopolymer concentrations in
3322 intertidal sediments from sediment chlorophyll a." Microbial Ecology **35**(2): 116-125.

3323 Vila, M., J. Camp, et al. (2001). "High resolution spatio-temporal detection of potentially harmful
3324 dinoflagellates in confined waters of the NW Mediterranean." JOURNAL OF PLANKTON
3325 RESEARCH **23**(5): 497-514.

3326 Werme, C., Taberski, K., McKee, L., Dugdale, R., Hall, T., Connor, M. (2011). A Growing Concern:
3327 Potential Effects of Nutrients on Bay Phytoplankton. Article in The Pulse of the Estuary, San
3328 Francisco Estuary Institute, Richmond, CA

3329 Werner, I. and J. T. Hollibaugh (1993). "POTAMOCORBULA-AMURENSIS - COMPARISON OF
3330 CLEARANCE RATES AND ASSIMILATION EFFICIENCIES FOR PHYTOPLANKTON
3331 AND BACTERIOPLANKTON." Limnology and Oceanography **38**(5): 949-964.

3332 Wilkerson, F. P., R. C. Dugdale, et al. (2006). "Phytoplankton blooms and nitrogen productivity in San
3333 Francisco Bay." Estuaries and Coasts **29**(3): 401-416.

3334 Wilkerson, F. P., R. C. Dugdale, et al. (2000). "Biomass and productivity in Monterey Bay, California:
3335 contribution of the large phytoplankton." Deep-Sea Research Part Ii-Topical Studies in
3336 Oceanography **47**(5-6): 1003-1022.

3337 Winder, M. and J. E. Cloern (2010). "The annual cycles of phytoplankton biomass." Philosophical
3338 Transactions of the Royal Society B-Biological Sciences **365**(1555): 3215-3226.

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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 ⁷ (C, N, P, and Si) HAB species cell count and toxin concentrations	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 conc. 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

⁷ Forms referred to relative distribution of dissolved inorganic, dissolved organic, and particulate forms of nutrients, including urea

Table 2.2 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
Raphe Kudela, PhD	University of California, Santa Cruz	Phytoplankton physiology and ecology
Anke Mueller-Solger, PhD	Interagency Ecological Program	Estuarine and freshwater food webs
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

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 Suisun 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 = microcystin, 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.)

Table 3.2 What would a problem look like in SFB? Potential impaired states

	Impaired State (S)	Rationale or Link to Beneficial Uses
IS.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)
IS.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.
IS.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
IS.4	HABs and algal toxins Occurrence of HABs 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.	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. Some species are considered HABs for reasons other than toxins (e.g., rapid biomass production leading to low DO).
IS.5	NABs: Occurrence of nuisance algal blooms with sufficient frequency and magnitude that they impair beneficial uses, for example similar to the red tide bloom in Spring 2004	Impaired aesthetics, surface scums, discoloration, odors
IS.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.
IS.7	Low Phytoplankton Biomass Low phytoplankton biomass in Suisun Bay or other habitats due to elevated NH ₄ which exacerbates 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.
IS.8	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.8

Table 5.1 Subembayment area and volume, and watershed area and landuse

	Boundary	Bay area¹ (10⁶ m²)	Bay volume¹ (10⁶ m³)	Watershed area (10⁶ m²)	% surface water²	% open²	% agriculture²	% commercial²	% industrial²	% residential²	% transportation²
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%

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

Process or Parameters	Importance for quantitative understanding	Current Level of Knowledge about magnitude, composition, or controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
Loads				
POTWs	High	Moderate: Comprehensive 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-PO ₄ , 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 NH ₄ and PO ₄ release below	Very High	Very High
Pelagic denitrification	Low	Low: not expected to be important because of oxic water column	Low	Low
Benthic nitrification	High	Low: see OM mineralization and NH ₄ and PO ₄ 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 NH ₄ and o-PO ₄ 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 NH ₄ , NO ₃ , and o-PO ₄ uptake by phytoplankton	High	Moderate: field measurements exist for NH ₄ and NO ₃ 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 NO ₃ , NH ₄ , and PO ₄	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 ₂ O	Low/Moderate	Moderate: not needed for nutrient budgets, but informative as diagnostic of processes	Moderate	Moderate
Concentration of DON, PON, DOP, POP within and loaded to the system	Moderate/uncertain	Low: Little current data, and information is needed. Given the high DIN and DIP concentrations, abundance organic forms may be relatively low.	High	High

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

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for <u>additional or continued</u> data collection, process studies, modeling	Priority for study in next 1-5 years
Processes				
Primary production rates	High	Low/Moderate: Basic understanding about light limited production is well modeled. Recent studies suggest that the relationship may have shifted, and revisiting this may be important for estimating system productivity.	Very High	High
Pelagic grazing	High	Low: Long-term program in Suisun Bay and Delta for macrozooplankton, but limited micro-zooplankton data, which may be more quantitatively important in terms of overall grazing rate. No systematic zooplankton sampling in LSB, South Bay, Central Bay.	Very High	High
Benthic grazing	High	Low: good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	Very High	Very High
Sinking, respiration, burial	High	Moderate: Discussed within context of Dissolved Oxygen	Low	Low
Inhibition of primary production rates by elevated NH ₄ ⁺	High/ Uncertain	Low: Several studies have been completed and others are underway. Uncertainty remains about mechanism and relative importance of the process. Field/lab studies and modeling work can be done in parallel, with the former designed to further elucidate the mechanism and thresholds and the latter to quantify its role relative to other factors.	Very High	Very High
Production in the shoals vs. channels (during stratification), and physical or biological controls on bloom growth/propagation	High	Low: Considered to be an important process but limited data available. Data needed to better predict bloom magnitudes.	Very High	Very High
Germination of resting stages	Low	Low: Not considered among the highest priority processes to study	Low	Low
Phytoplankton - Ambient concentration data				
High temporal resolution data in channel	High	Low: Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	Very High	Very High
High temporal resolution data in shoals	High	Low: Very limited high temporal resolution (continuous) phytoplankton biomass data beyond of Suisun Bay. Needed to better predict blooms.	Very High	Very High
Biomass data along the Bay's deep channel	High	Moderate/High: USGS program has been collecting monthly data at along the channel for the past 35 years, and needs to be continued.	Very High	Very High
Phytoplankton C:N ,C:chl-a, and size-fractionated chl-a	High	Low: Valuable information to inform understanding of processes and for modeling	Very High	Very High

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

Process or Parameters	Importance for quantitative understanding	Current Level of confidence about magnitude or mechanistic controls	Need for additional or continued data collection, process studies, modeling	Priority for study in next 1-5 years
<i>Microphytobenthos - Processes</i>				
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
<i>Microphytobenthos - Ambient abundance data</i>				
Basic biomass information, seasonal, spatial	High	Low: Very limited data on MPB abundance and productivity, despite the fact that MPB productivity may be comparable in magnitude to phytoplankton productivity.	Very High	Very High

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

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

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

Process or Parameters	Importance for quantitative understanding	Current Level of Certainty about magnitude, composition, or controls	Need for additional or on-going data collection or process studies	Priority for study in next 1-5 years
Processes				
Pelagic grazing rates (size-selective)	High	Low: No systematic zooplankton sampling in LSB, South Bay, Central Bay. Only 1 station in San Pablo.	Moderate	Moderate
Size-selective benthic grazing rates	High	Low: Good data to support estimates in Suisun Bay. Limited data in LSB South Bay. Monitoring of benthos abundance would inform this.	Very High	Very High
Temperature, light, and nutrient (concentration, N:P, form of N) preferences of phytoplankton PFTs specific to SFB subembayments	High	Low: Limited understanding of how these factors/preferences may shape phytoplankton community composition, in particular in a light-limited nutrient-replete system.	Very High	Very High
Effects of trace metals, organics or pesticides	Moderate/Uncertain	Low: Limited information on vitamins, trace-metals, and the influence of anthropogenic contaminants such as pesticides that may be influencing community composition. competition with diatoms.	Moderate	Moderate
Effect of physical forcings, including exchange between subembayments, oceanic and terrestrial (including wetlands, salt ponds) end-member inputs, large scale climate forcings	High	Moderate: Data on community composition over the past 20 years (Bay wide) and up to 40 years (Suisun and Delta) to explore different explanations.	Very High	Very High
NH ₄ inhibition: diatom productivity	High/ Uncertain	Low: Several studies completed, others underway.	Very high	Very high
Ambient composition data				
Size-fractionated chl-a	High	Low: Provides a coarse measure of in which classes phytoplankton biomass resides, which is a useful albeit coarse surrogate for food quality. Not currently being collected but could be easily added to monitoring.	High	High
Phytoplankton community composition, monthly time-scales, at sufficiently high spatial resolution, and higher temporal/spatial resolution to test mechanisms	High	Moderate: 20 year near-monthly Bay-wide record from USGS and ~40 year record for Suisun and Delta. But few higher resolution data sets or special studies.	Very high	Very high

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

Table 11.1 Typical concentrations and forms of N and P in treated wastewater effluent at different treatment levels

Treatment type	NH ₄ (mg N L ⁻¹)	NO ₃ (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

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 <i>Corbula</i> 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

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

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

Table 11.5 Highest priority mitigation scenarios and related science questions

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

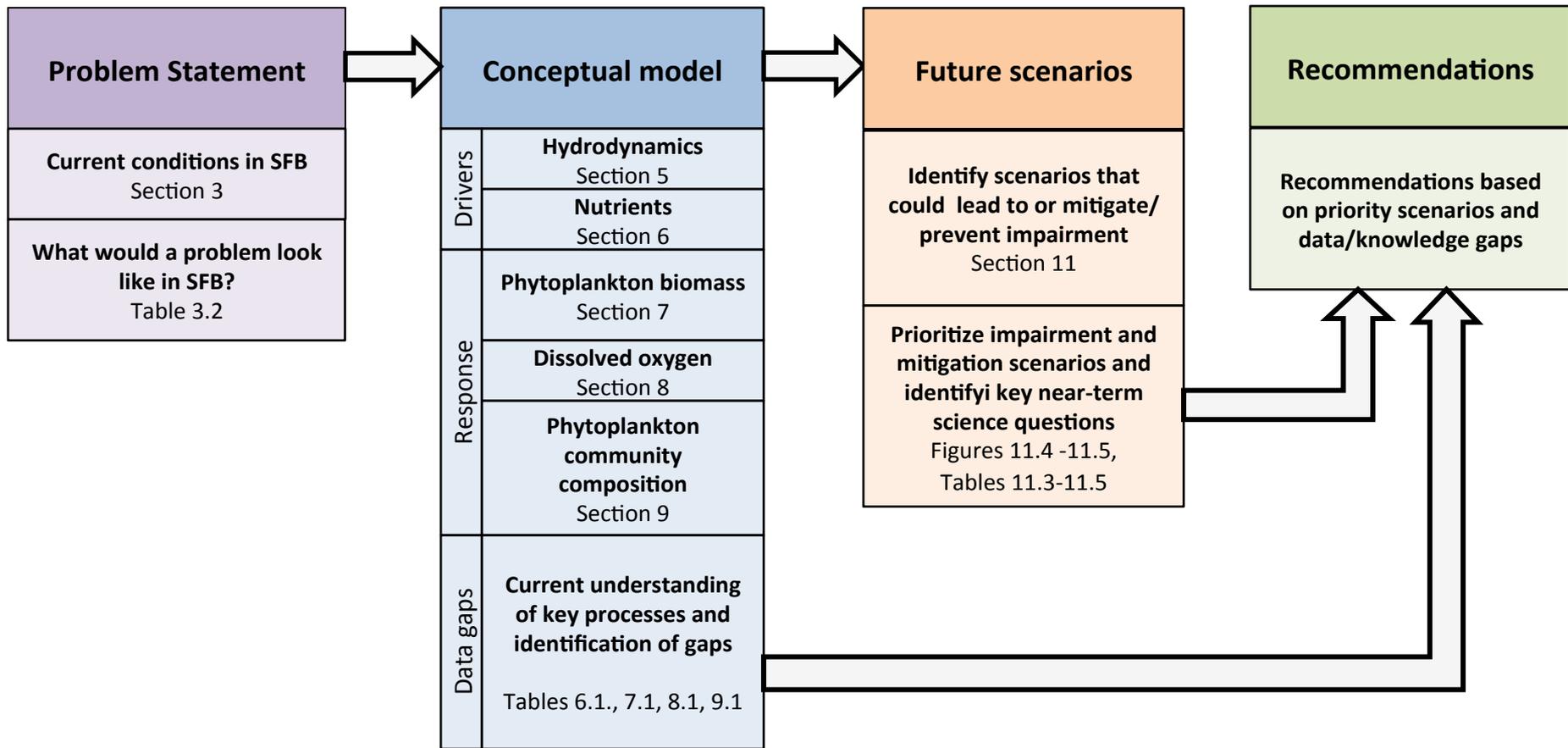


Figure 1.1 Conceptual model project overview and report structure

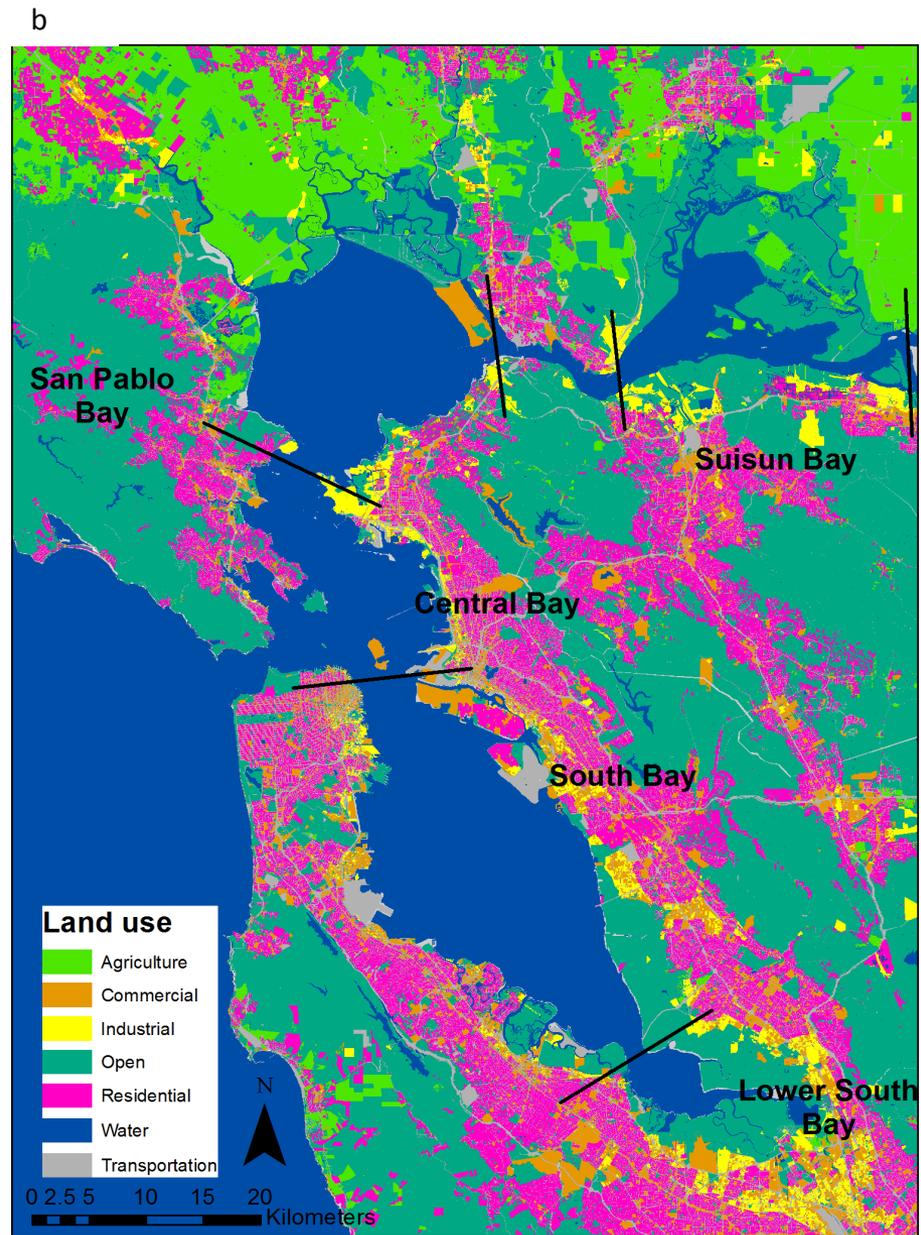
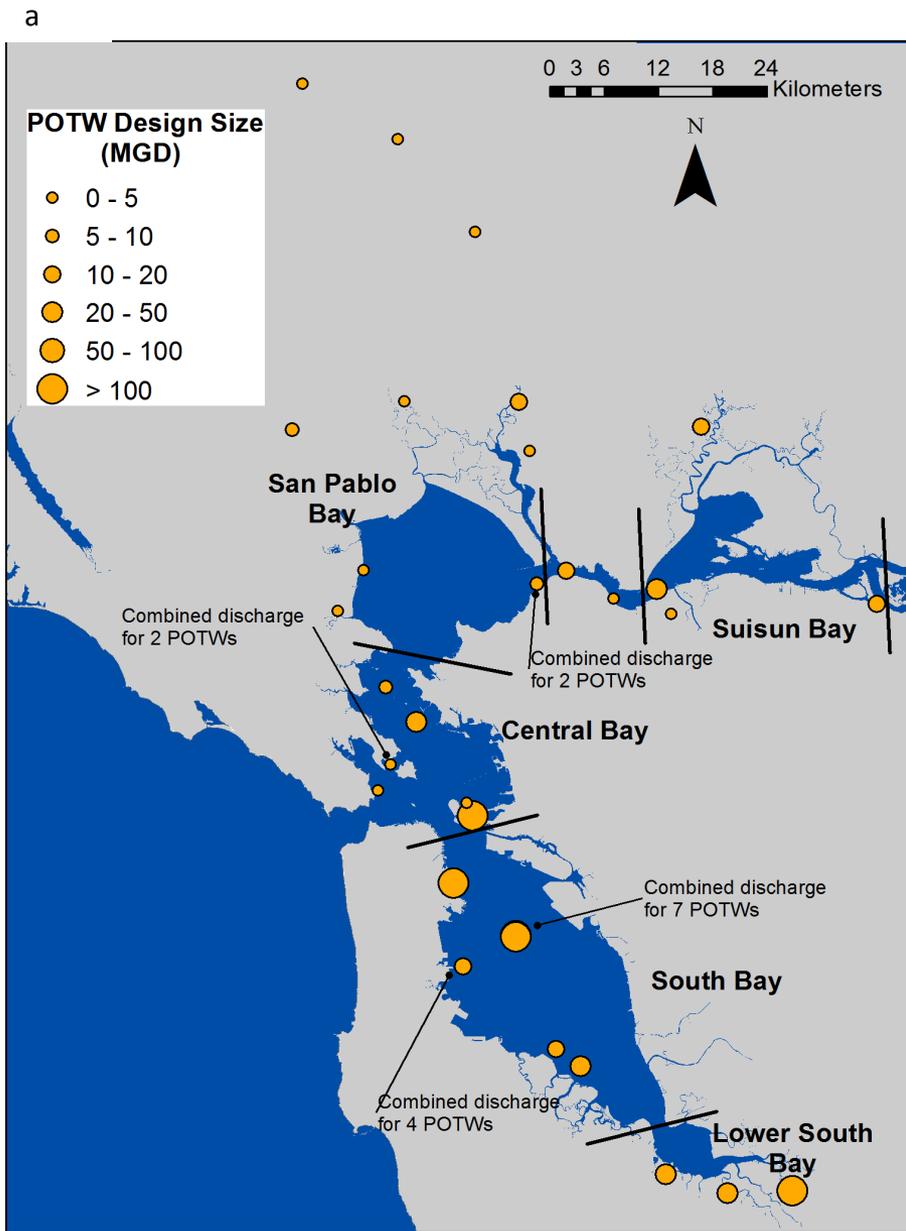


Figure 2.1 a) Location and design size (in million gallons per day) for POTWs that discharge directly in SFB or in watersheds directly adjacent to subembayments; b) Land use in watersheds that drain to SFB (Data from Association of Bay Area Governments, 2000). In both figures, Water Board subembayment boundaries are shown in black.

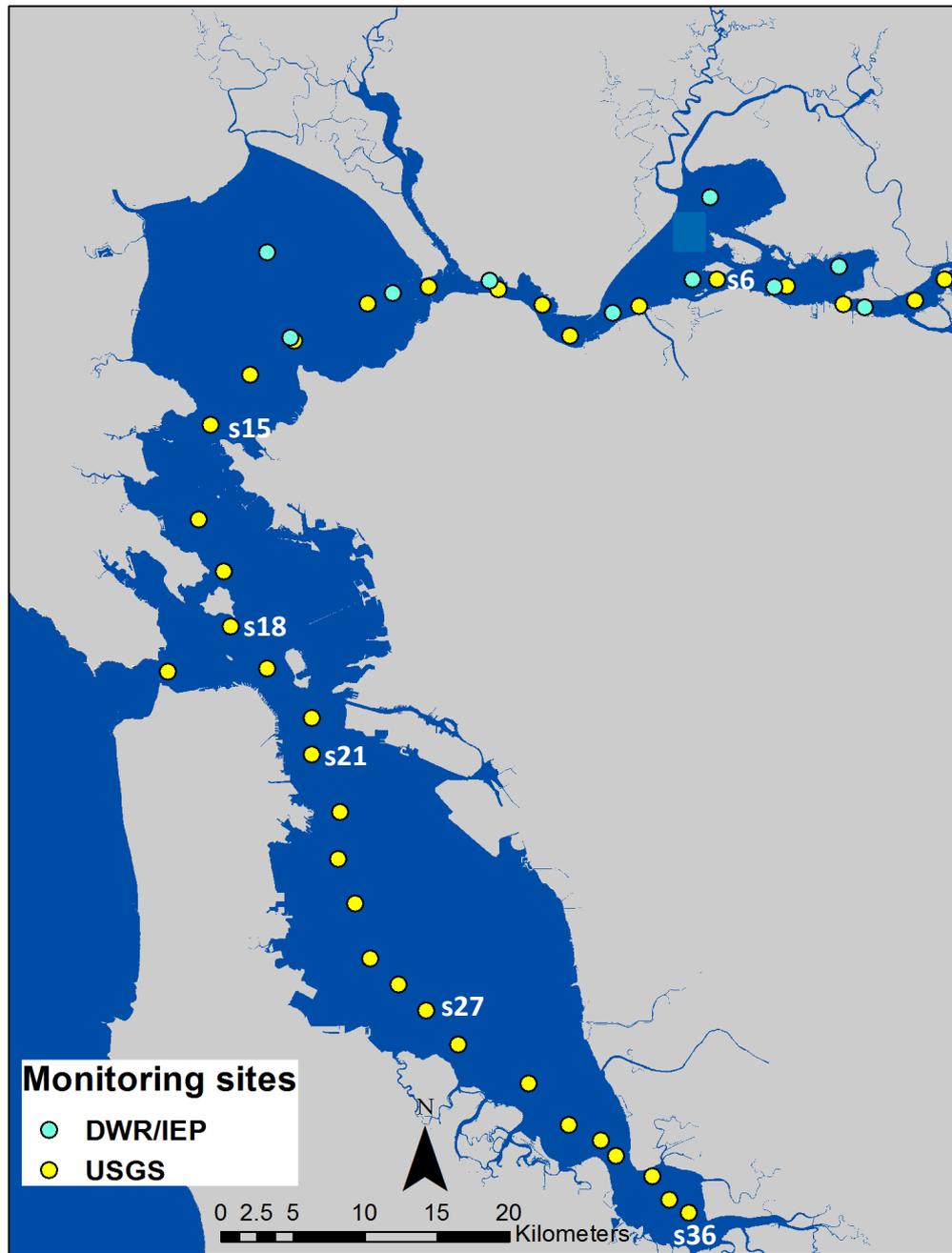
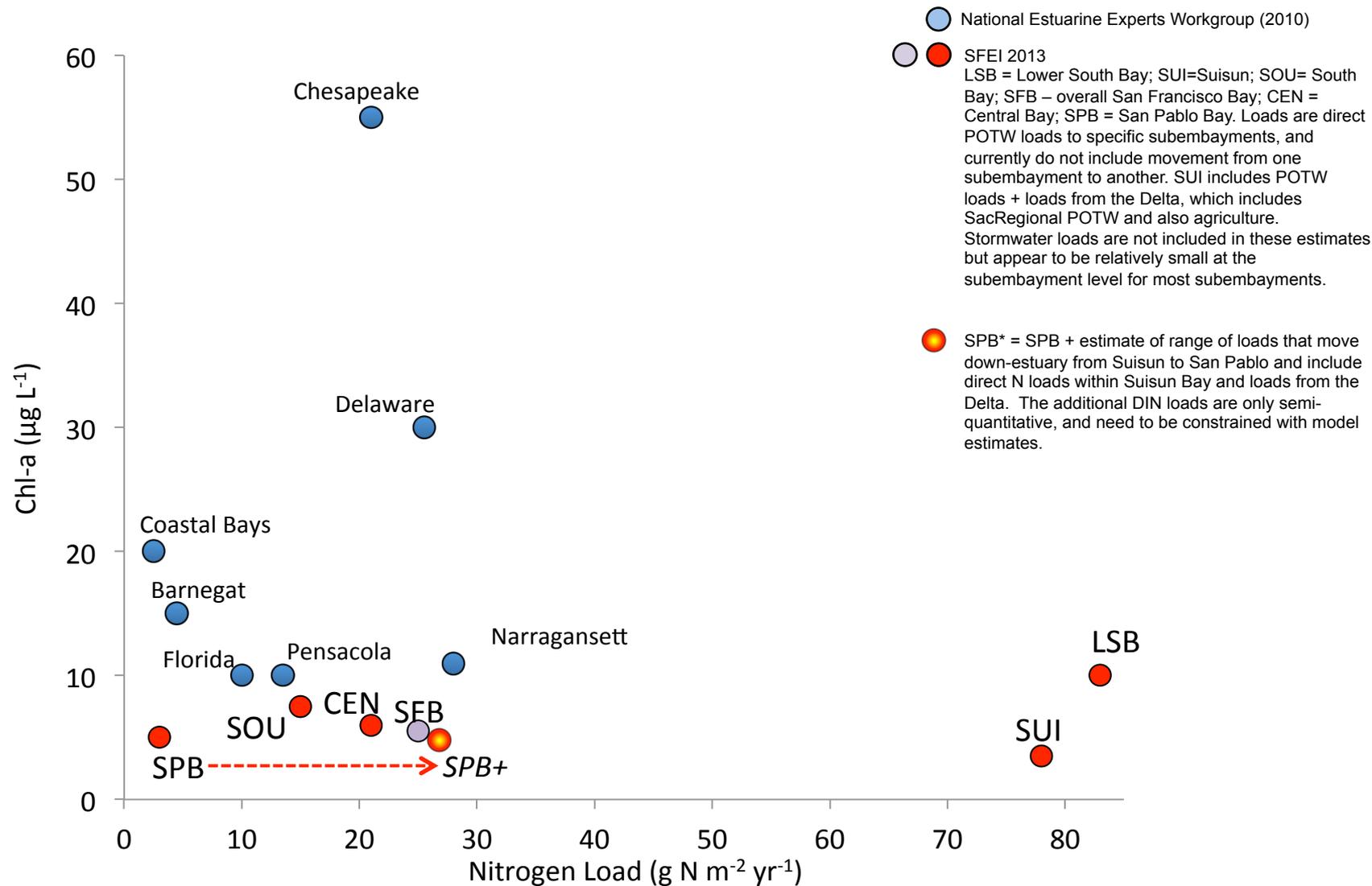


Figure 2.2 Location of DWR/IEP and USGS monthly sampling stations. Data from labeled USGS Stations (s6, s15, s18, s21, s27, s36) are used in Figures 5.7, 6.4-6.6 and 7.11.

Figure 3.1 Nutrient loads to San Francisco Bay subembayments, compared to other nutrient-impaired estuaries. Loads considered include those from POTWs and loads entering from the Delta (which include N derived from upstream treated wastewater effluent and agriculture)



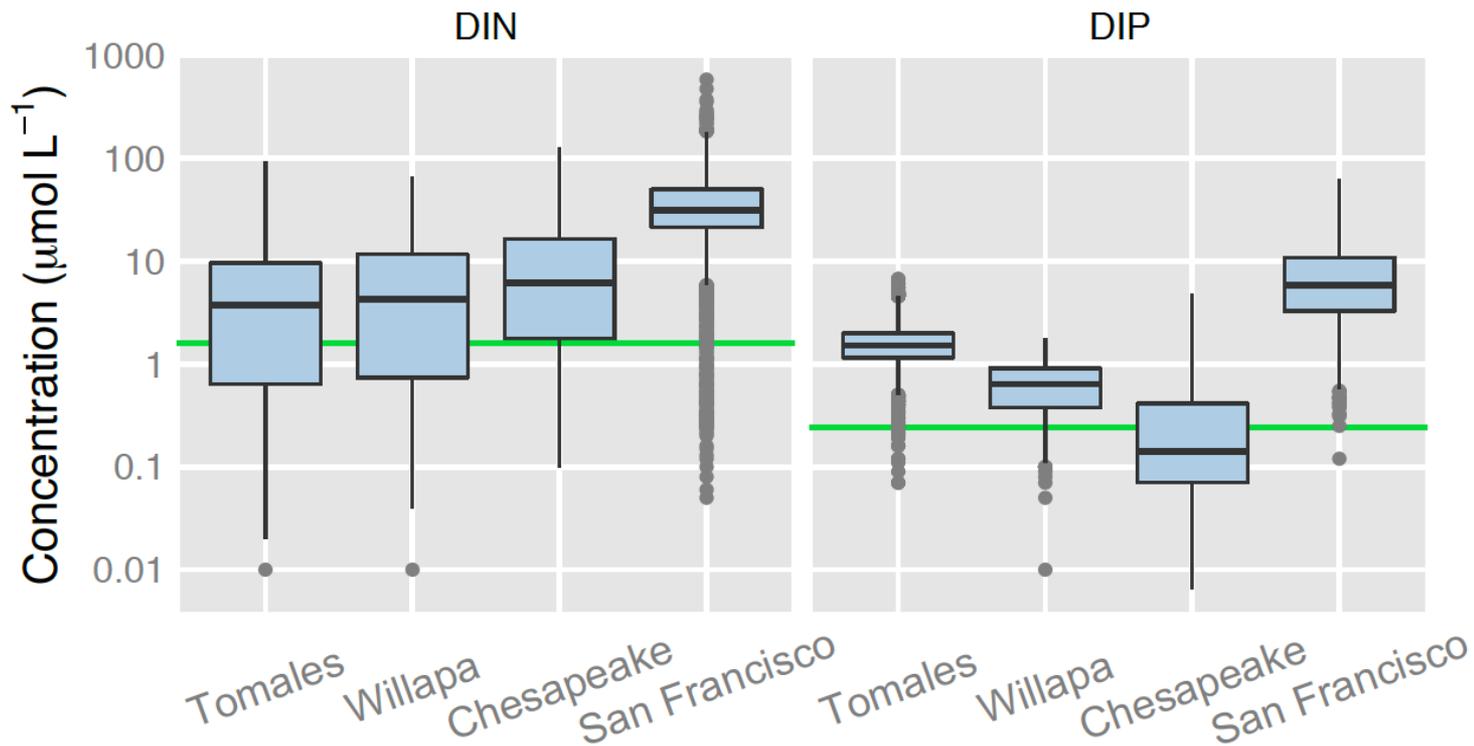


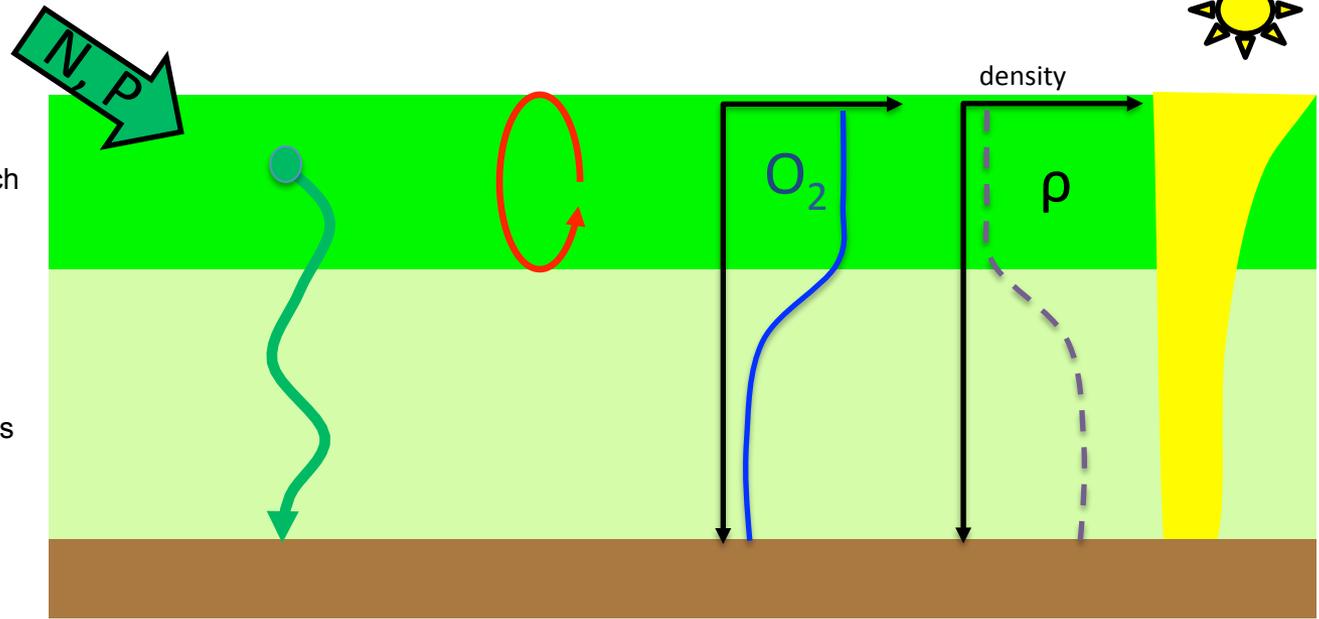
Figure 3.2 Nutrient concentrations in South Bay compared to other estuaries. Source: Cloern and Jassby (2012)

'Typical' estuary

1. Relatively high light levels

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

These two features allow nutrients to be efficiently converted to phytoplankton biomass, and also cause dissolved O_2 to reach low levels in the un-ventilated bottom waters where dead phytoplankton are respired by O_2 -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

These three features minimize the efficiency of nutrient conversion into biomass, and mixing ventilates bottom waters and prevents development of low DO.

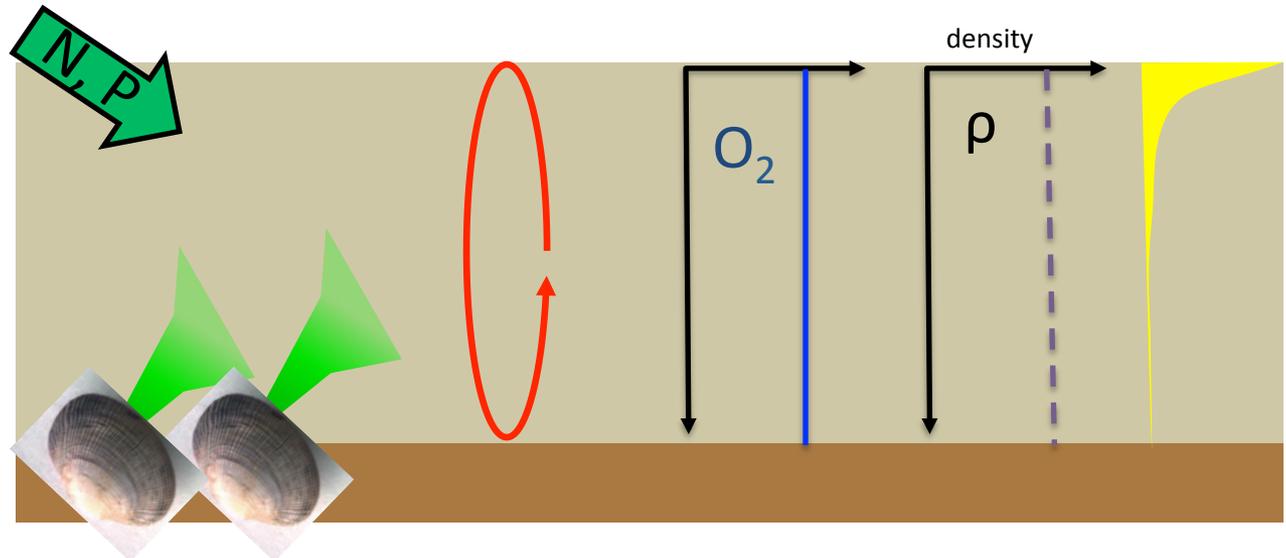


Figure 3.3 Simplified schematic illustrating key differences between SFB and many other estuaries that lead to SFB's attenuated phytoplankton biomass and dissolved oxygen responses to high nutrient loads

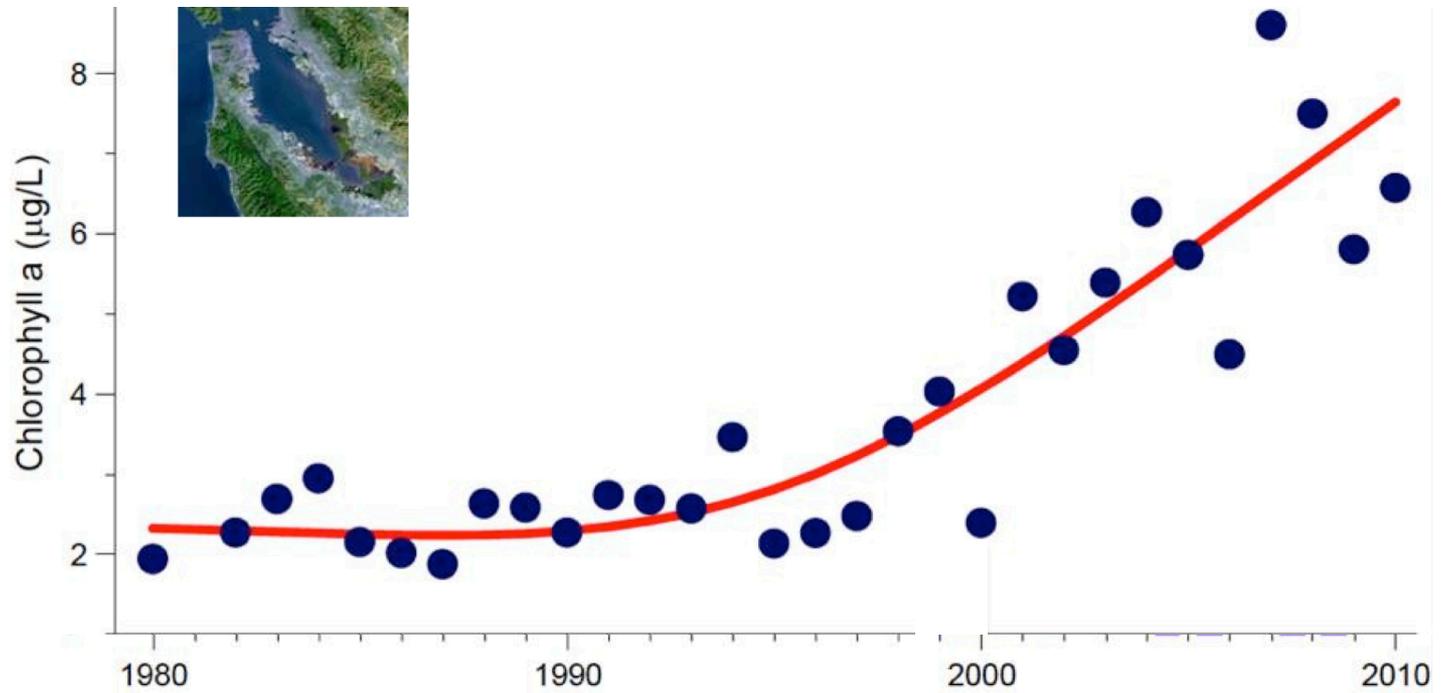


Figure 3.4 June-October concentrations of chl-a averaged across all USGS stations south of the Bay Bridge. Source: J Cloern, USGS

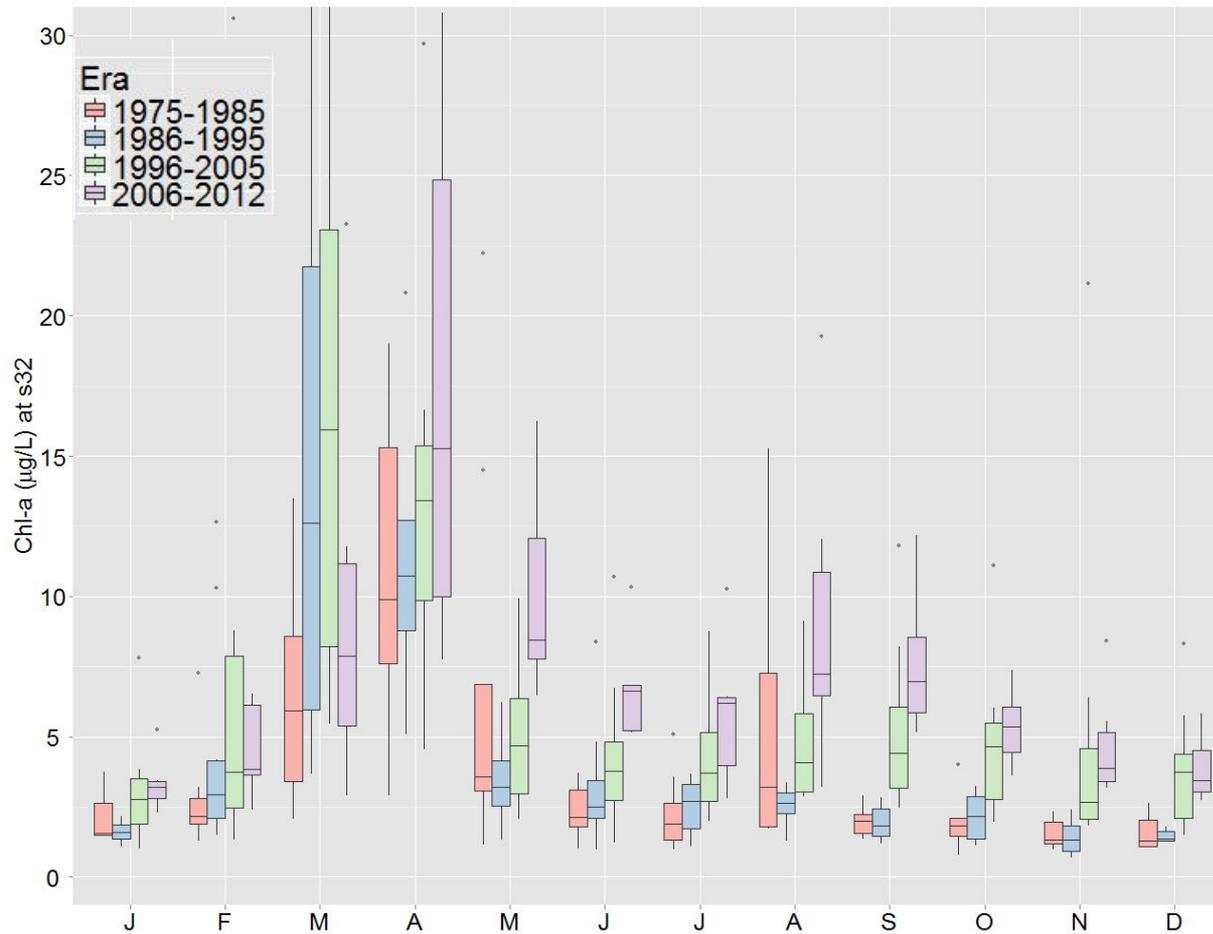


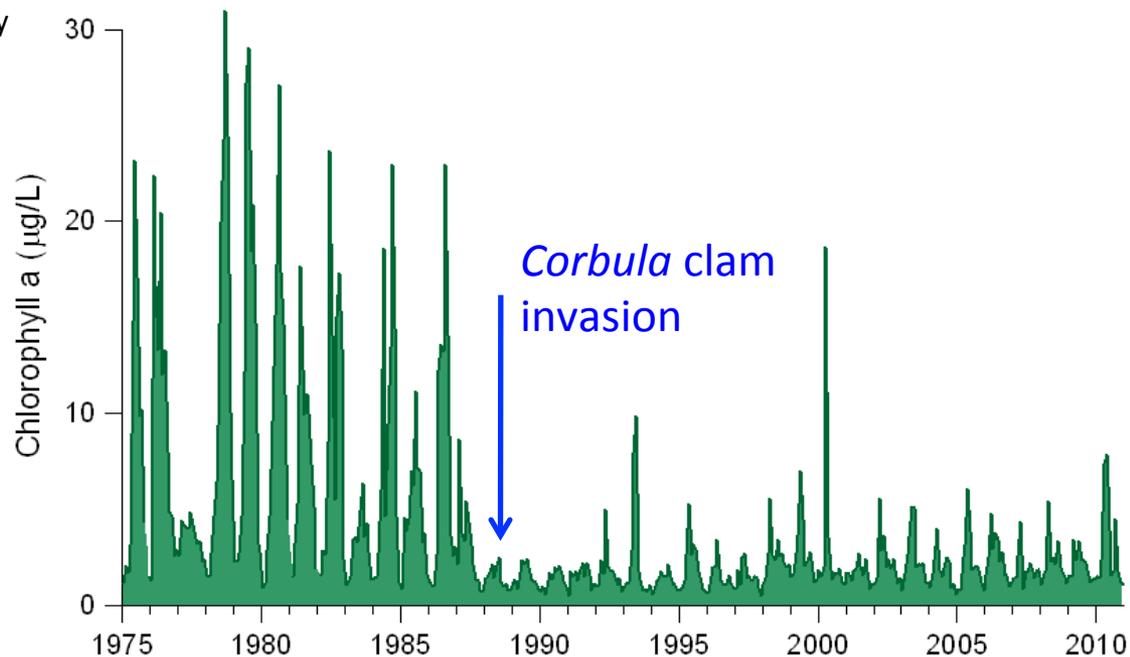
Figure 3.6 Seasonal box plot of chlorophyll-a concentrations near the Dumbarton Bridge, divided into ~10 year eras. Increases in summer baseline chl-a concentrations have been evident since 1996-2005. Fall blooms have also become a regular occurrence. The increases are statistically significant during all months except March and April.

Figure 3.7 A. Phytoplankton biomass and **B.** community composition in Suisun Bay, 1975-2010

Proposed drivers/stressors

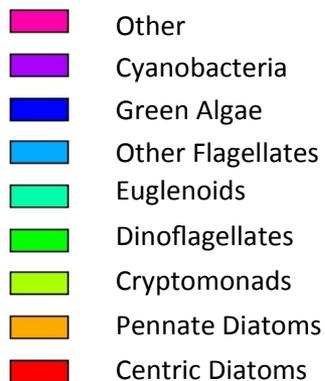
- Clams
- Light limitation
- Nutrients (NH₄)
- Residence time

A.

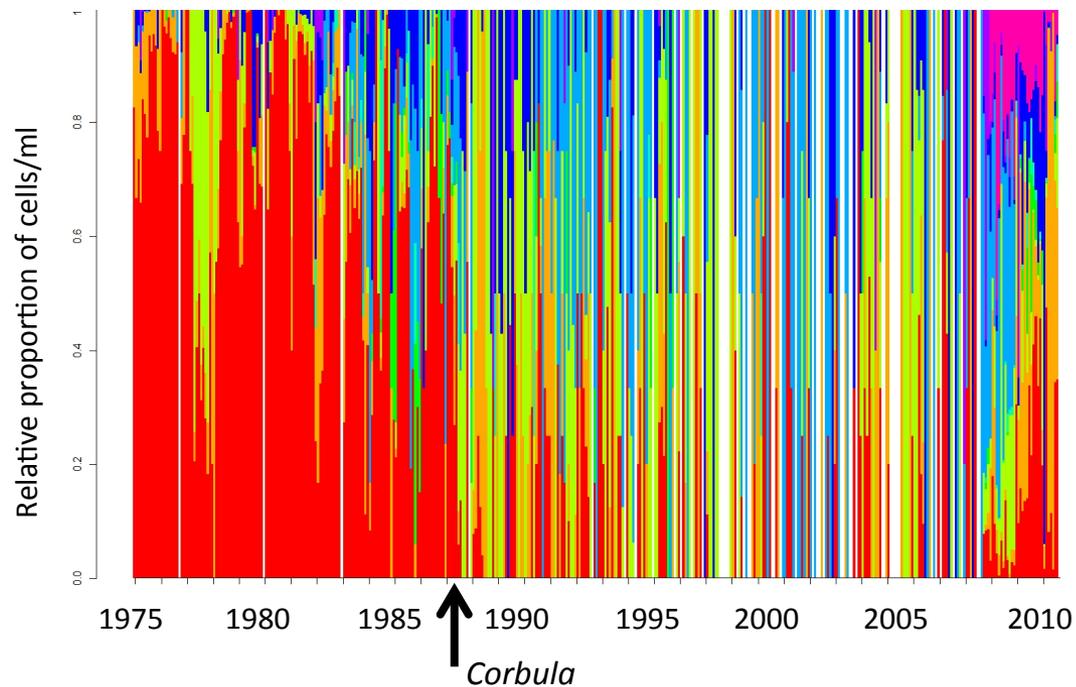


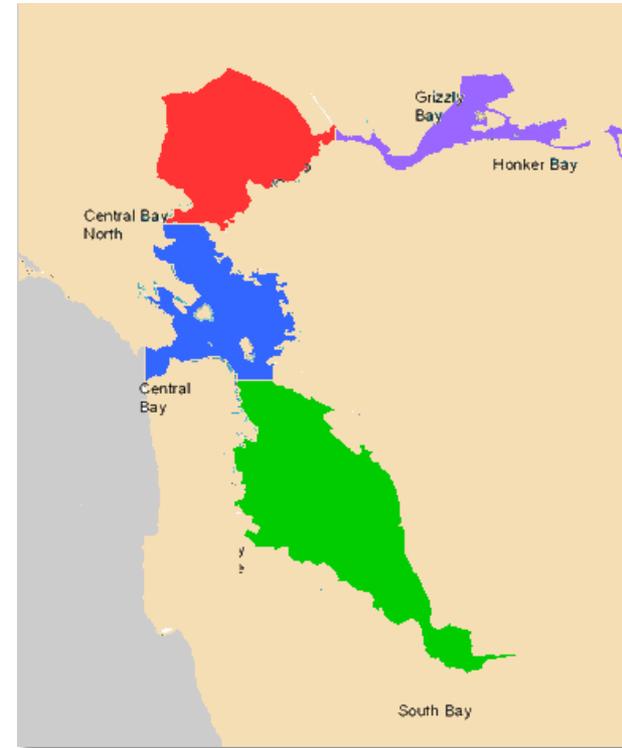
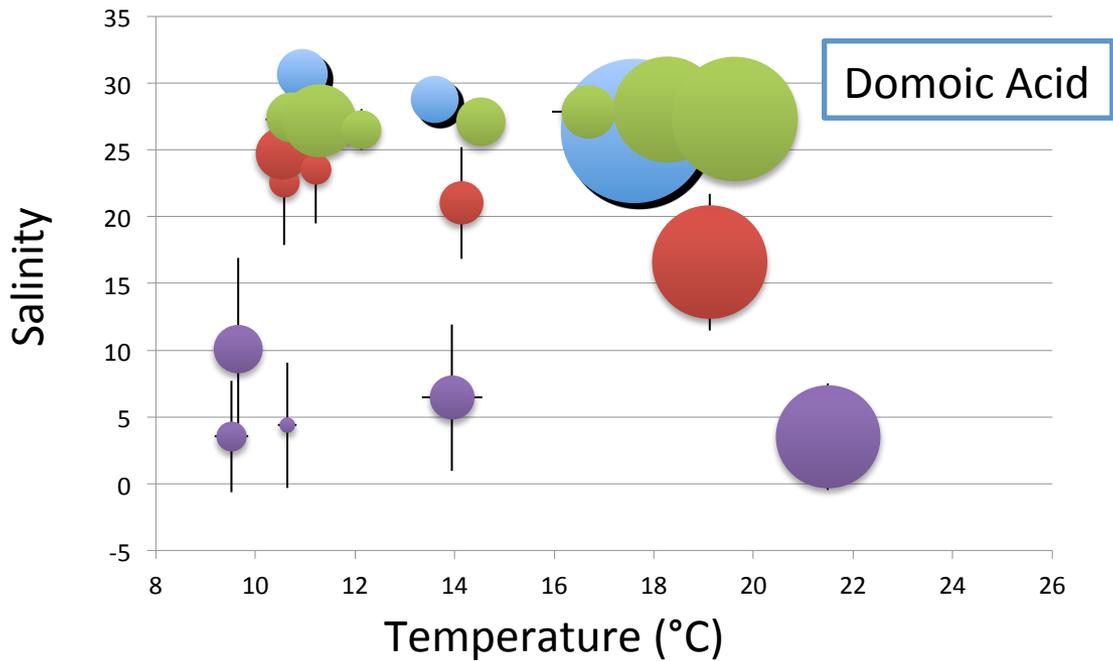
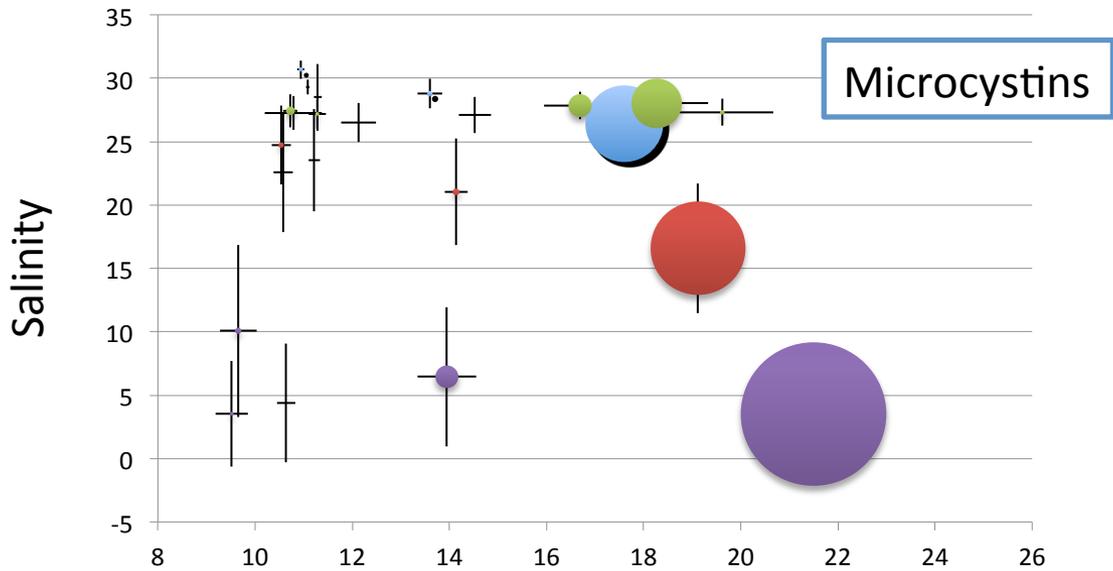
Proposed drivers/stressors

- Clams (size-selective grazing)
- Nutrients
- other



B.





*Bubble size = toxin concentration;
color corresponds to Bay regions*

Figure 3.8 HAB toxins detected in SFB during 2011. Bars represent 1 SD for Salinity and Temperature

◆ *Heterosigma akashiwo*

▲ *Karenia mikimotoi*

● *Karlodinium veneficum*

◆ *Chattonella marina*

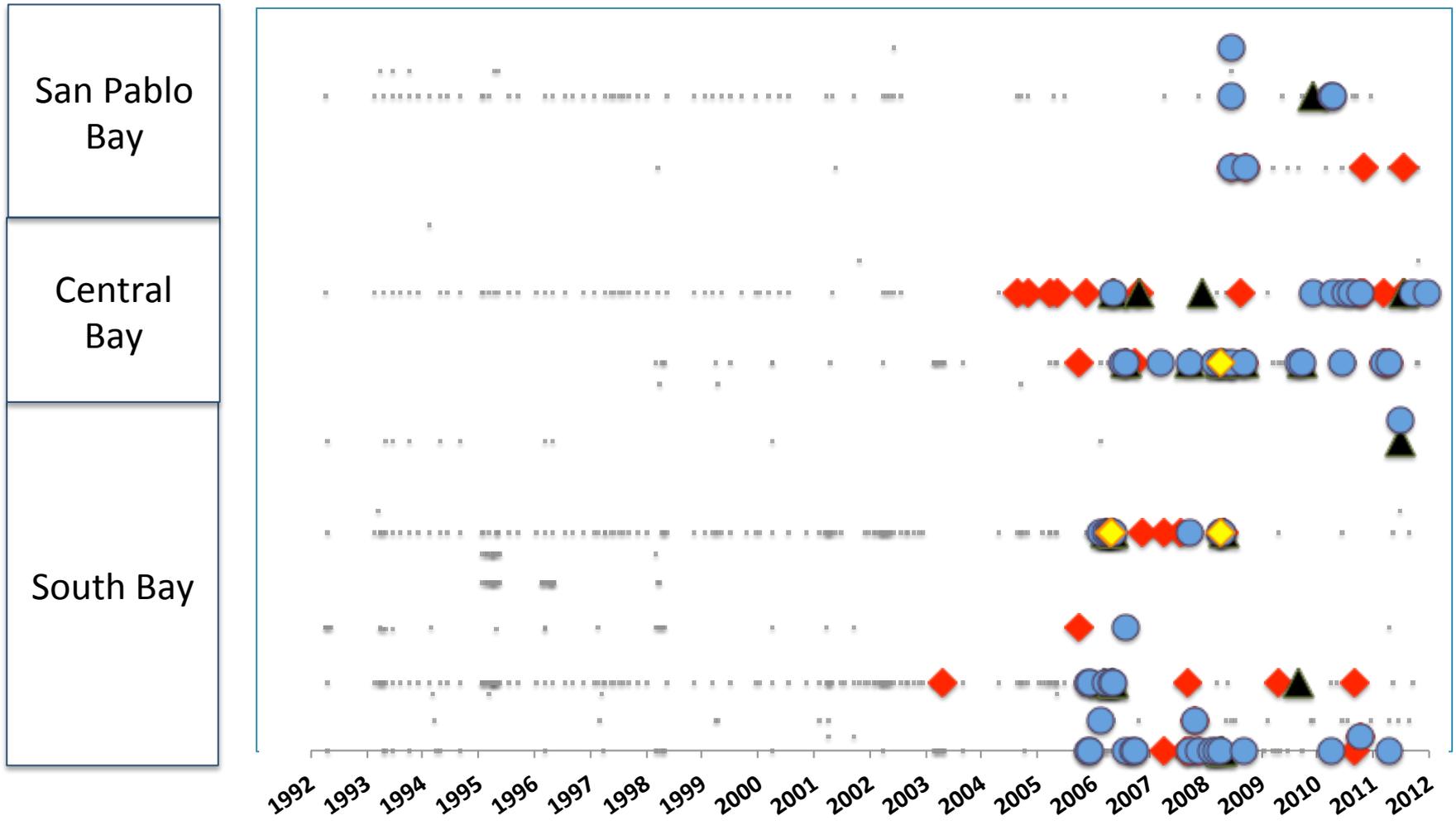


Figure 3.9 Several potentially harmful algal species detected in South Bay, Central Bay, and San Pablo Bay over the past 20 years. Y-axis represents distance to USGS stations from Lower South Bay. Grey dots represent sample collection/analysis, colored dots represent one of the 4 species species detected in a collected sample. Source: T Schraga, USGS

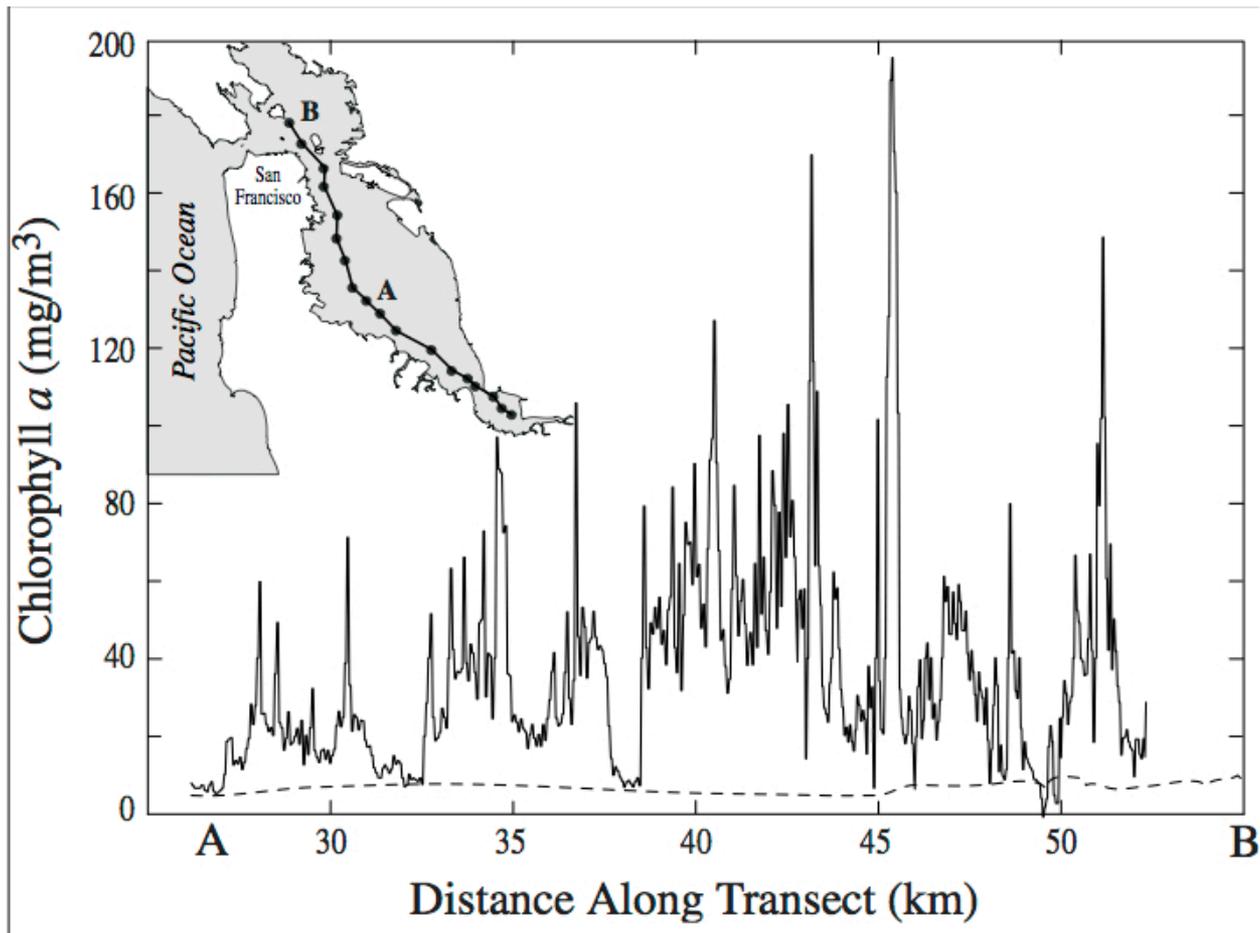


Figure 3.10 Phytoplankton biomass South and Central Bays. Measurements taken during a red tide on 8 September 2004 (solid curve). Phytoplankton biomass returned to typical seasonal levels on 14 September (dashed curve). Inset map shows location of the sampling transect A-B. Source: Cloern et al. 2005

A.

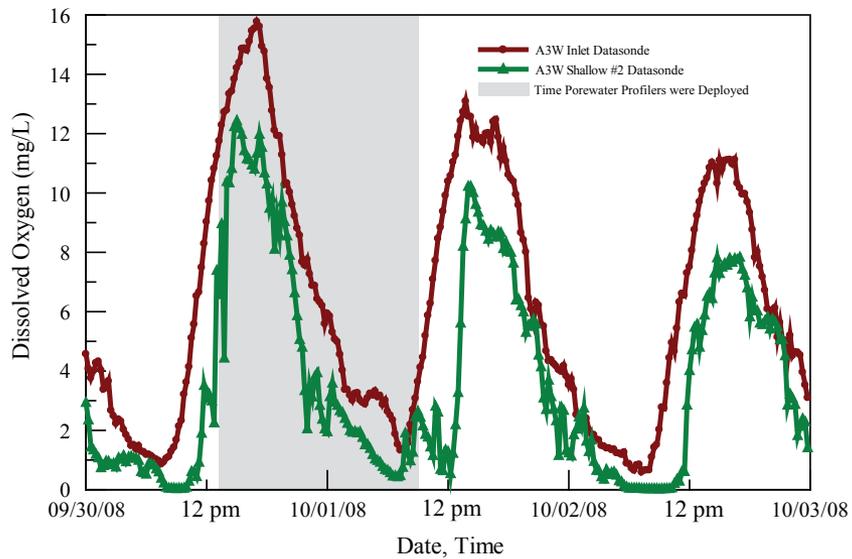


Figure 5. Plot of dissolved oxygen data in the water-column as monitored by dataloggers (Pond A3W)

B.

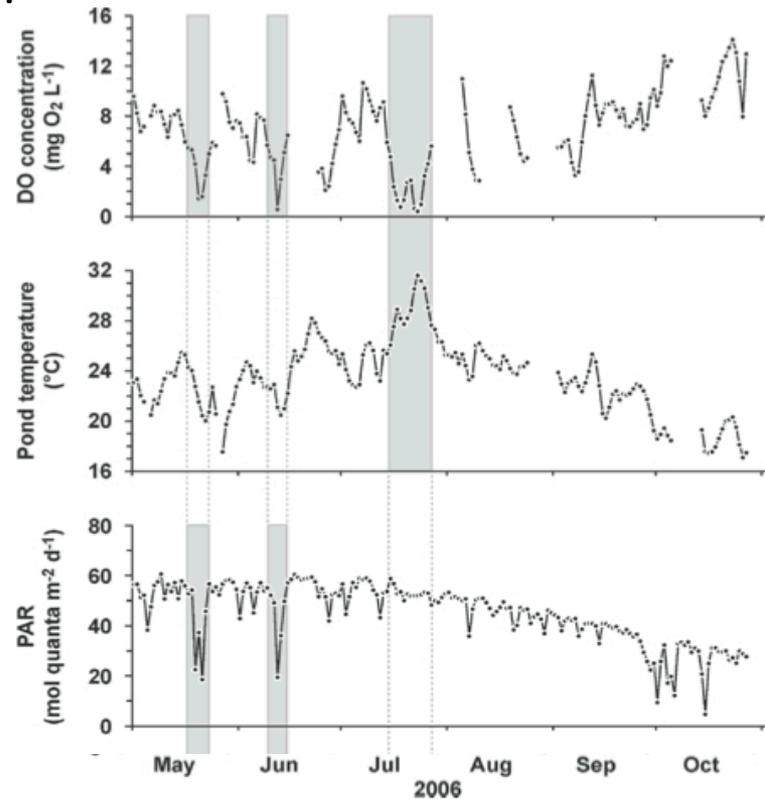
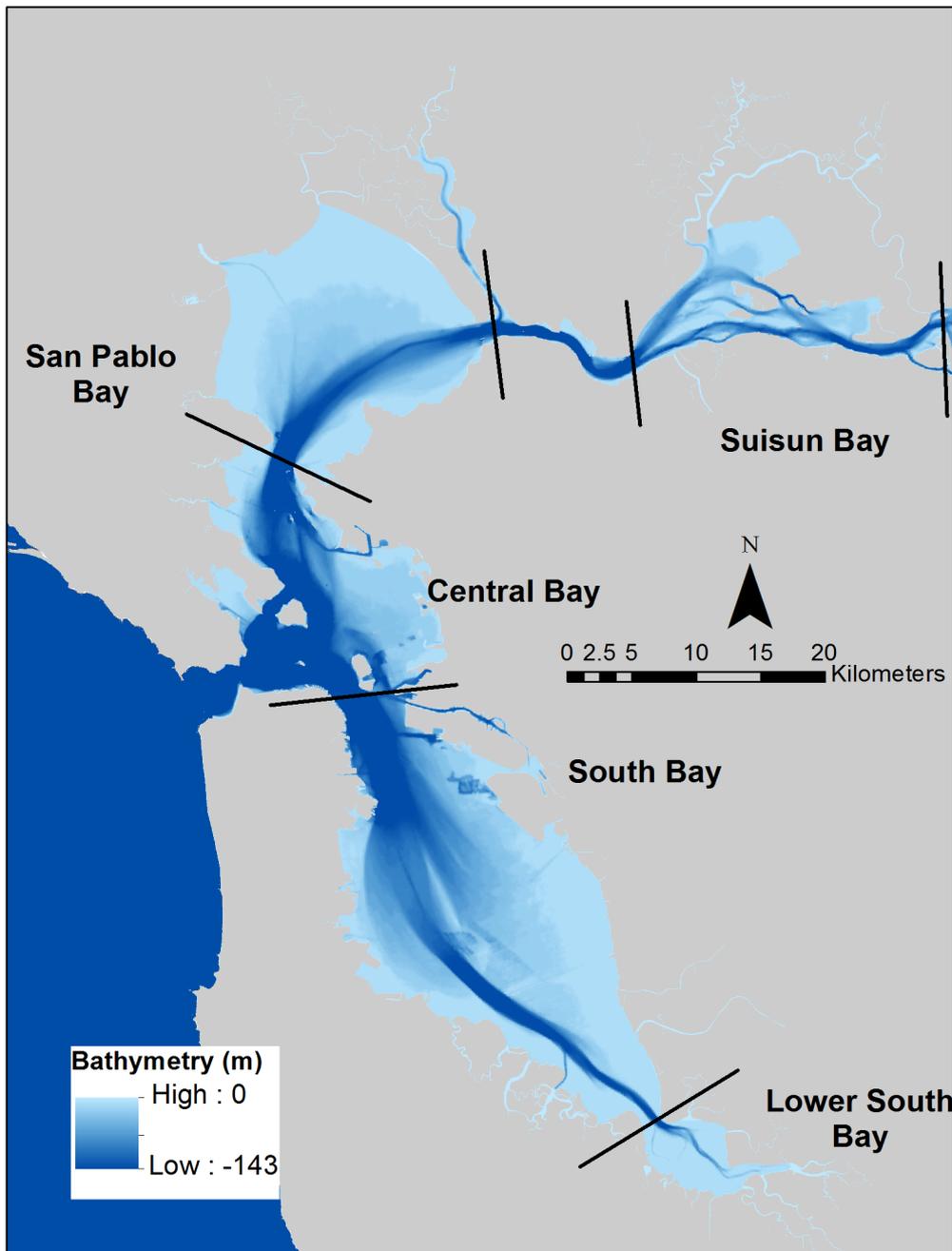


Figure 3.11 A. Dissolved oxygen concentrations in LSB salt pond A3W undergoing restoration Source: Topping et al. 2008
 B. Dissolved oxygen concentration in LSB salt pond A18. Grey bars indicate time periods when incident light was low (clouds) or temperatures were high enough to inhibit primary production. These factors lead to sustained periods of low DO. Source: Thebault et al. 2008

Figure 5.1 Bathymetry in SFB, shown as distance below surface (m). Water Board subembayment boundaries are shown in black. Source: NOAA bathymetry soundings



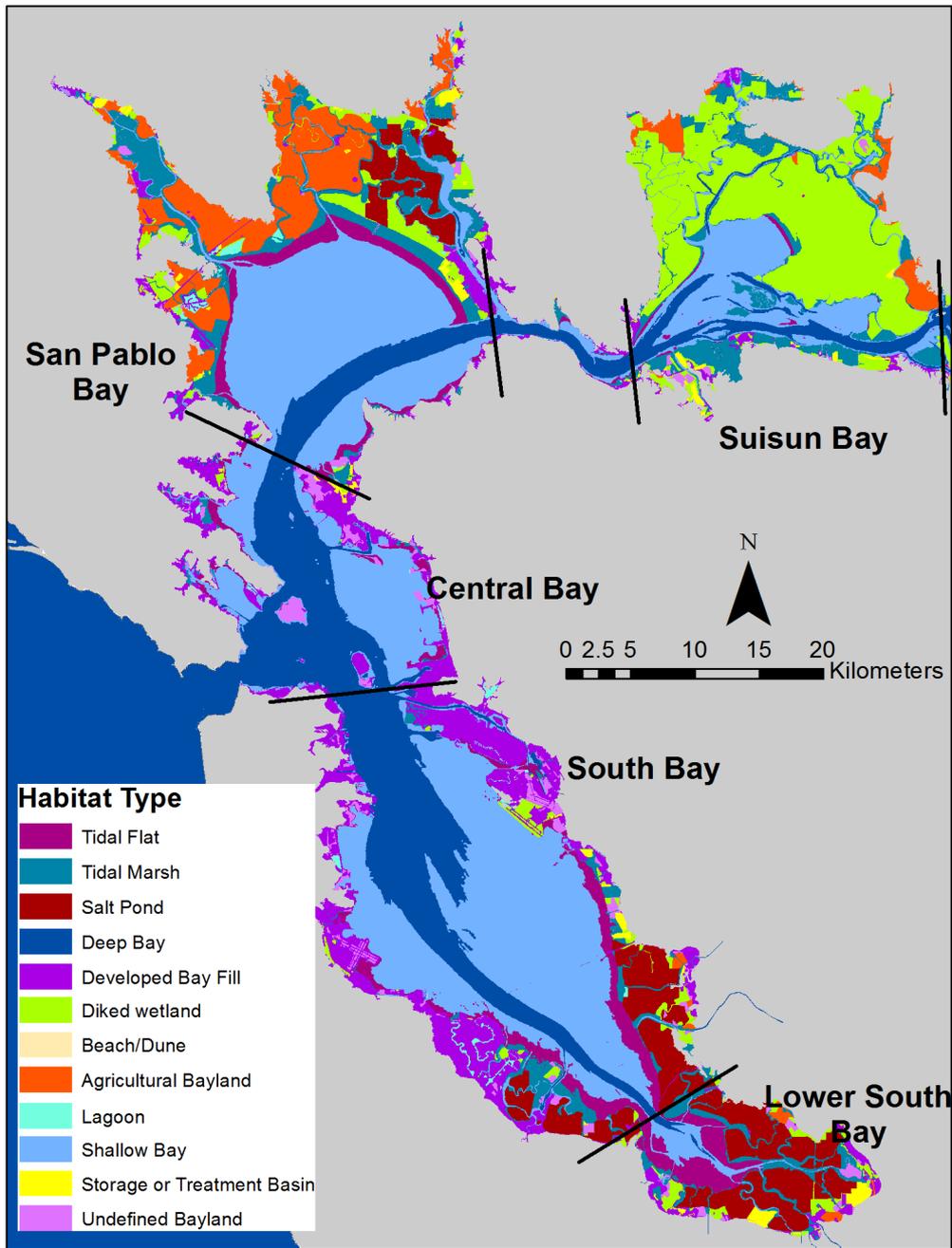


Figure 5.2 Habitat types of SFB and surrounding Baylands. Water Board subembayments boundaries are shown in black. Habitat data from CA State Lands Commission, USGS, UFWs, US NASA and local experts were compiled by SFEI.

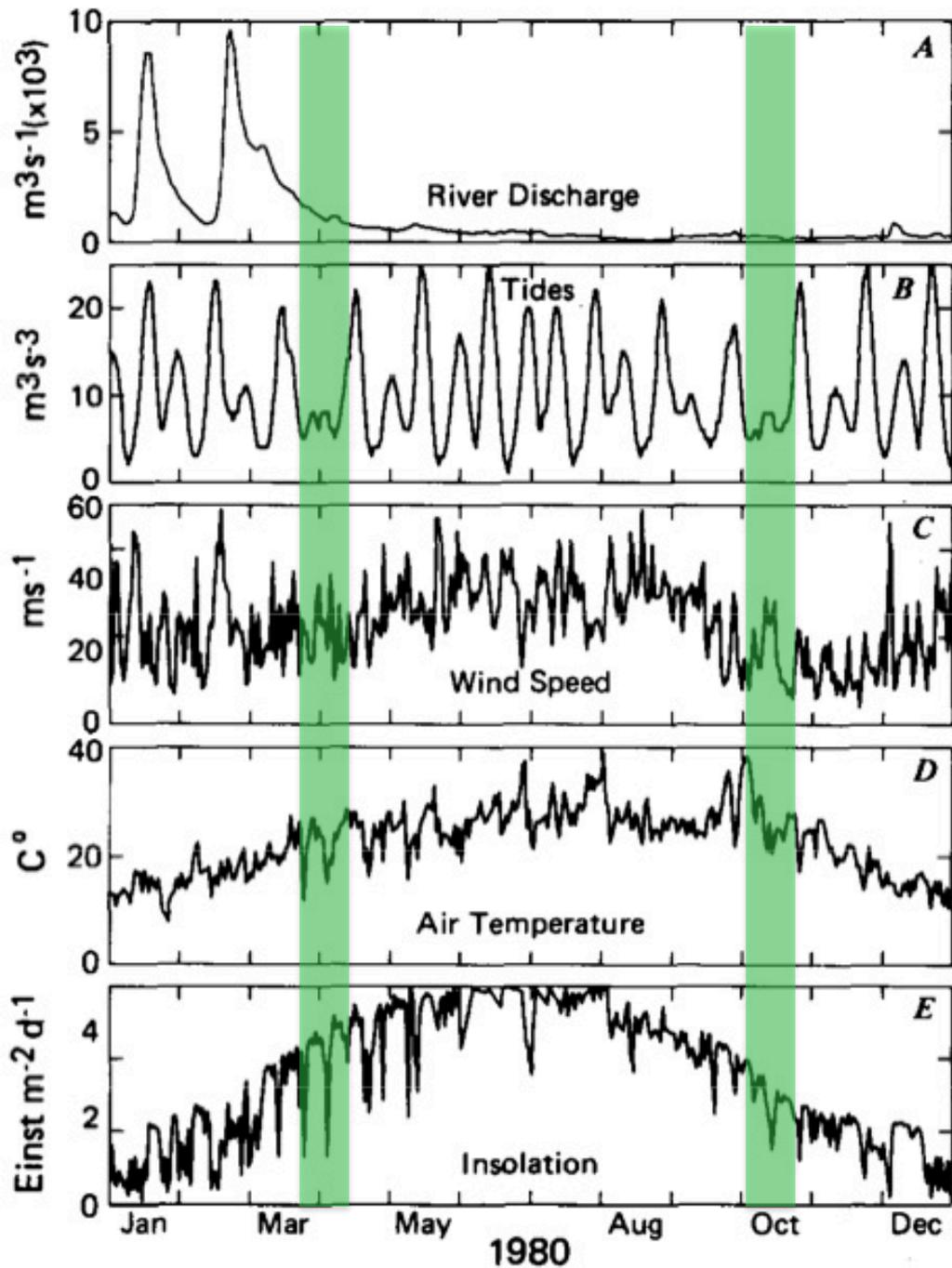


Figure 5.3 Physical drivers in San Francisco Bay. The green vertical bars illustrate the periods of minimum tidal mixing energy. In March/April, freshwater inputs and relatively low mixing energy allow the water column to stratify for ~10-14 days. In September/October, lower freshwater inputs limit the 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

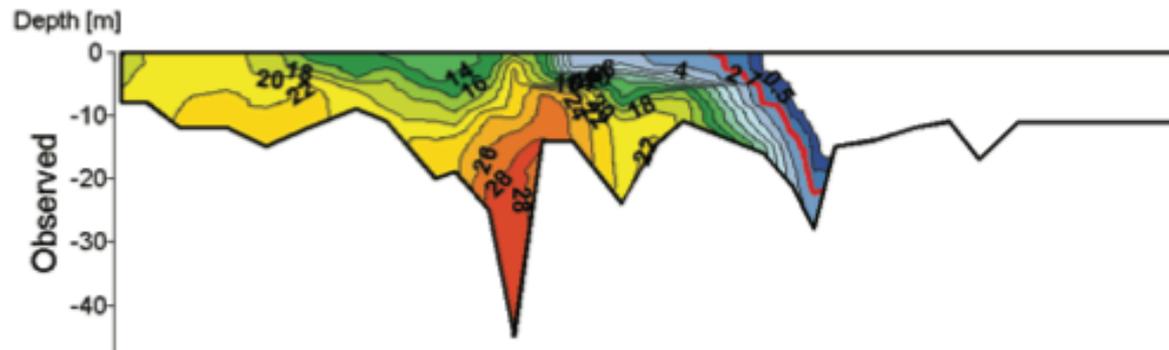
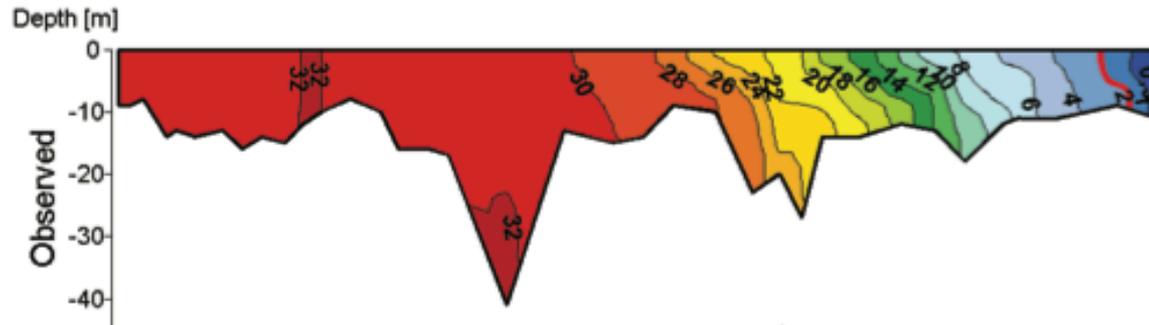


Figure 5.4 Observed salinity along main channel surveys of SFB. A. October 26 1994. B. January 18 1995. Source: Gross et al., 2009

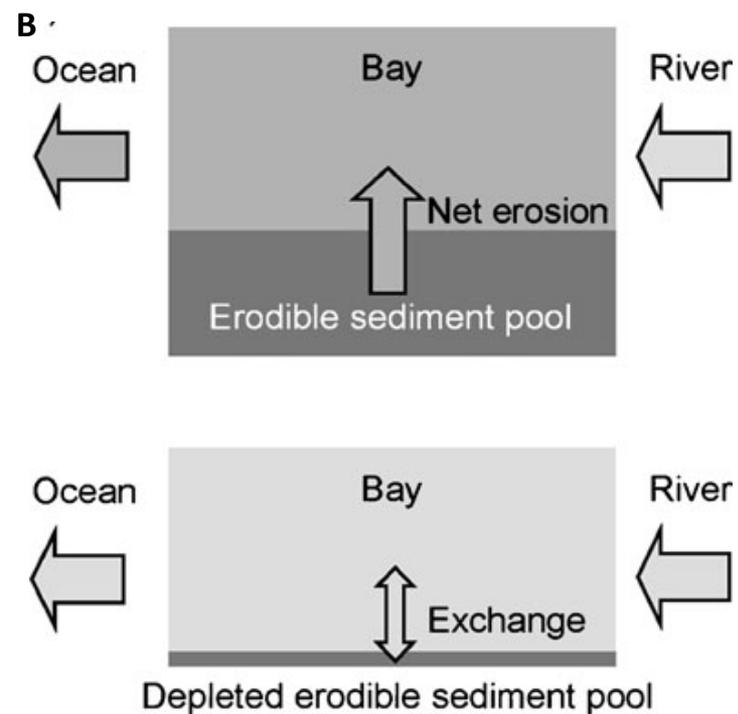
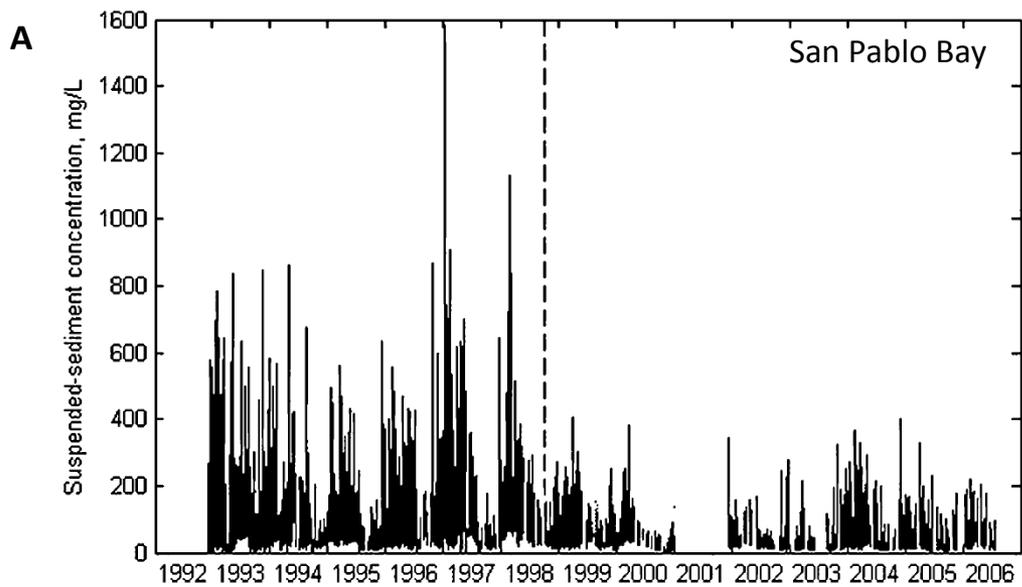


Figure 5.5 A. Time series of suspended particulate matter concentrations in Suisun Bay measured by a continuous monitoring. B. Conceptualization of cause of declining sediment concentrations. Sediment inputs to SFB have declined substantially in recent years. Due to the lack of replenishment, the erodible sediment pool in the bed has been gradually depleted. As a result, less material is resuspended, resulting in lower concentrations.

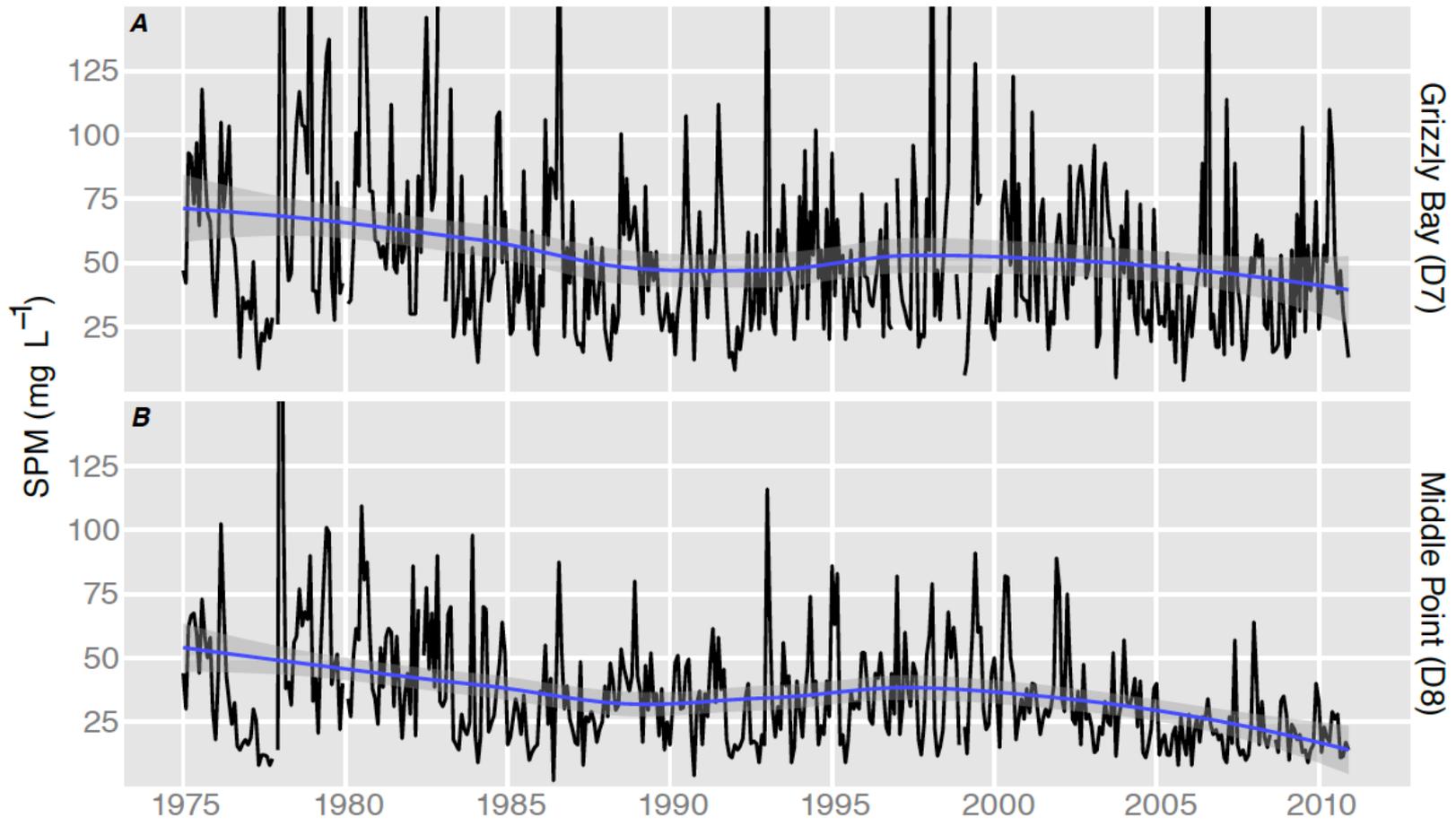


Figure 5.6 Suspended sediment concentrations in Suisun Bay: shallow Grizzly Bay (top) and in the channel (bottom). Source: Cloern and Jassby 2012

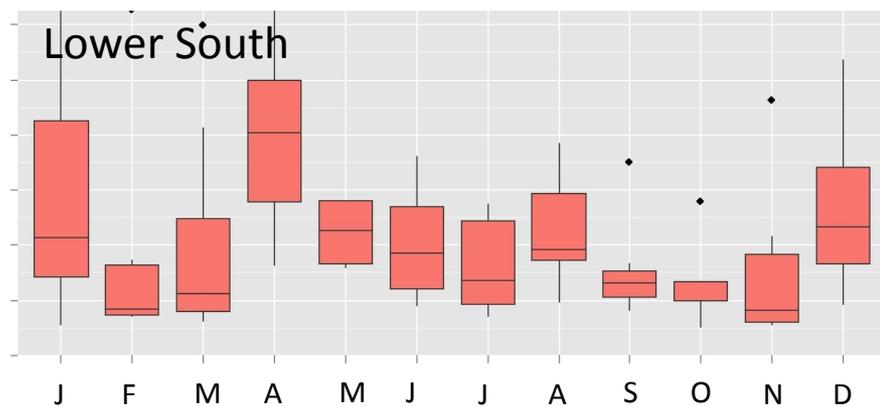
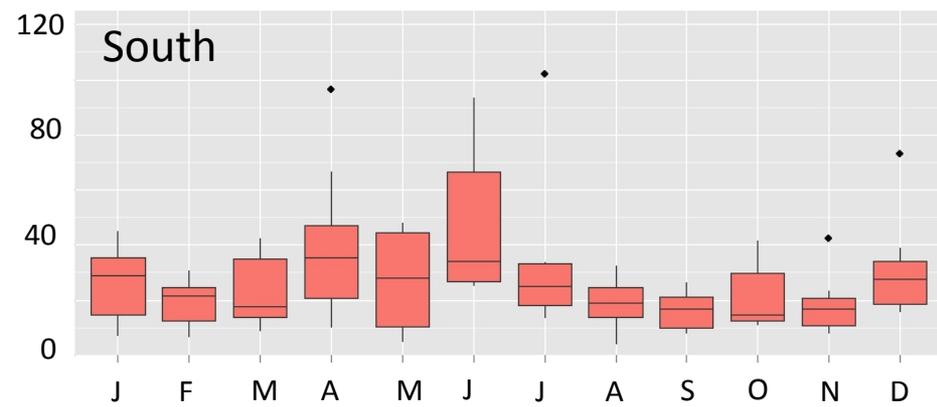
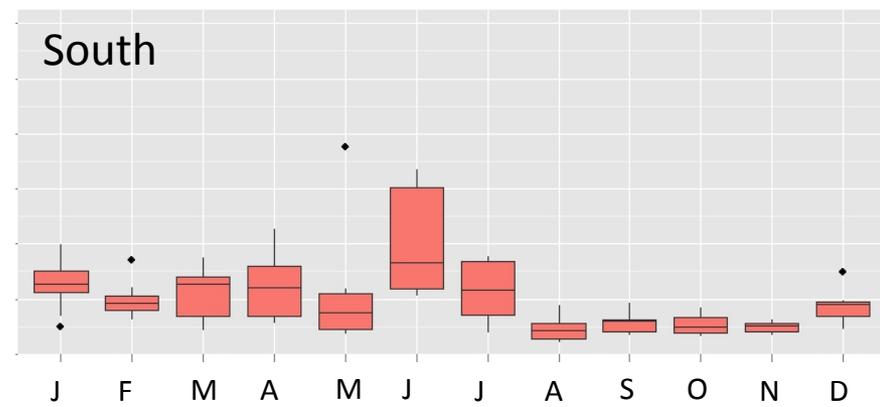
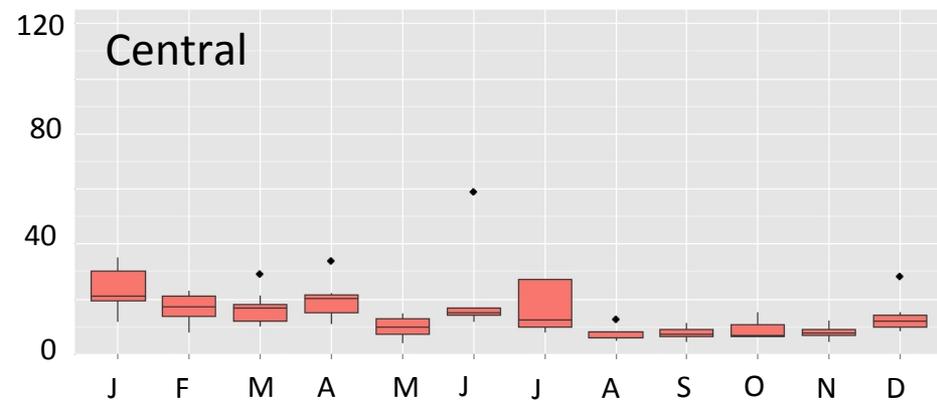
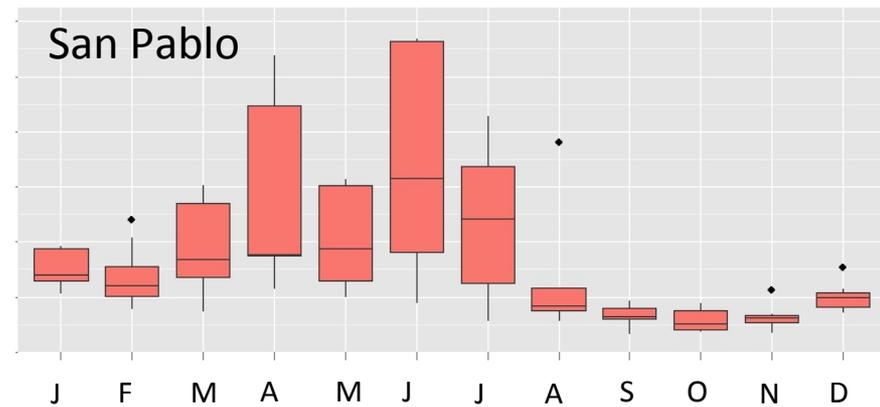
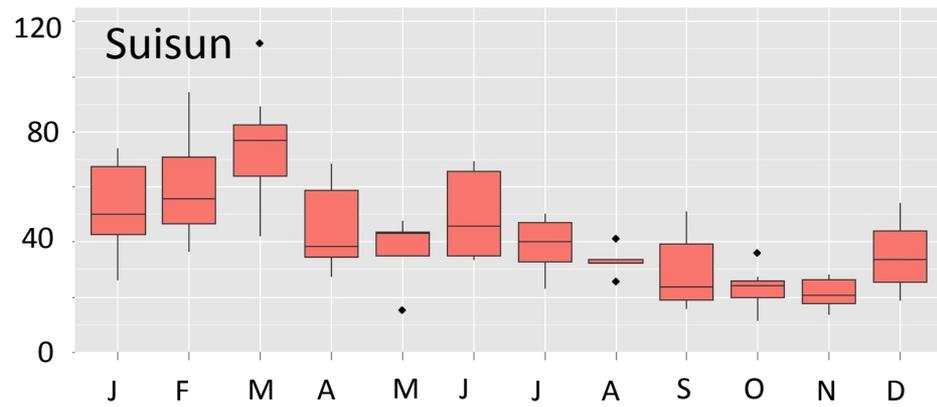


Figure 5.7 Monthly average SPM (mg/L) – 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

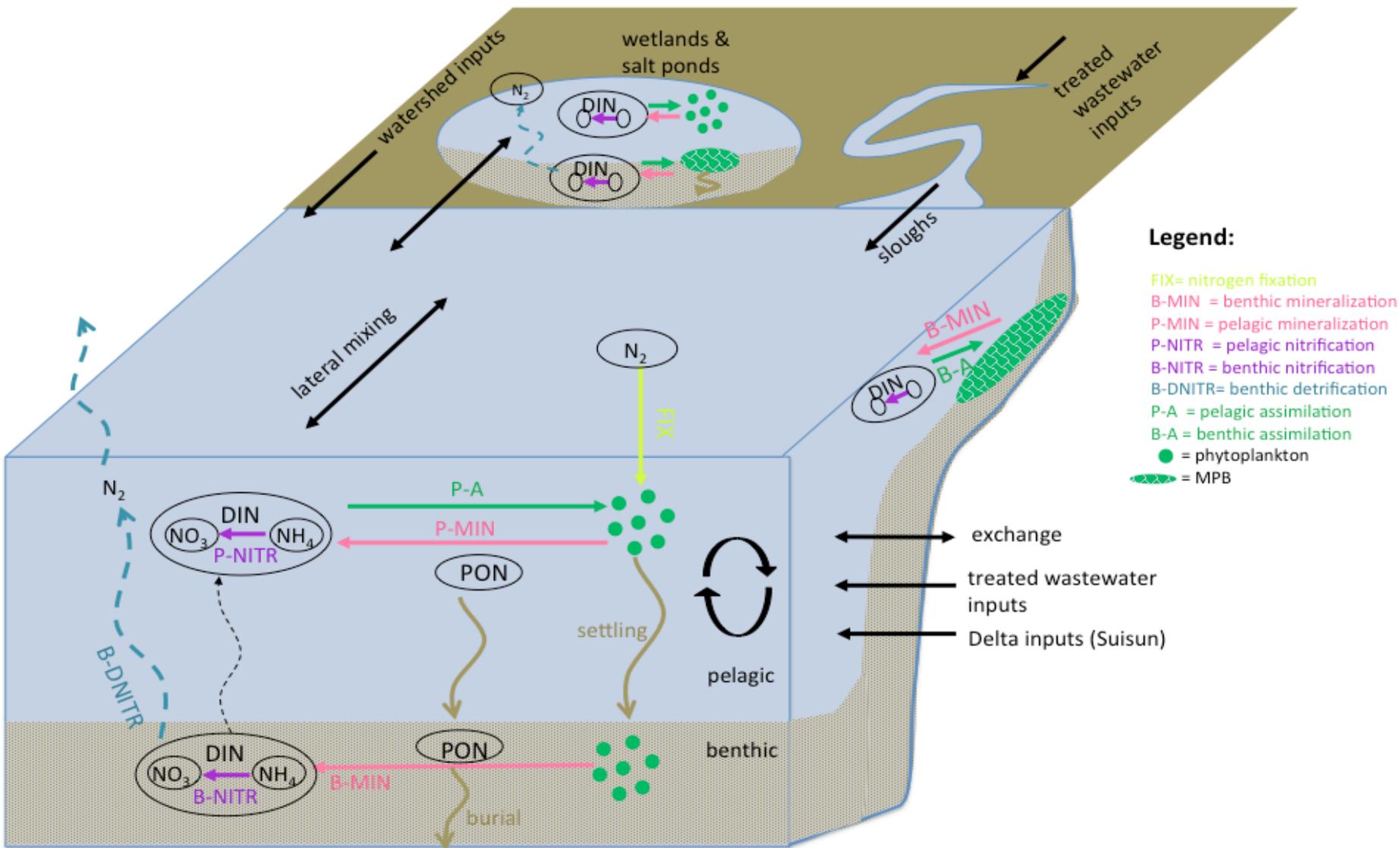


Figure 6.1 N overview conceptual model.

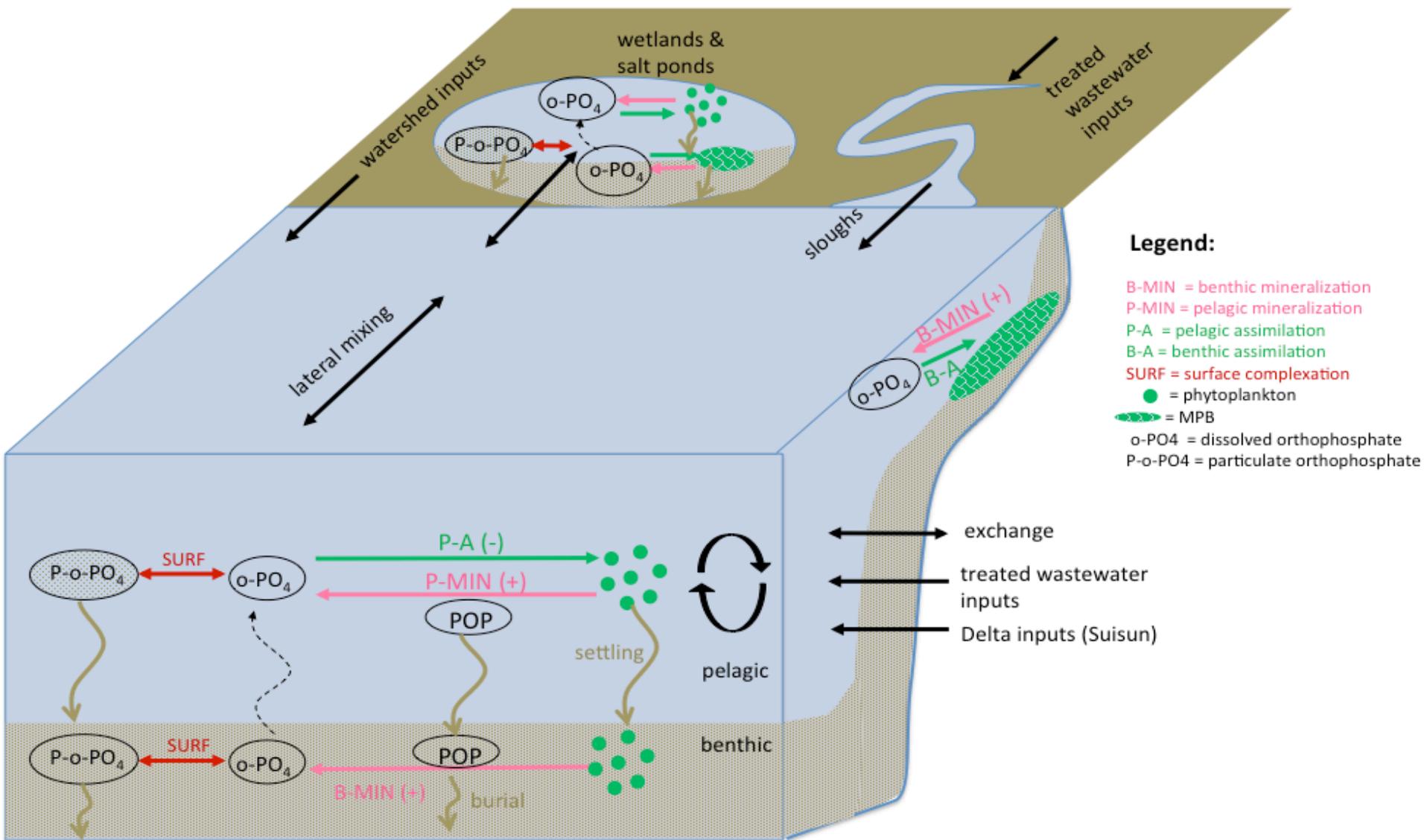


Figure 6.2 P overview conceptual model.

DIN legend



PO4 legend

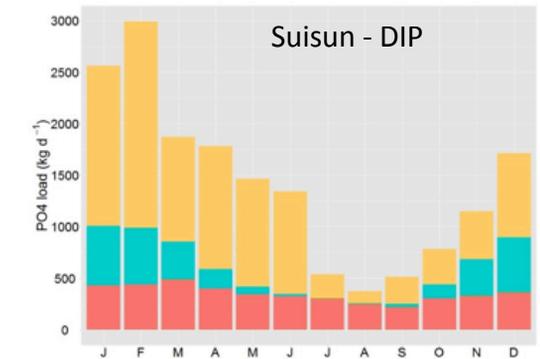
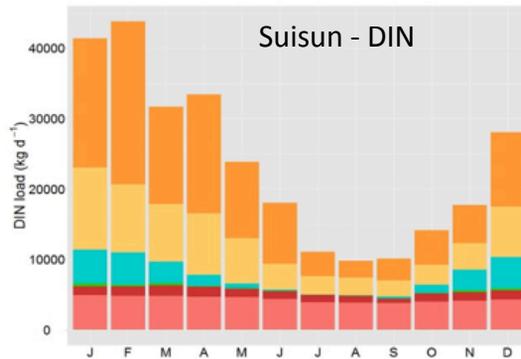
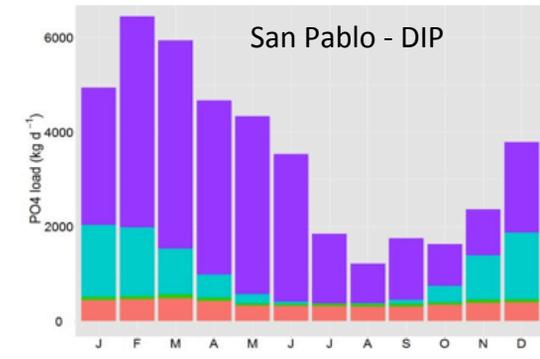
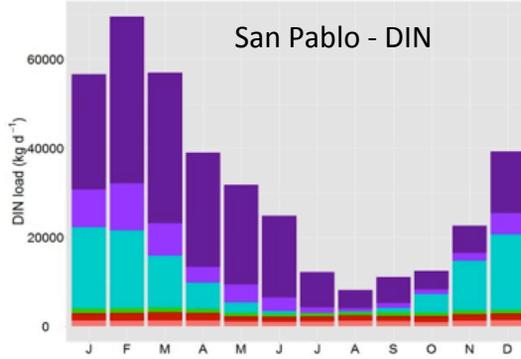
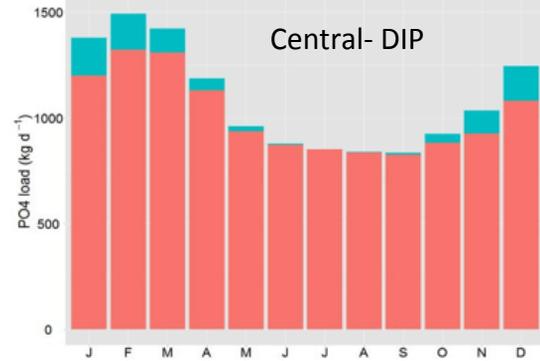
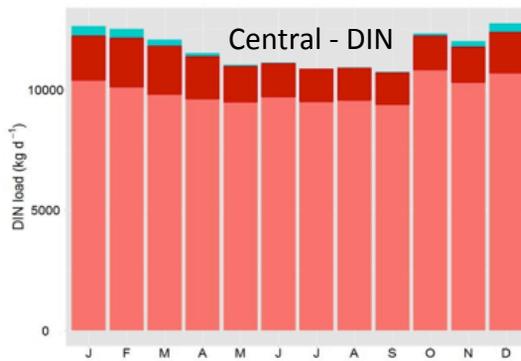
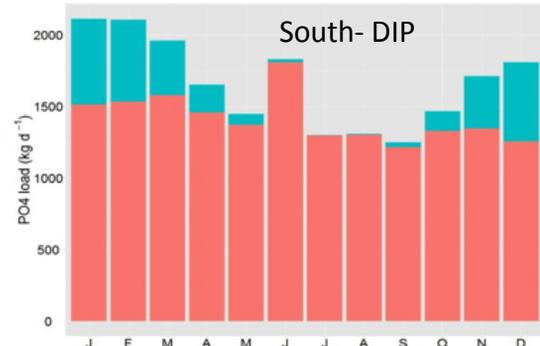
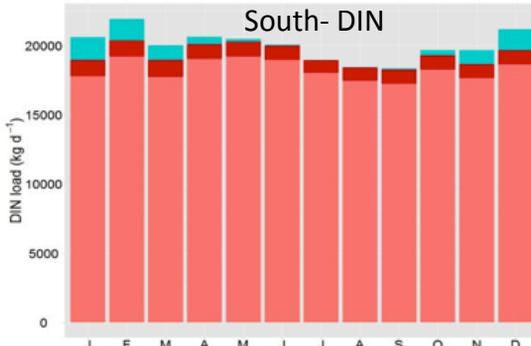
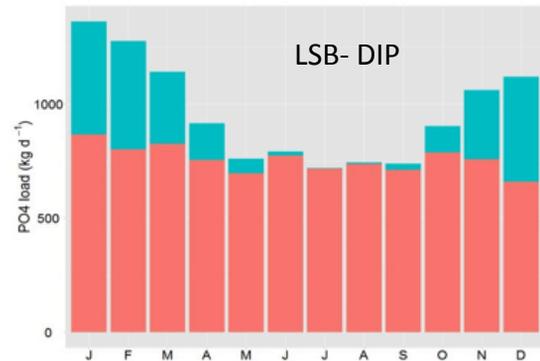
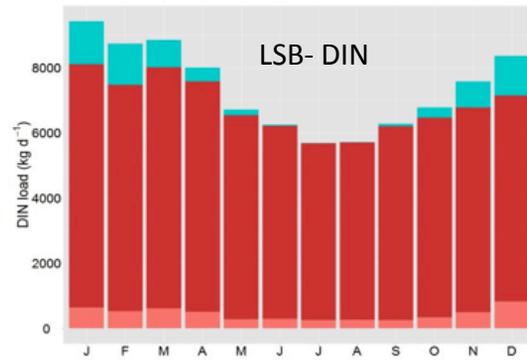


Figure 6.3 N and P loads to SFB subembayments. In the cases of LSB, South Bay, and Central Bay, only direct loads to the subembayments were considered and not exchange between subembayments. Loads to San Pablo Bay include estimates of up-estuary loads from Suisun Bay. See Novick and Senn 2013 for more details

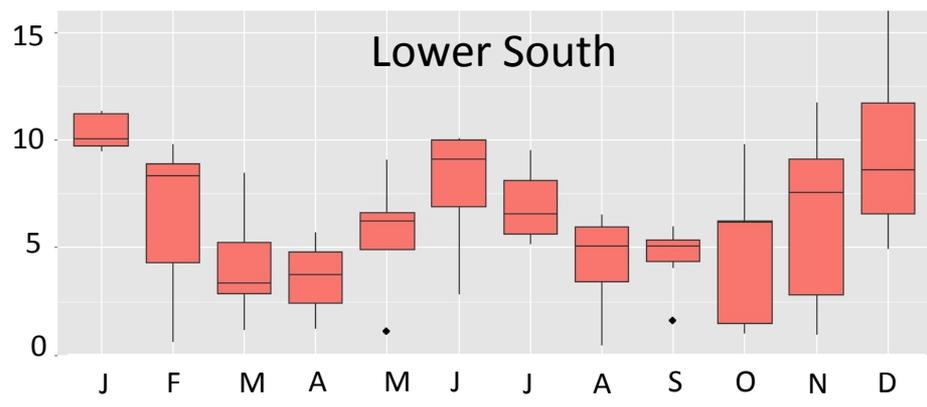
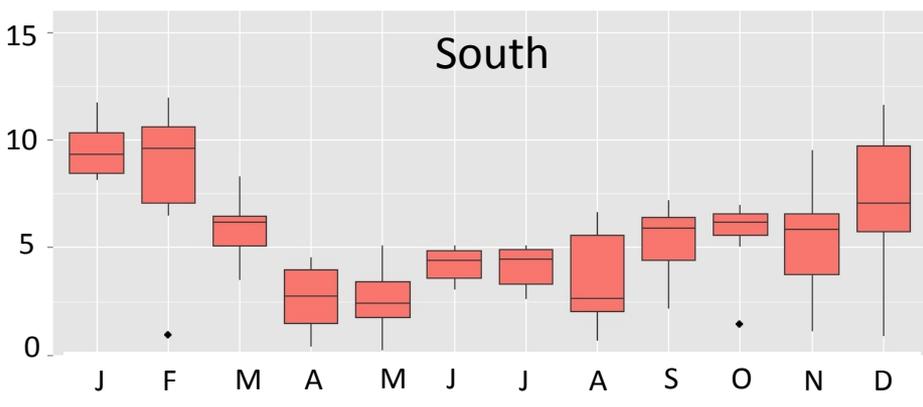
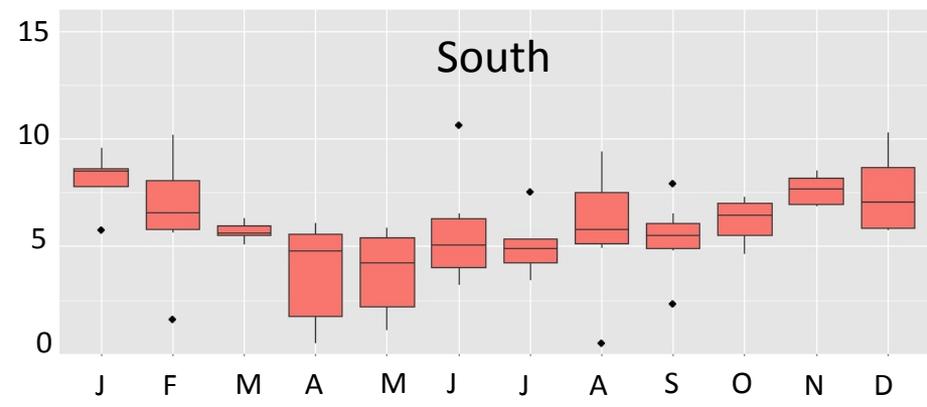
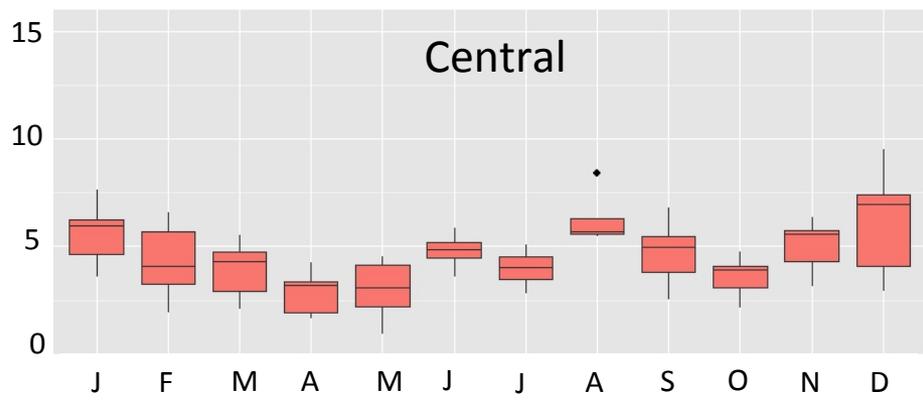
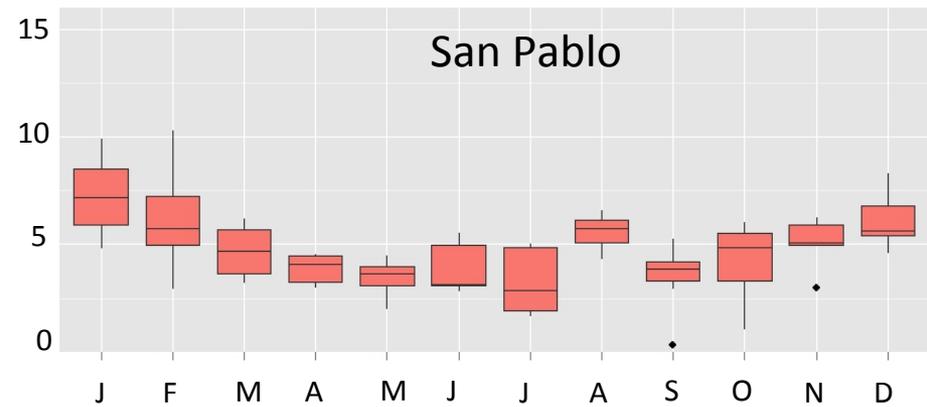
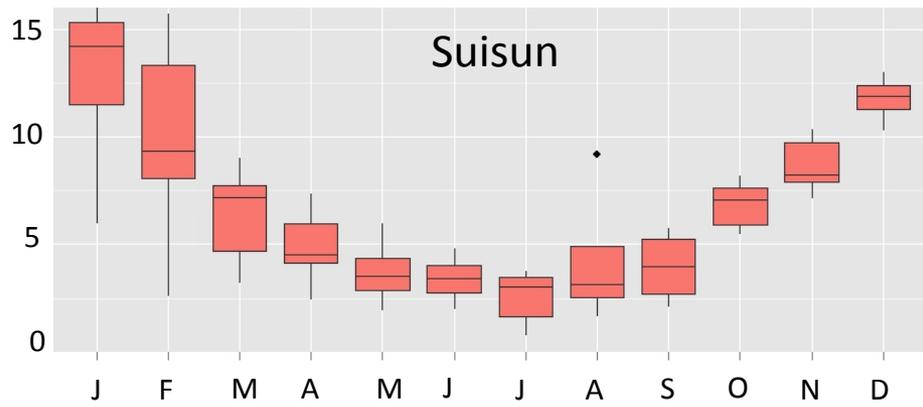


Figure 6.4 Monthly variations in NH₄ (μM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

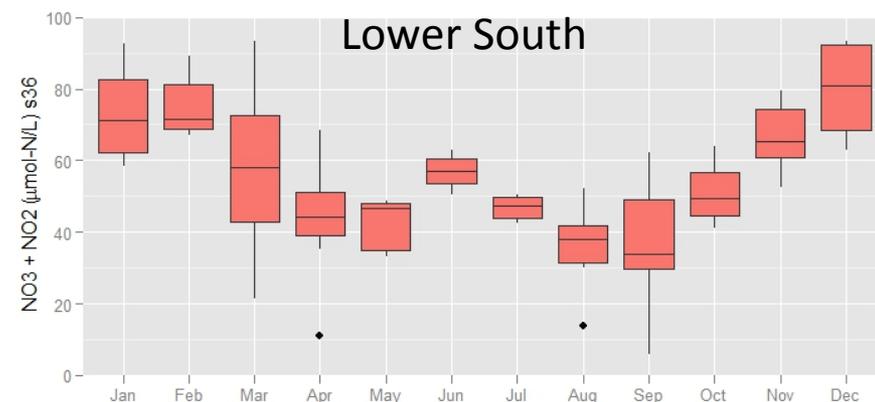
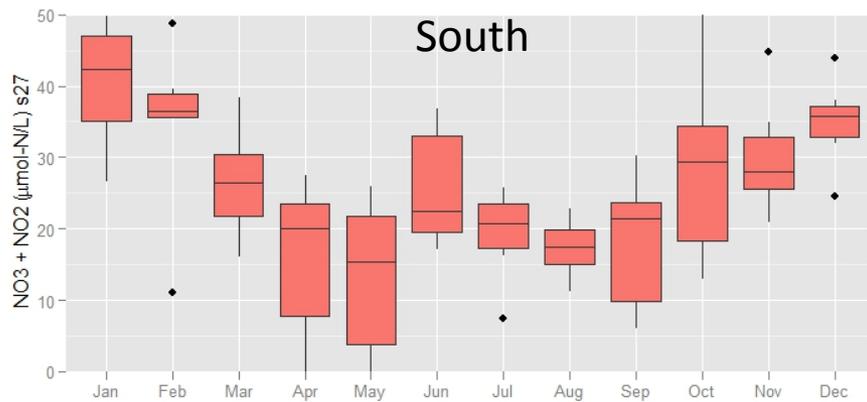
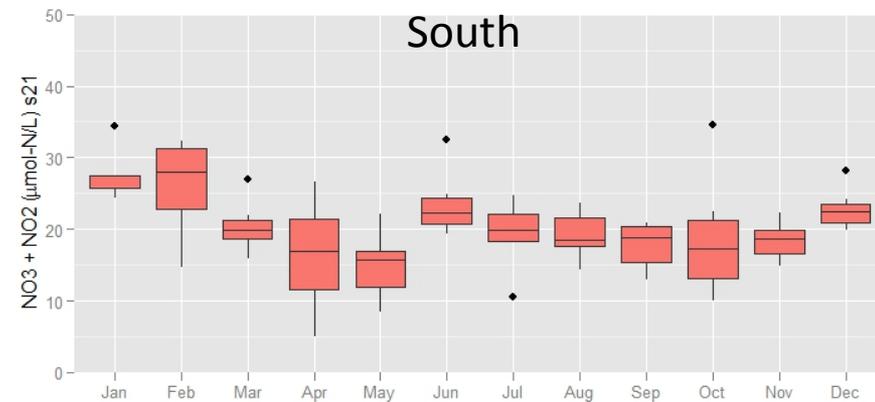
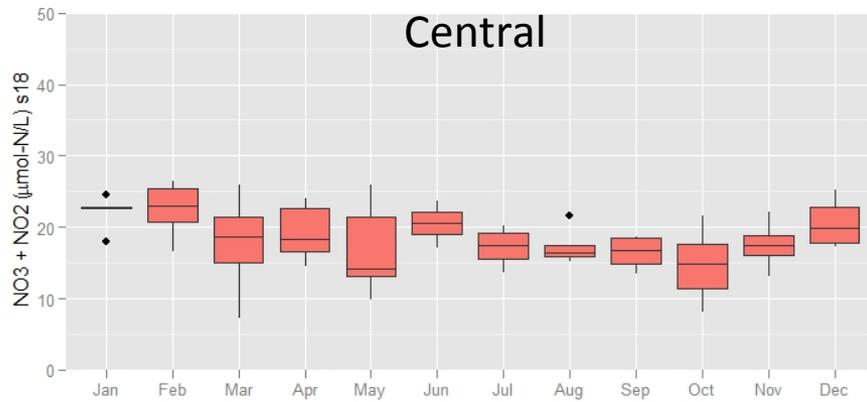
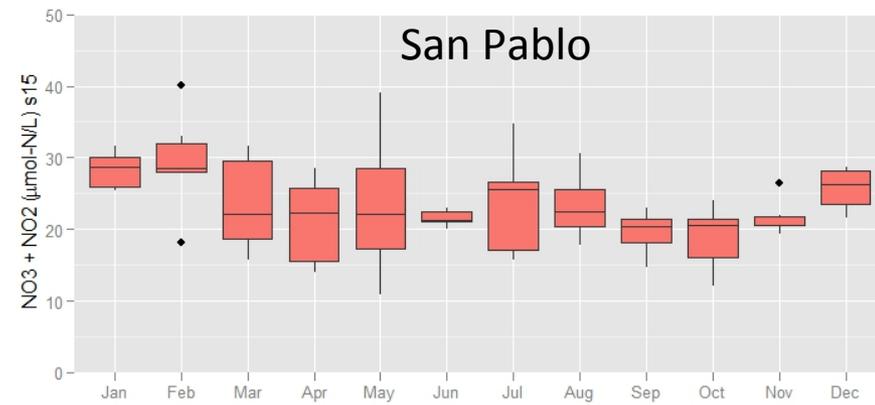
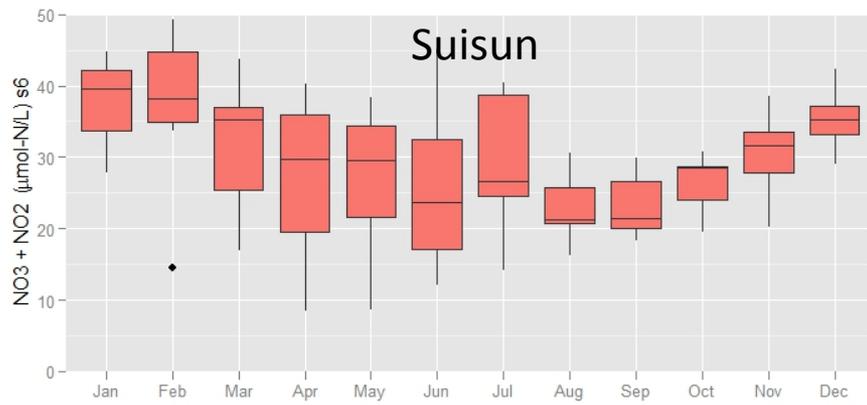


Figure 6.5 Monthly variations in NO₃ (μM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the vertical different scales. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

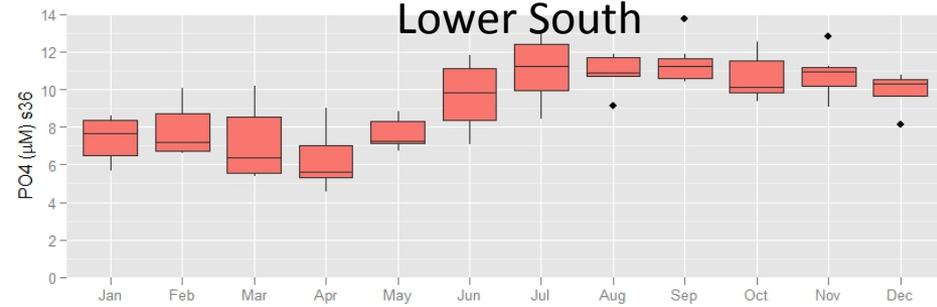
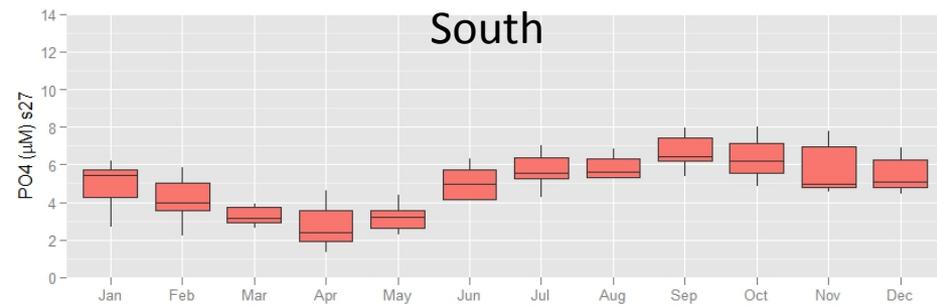
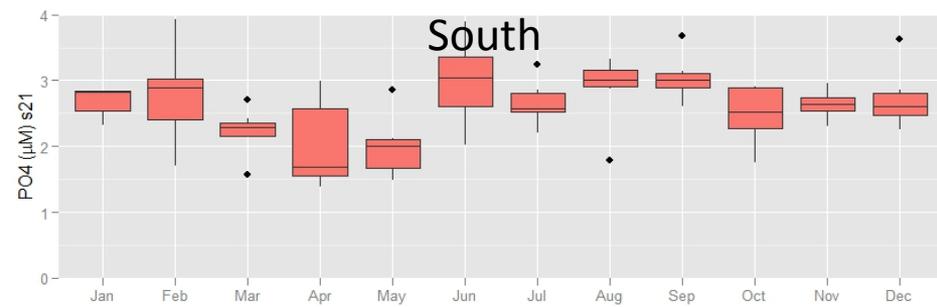
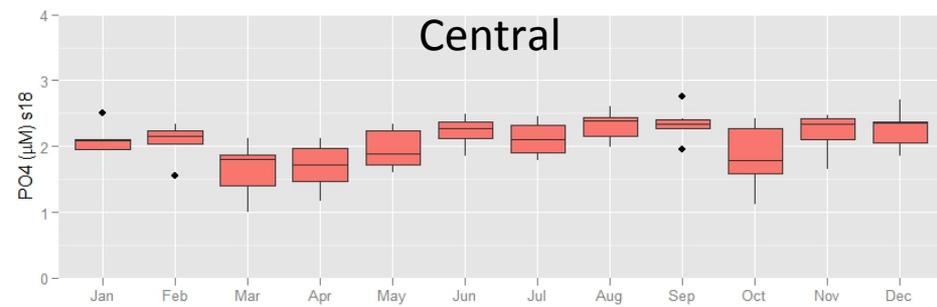
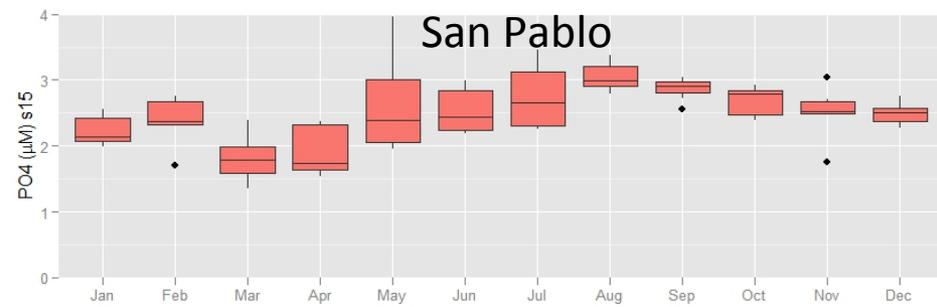
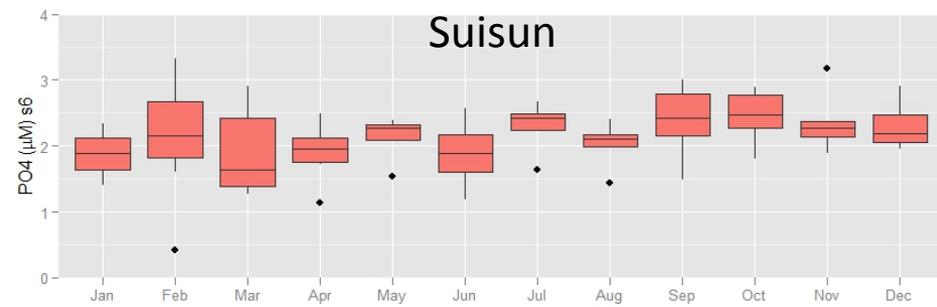


Figure 6.6 Monthly variations in PO4 (μM): 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Note the different vertical scales. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

Phytoplankton biomass

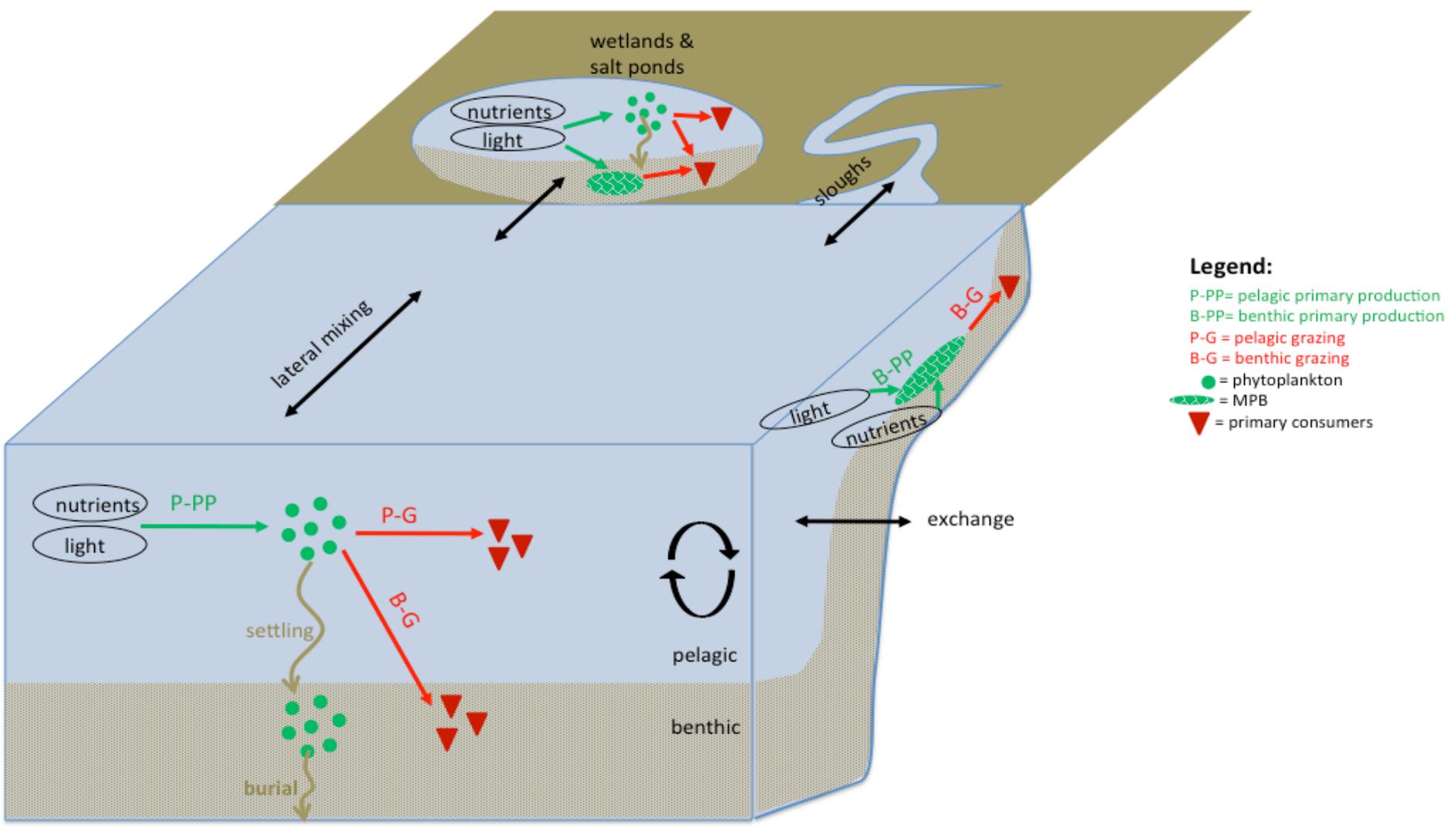
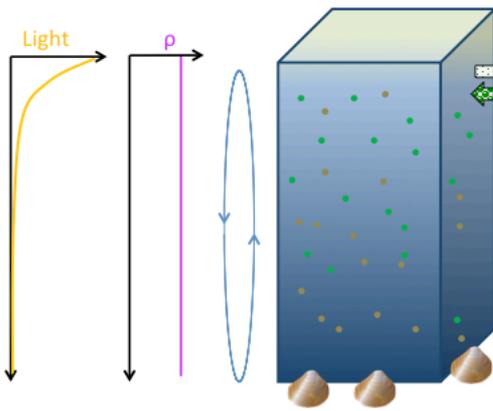


Figure 7.1 Conceptual overview of processes or factors that influence phytoplankton biomass accumulation. The importance of stratification and light are diagramed here, see Figure 7.2

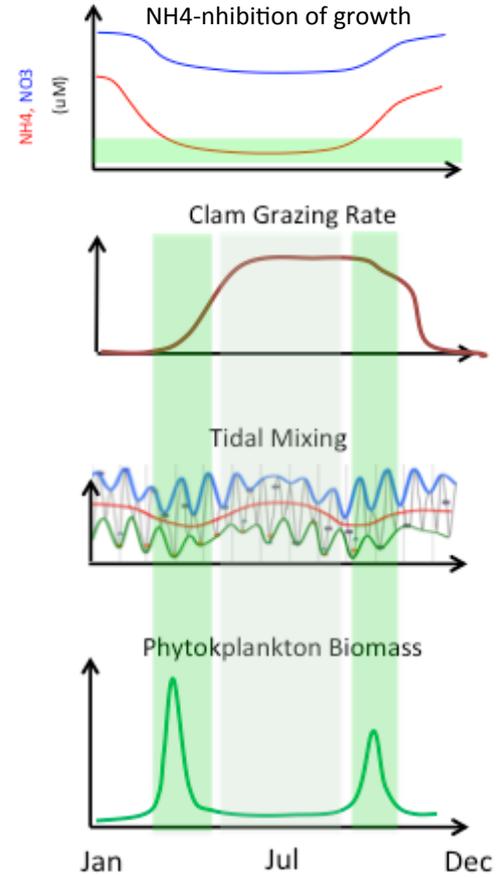
a. No bloom, baseline



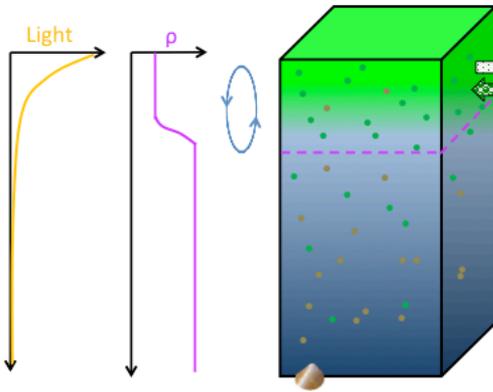
Dominant condition. Occurs in multiple situations:

- 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.

Figure 7.2 Modes of productivity in SFB, and factors influencing timing and magnitude.



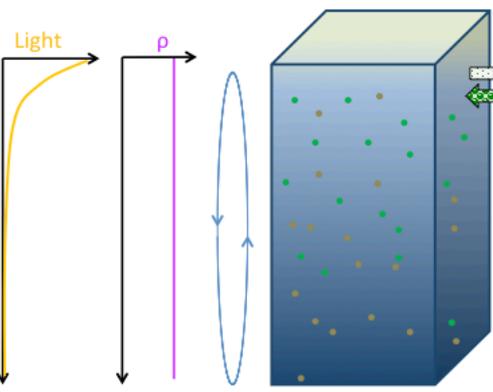
b. Stratification-induced bloom



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)

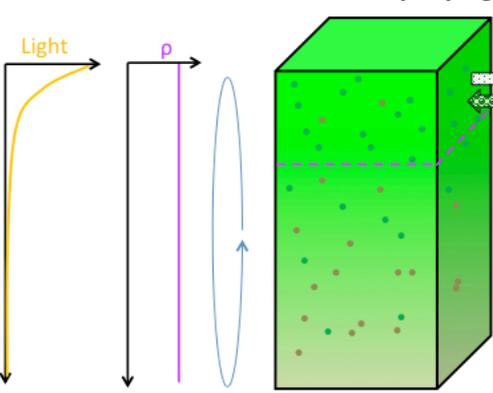
c. Shoal-induced bloom



Requires:

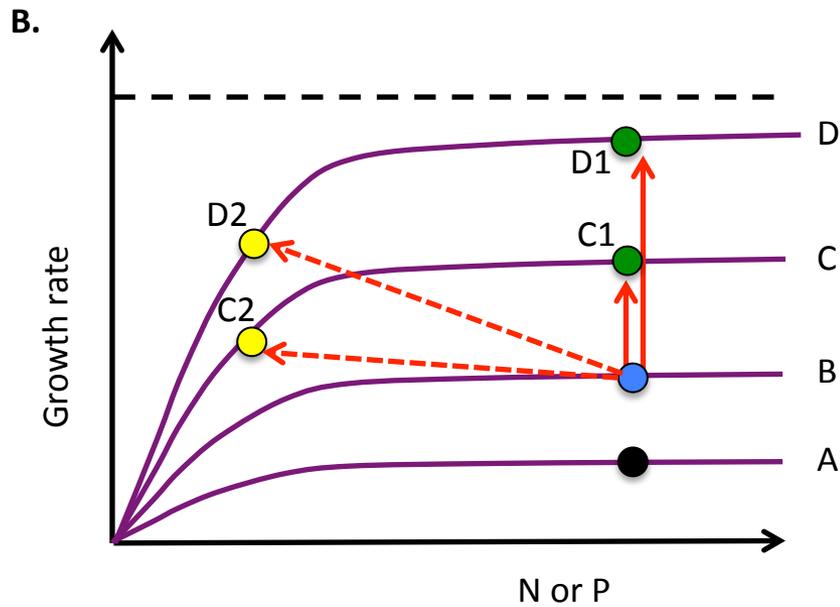
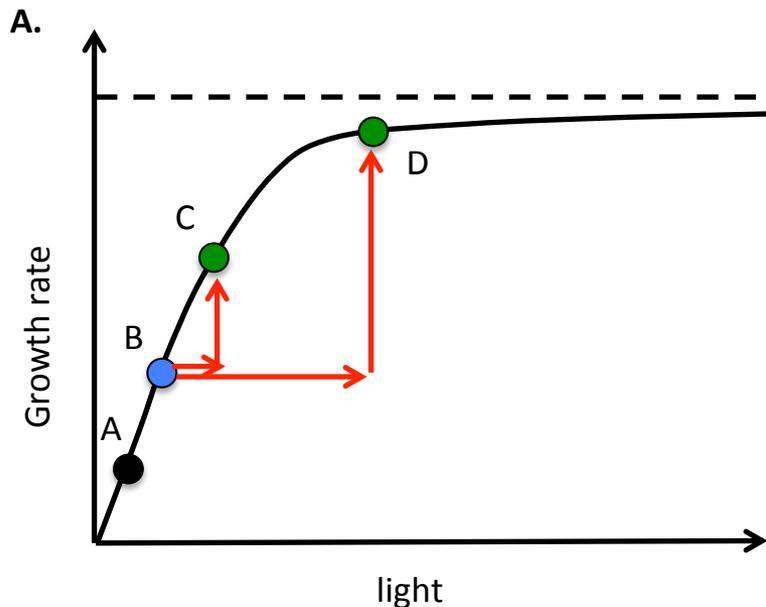
- Moderate to high productivity
- Low clam biomass/grazing

d. Shoal-induced bloom that propagates to channel



- 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 7.3 Phytoplankton Growth Rates: Light limitation vs. nutrient limitation. In general, throughout most of SFB, light limits phytoplankton growth most of the time. **Panel 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 is commonly considered to vary by temperature and by species). Growth rates increase as light levels increase. **Panel B.** The four curves 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.



- Current conditions in the well-mixed deep channel or in shallow environments when SPM is high
- Growth rates for phytoplankton in the surface layer when water column stratifies, or growth rates in shallow environments when SPM concentrations are low. Potential future growth rates if light levels increase and nutrients remain constant

— Growth rate curves for light conditions A-D with varying nutrient levels

→ Change in growth rates in response to increased light, depending on same or decreased nutrient concentrations

● Potential future growth rates if light levels increase and nutrient loads decrease

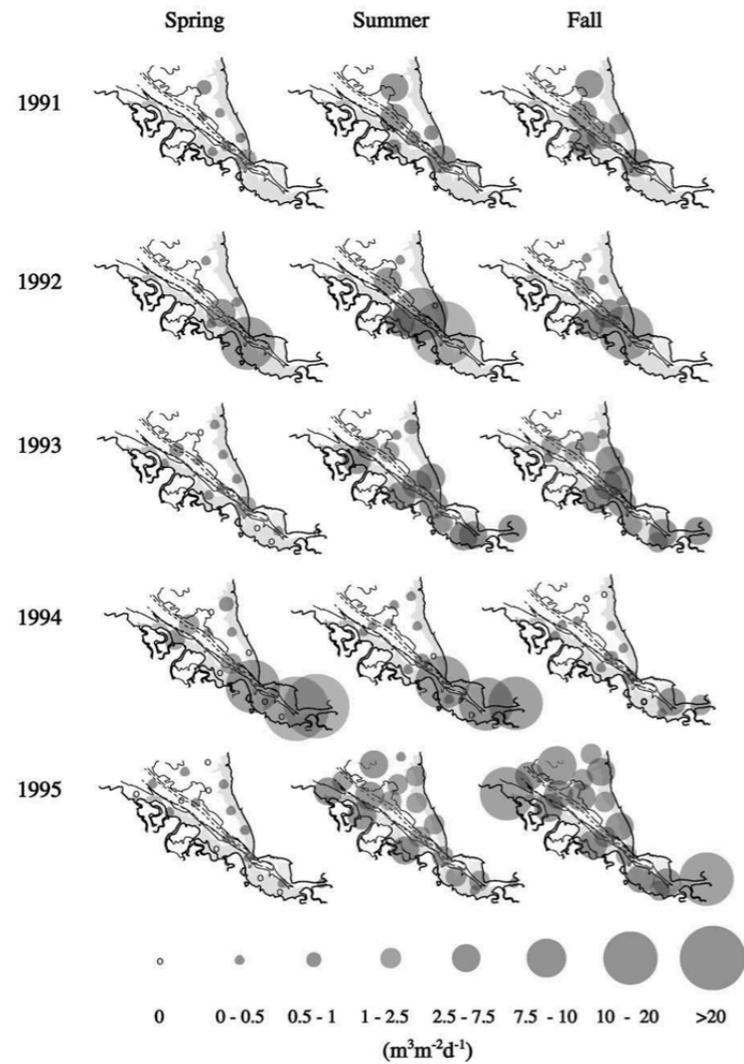
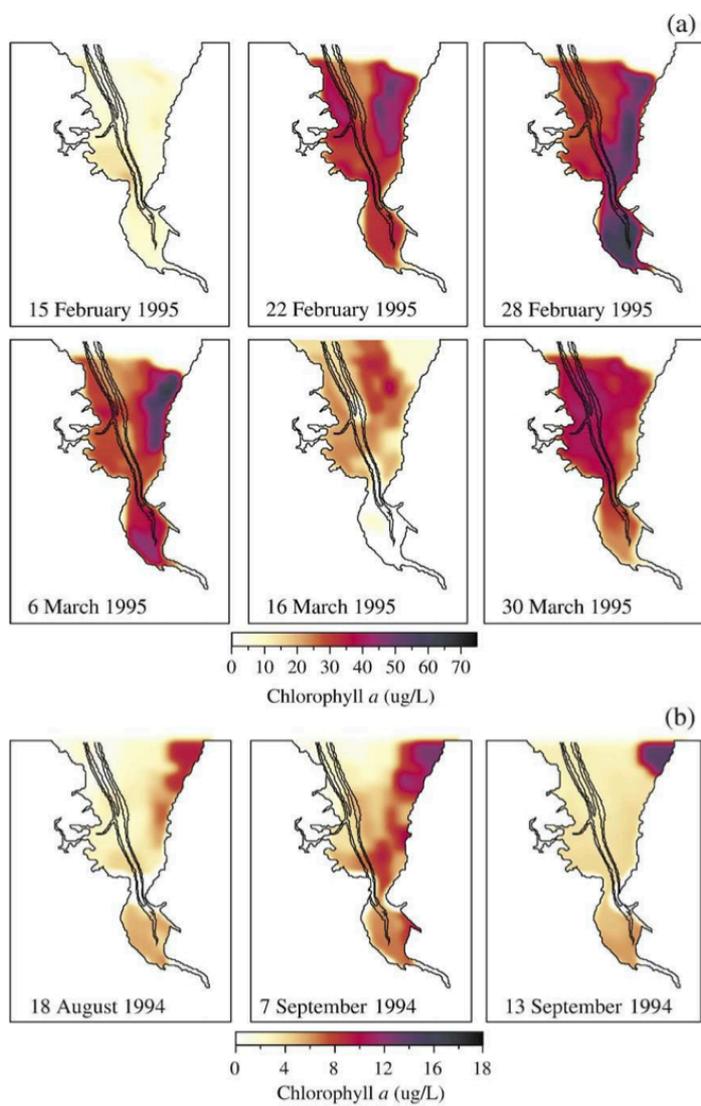


Figure 7.4 A. Phytoplankton biomass South Bay illustrating bloom initiation on shoals and propagating to the channel. B. Spatial, seasonal, and interannual variation in bivalve grazing rates in South Bay and LSB. Source: Thompson et al. 2008

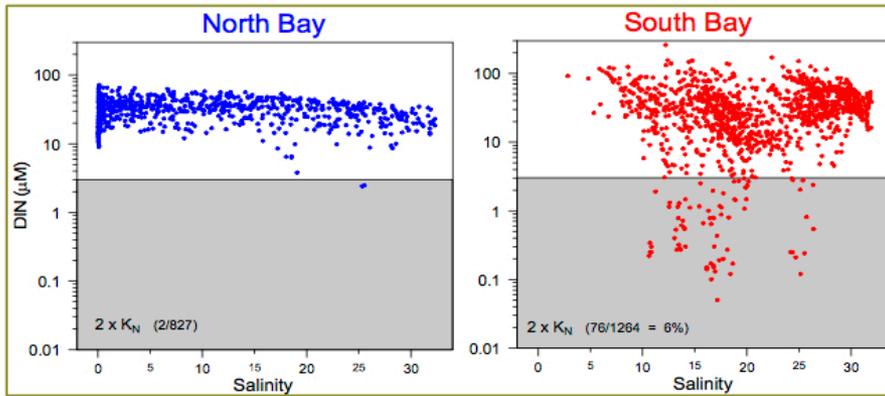


Figure 5.6.5. Near-surface DIN concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential N limitation.

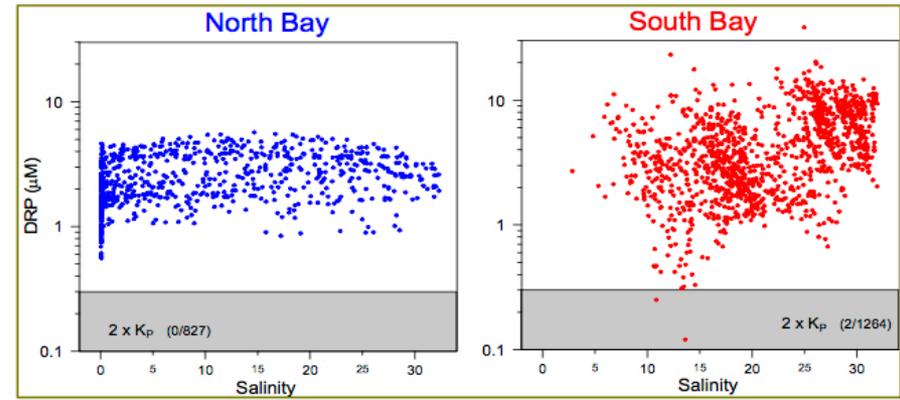


Figure 5.6.6. Near-surface DRP (PO_4^{3-}) concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential P limitation.

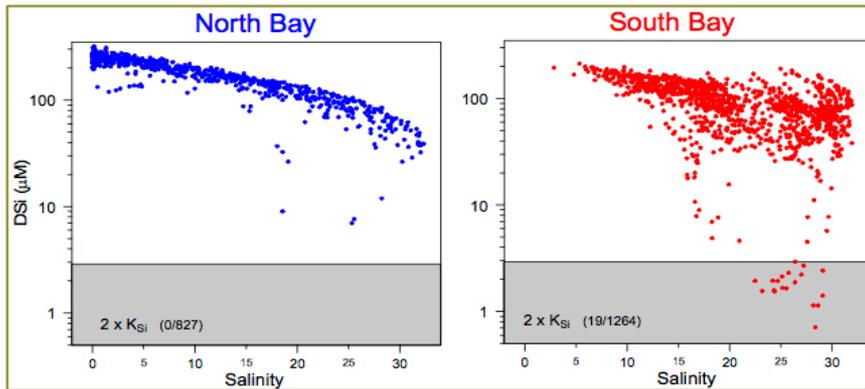


Figure 5.6.7. Near-surface $Si(OH)_4$ (DSi) concentration vs. salinity in North and South Bay. Data shown are all measurements made by USGS from 1988-2000. Gray rectangle indicates potential Si limitation.

Figure 7.5 Nutrient concentrations in SFB compared to thresholds for kinetic limitation of phytoplankton growth. Source: Cloern and Dugdale 2010.

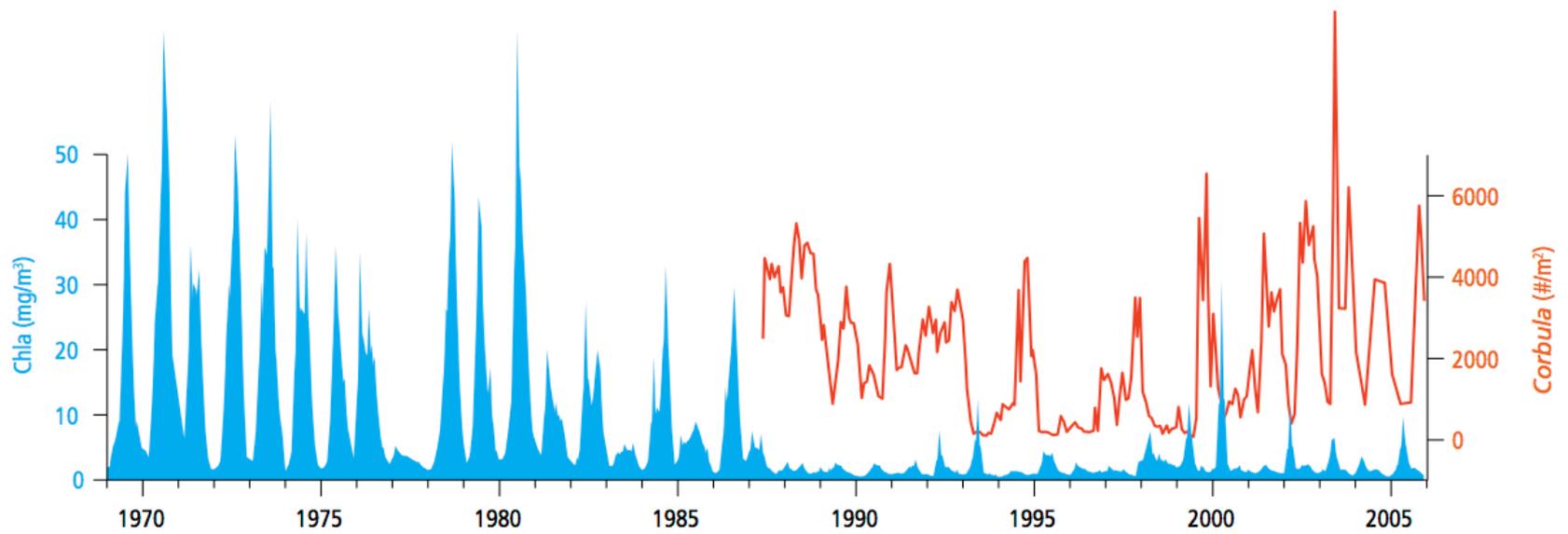


Figure 7.6 Chl-a biomass and *Corbula* biomass in Suisun Bay. Note the temporal coincidence of *Corbula* biomass minima and phytoplankton biomass maxima. Plot from Werme et al 2011. Data from IEP/DWR.

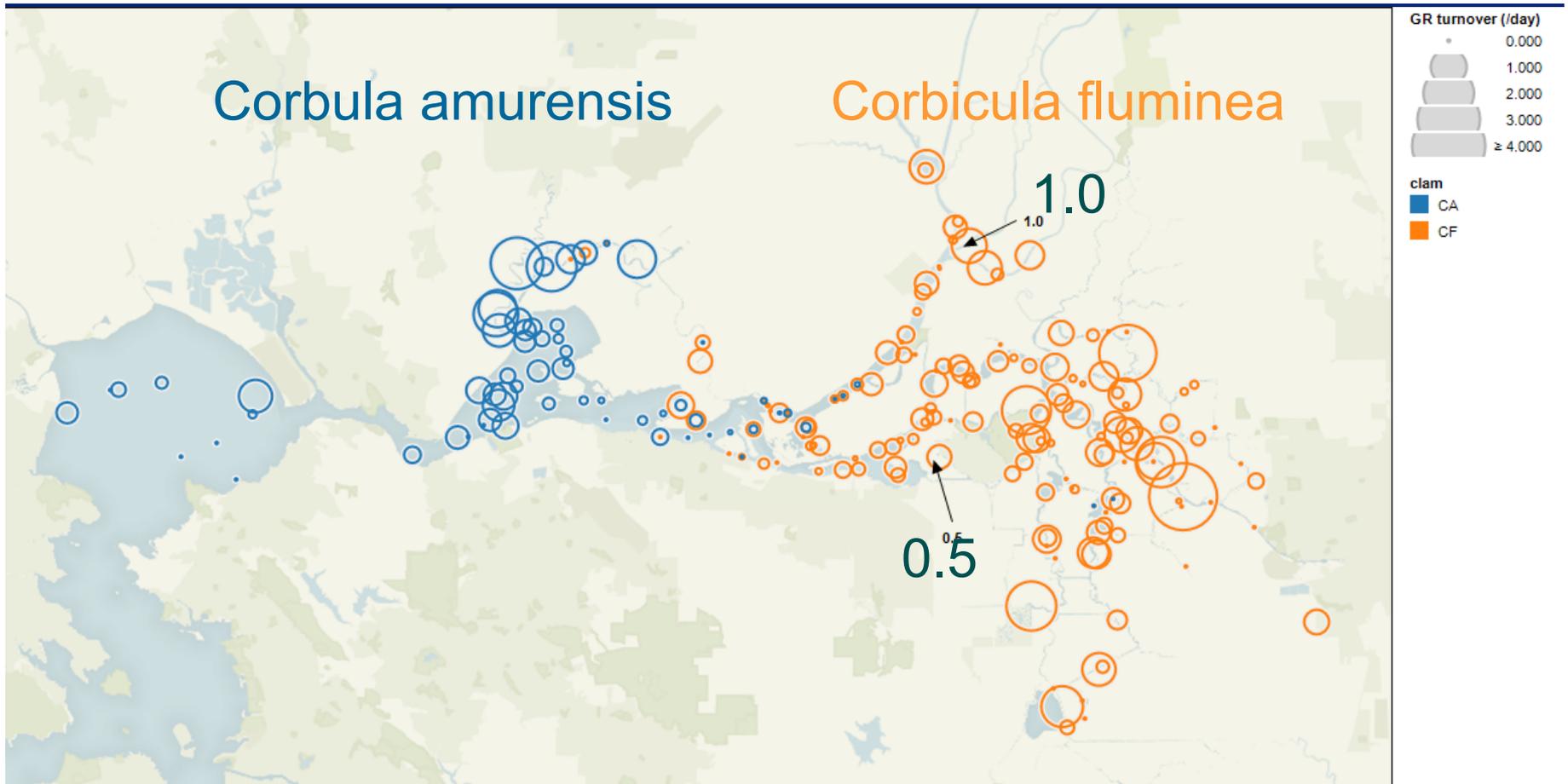


Figure 7.7 Grazing water column turnover rates (units of d^{-1}) for *Corbula* in Suisun *Corbicula fluminea* in the Delta. Source: Kimmerer et al. 2011

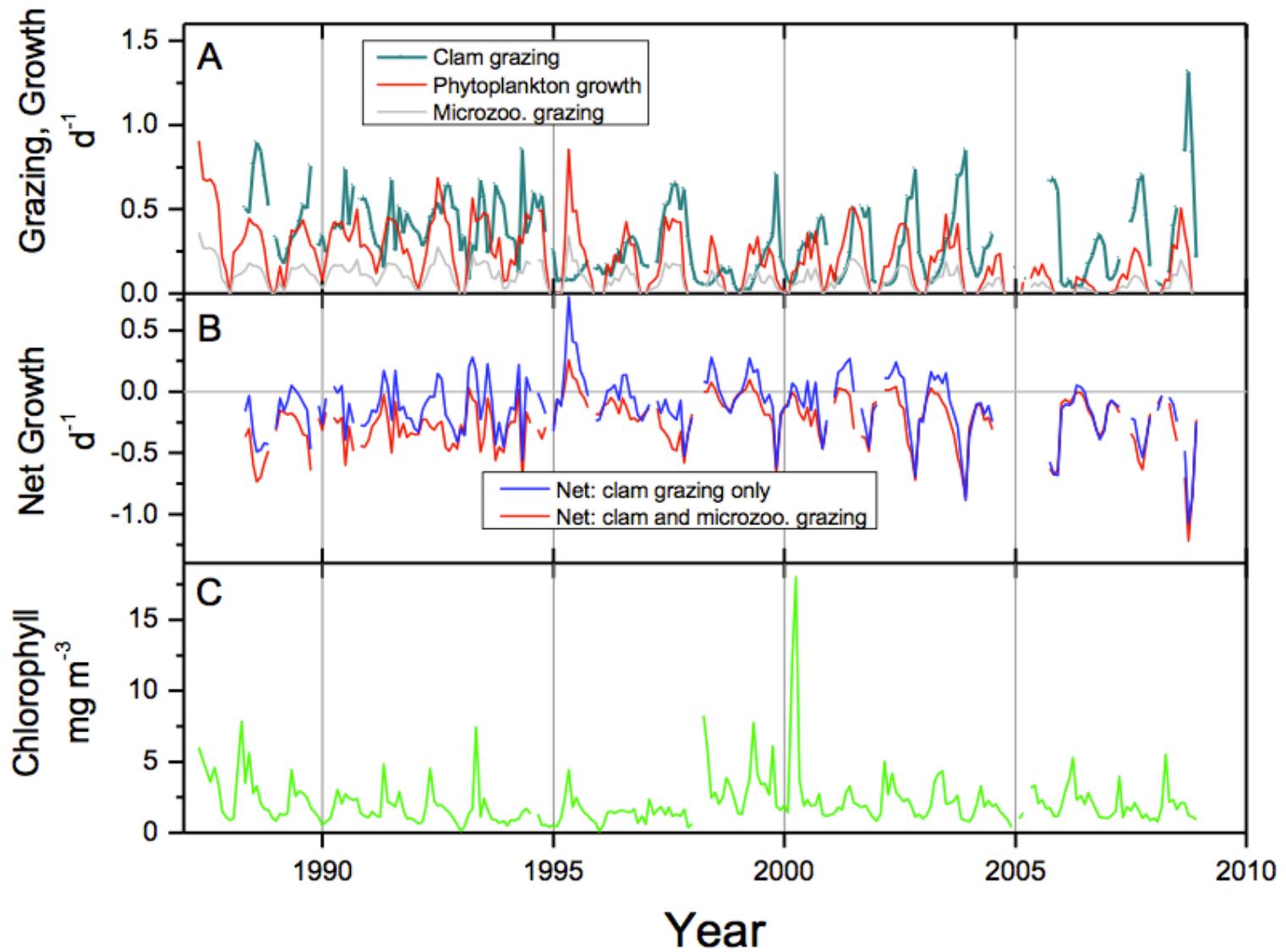


Figure 7.8 Calculated growth and grazing rates in the Low Salinity Zone (essentially Suisun Bay)

Figure 7.9 Phytoplankton biomass south of the Bay Bridge. Source: Cloern et al., 2007

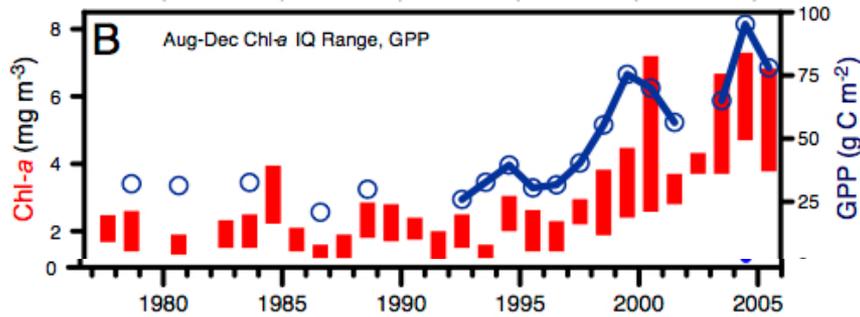


Figure 7.10 Bivalve biomass, benthivorous predators, upwelling index, and sea surface temperature time series. Source: Cloern et al. 2007.

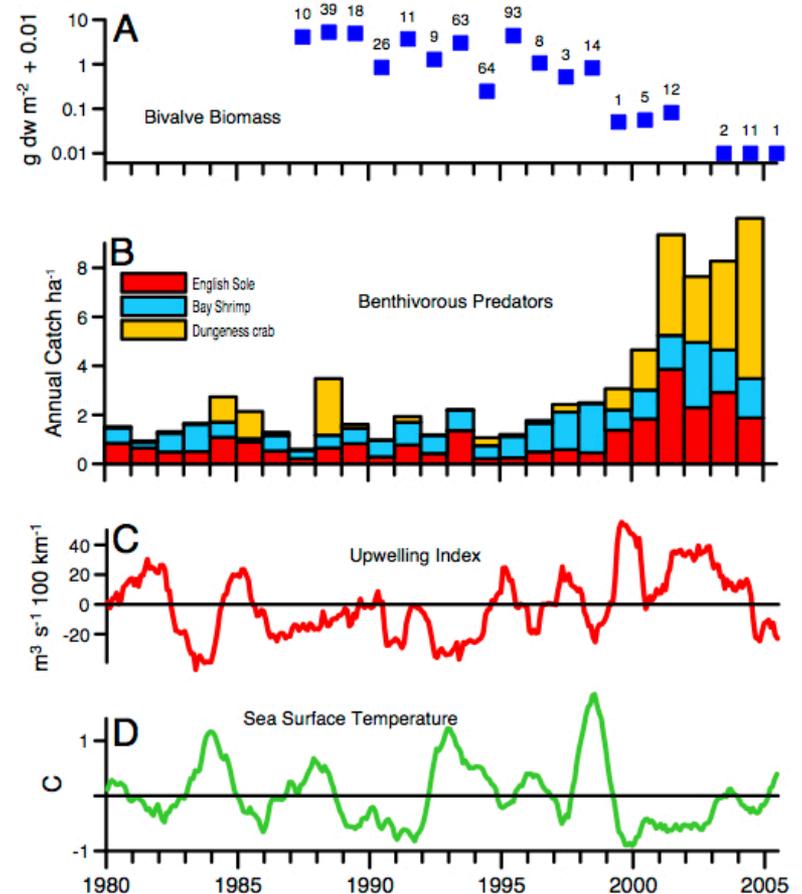


Fig. 3. Indices of biological community change within SFB and physical changes in the adjacent California Current. (A) Annual median biomass of filter-feeding bivalves across shallow habitats in South SFB; numbers above squares indicate sample number per year. (B) Mean annual catch ha^{-1} , normalized 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.

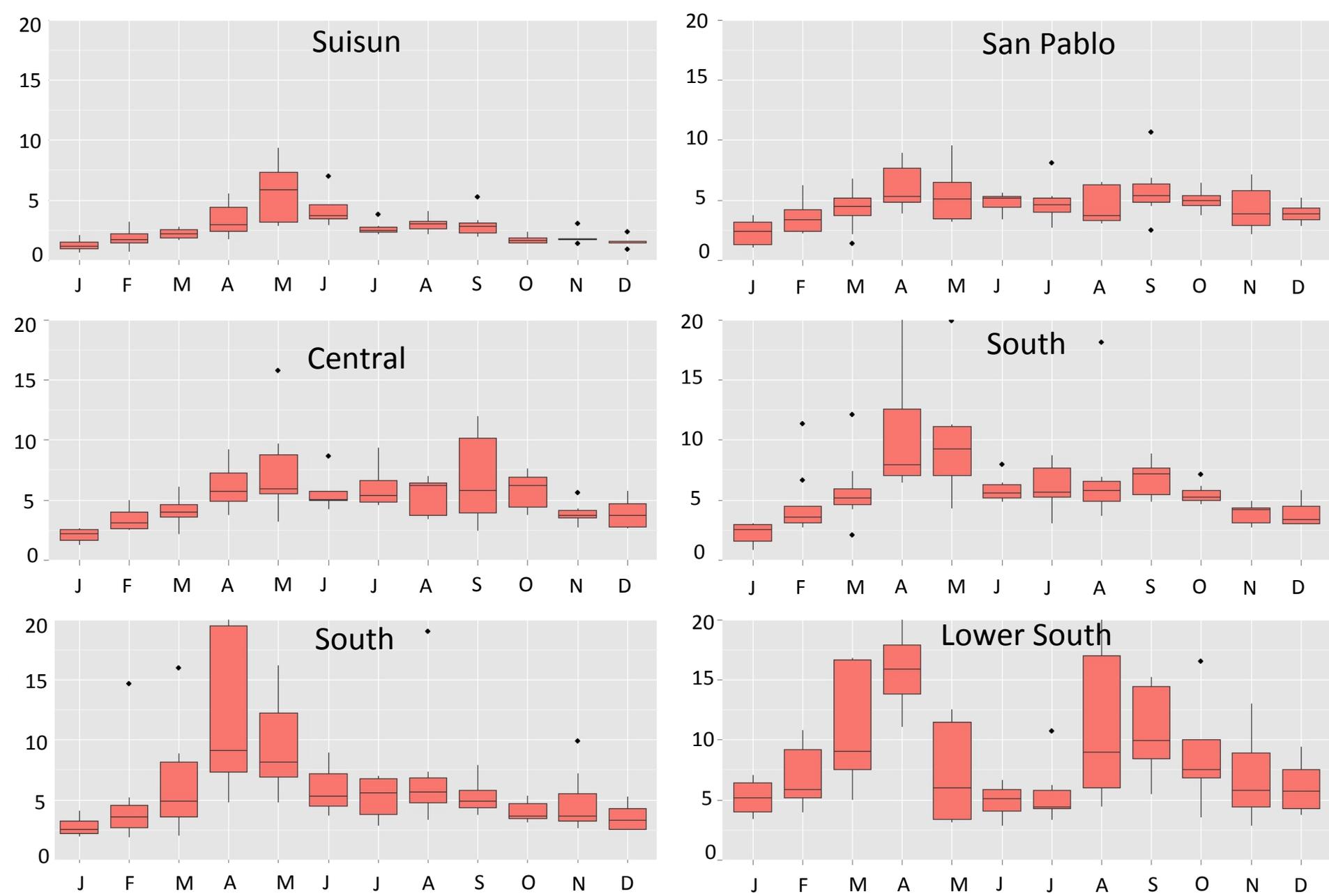


Figure 7.11 Monthly variations in chl-a ($\mu\text{g L}^{-1}$) 2006-2011. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

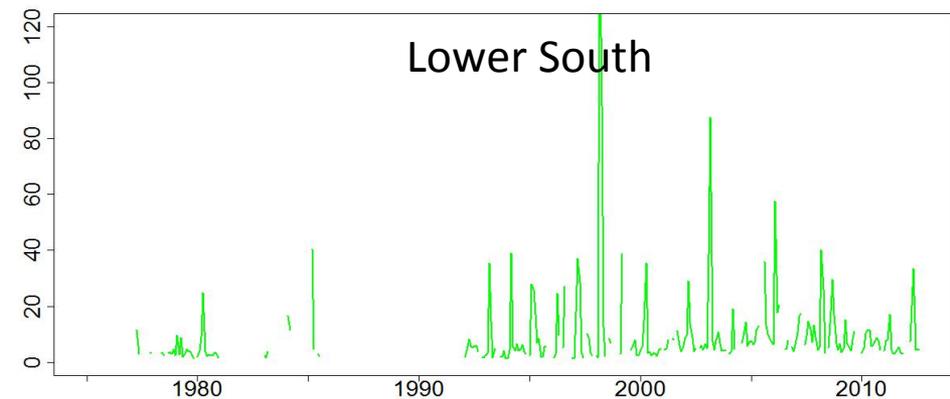
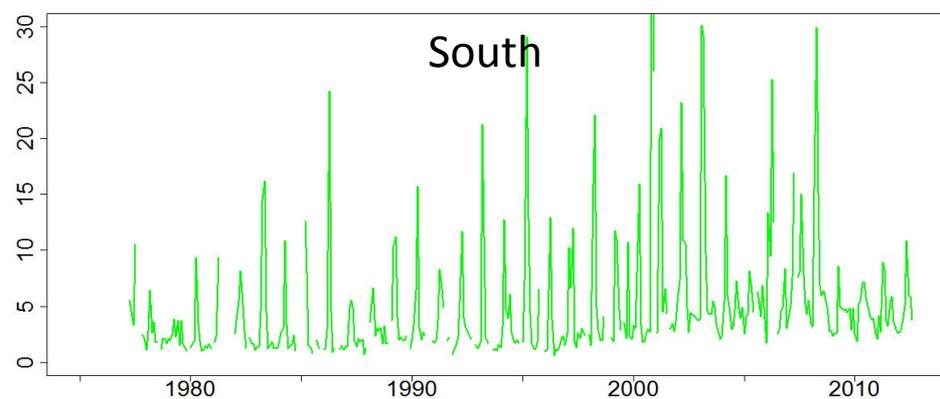
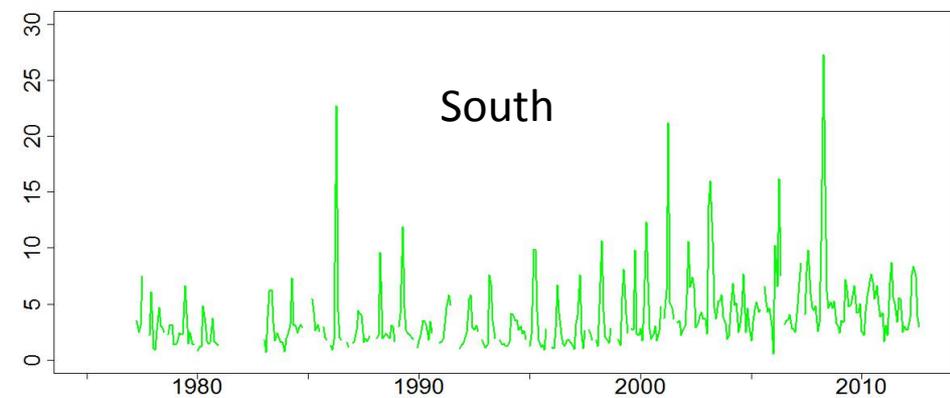
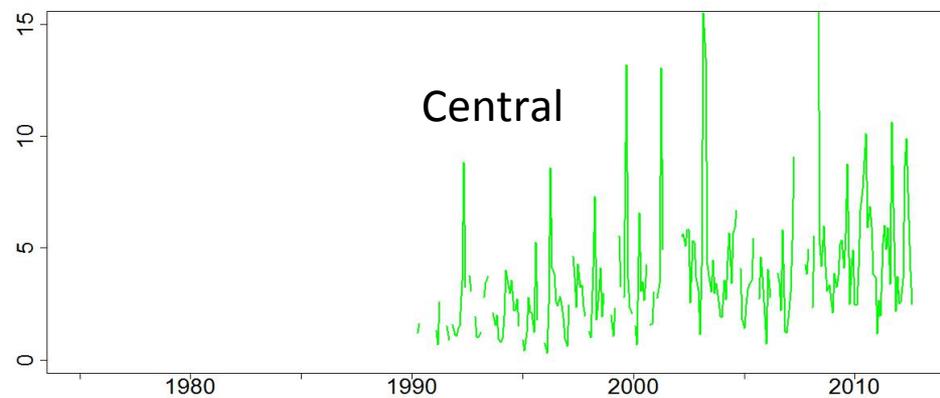
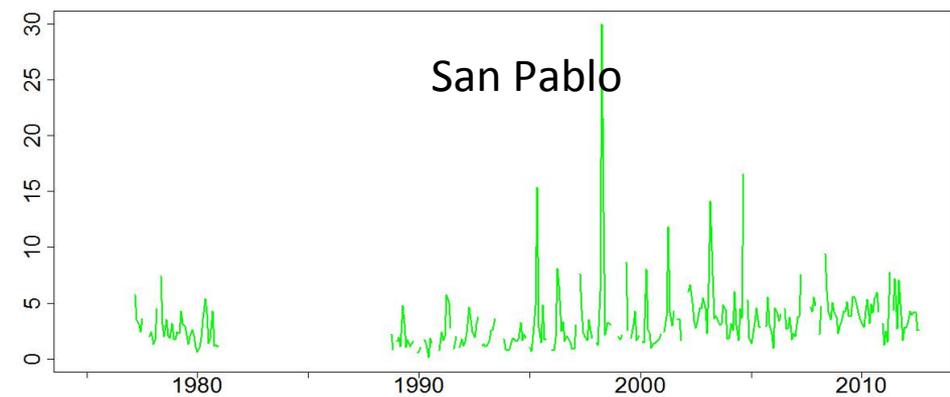
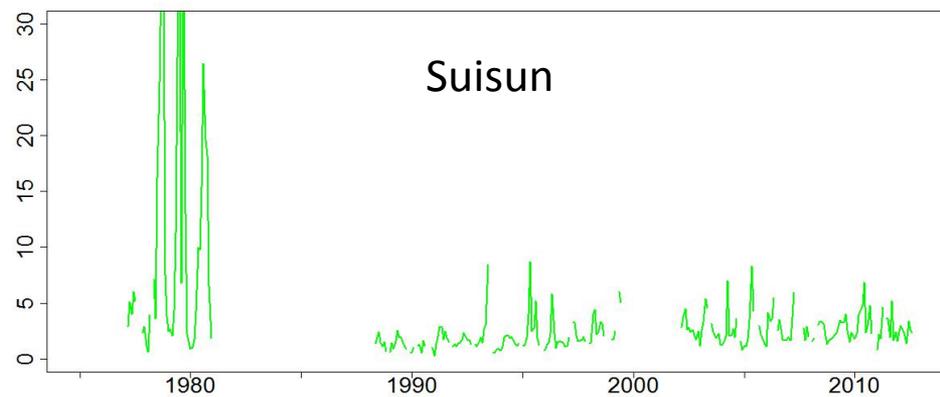
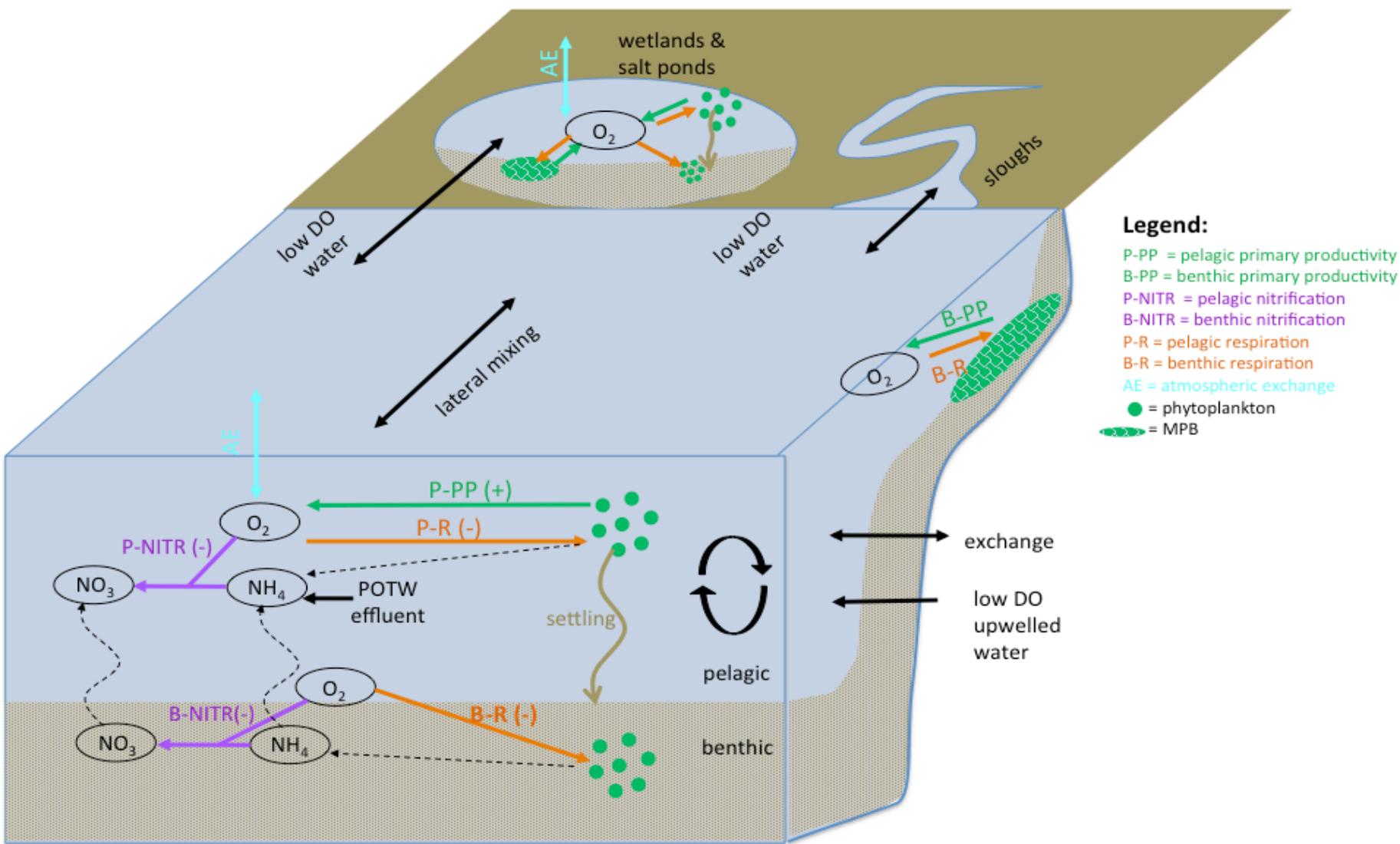


Figure 7.12 Phytoplankton biomass (mg chl-a m^{-3}). Note different y-axes. Data from USGS stations s6 (Suisun), s15 (San Pablo), s18 (Central), s21 (northern South Bay), s27 (southern South Bay) and s36 (Lower South) were used. Data source: <http://sfbay.wr.usgs.gov/access/wqdata/>

Dissolved Oxygen



Legend:

- P-PP = pelagic primary productivity
- B-PP = benthic primary productivity
- P-NITR = pelagic nitrification
- B-NITR = benthic nitrification
- P-R = pelagic respiration
- B-R = benthic respiration
- AE = atmospheric exchange
- = phytoplankton
- = MPB

Figure 8.1 DO overview CM diagram. Processes in red are further defined below the diagram, and their rates are dependent upon the properties in brackets.

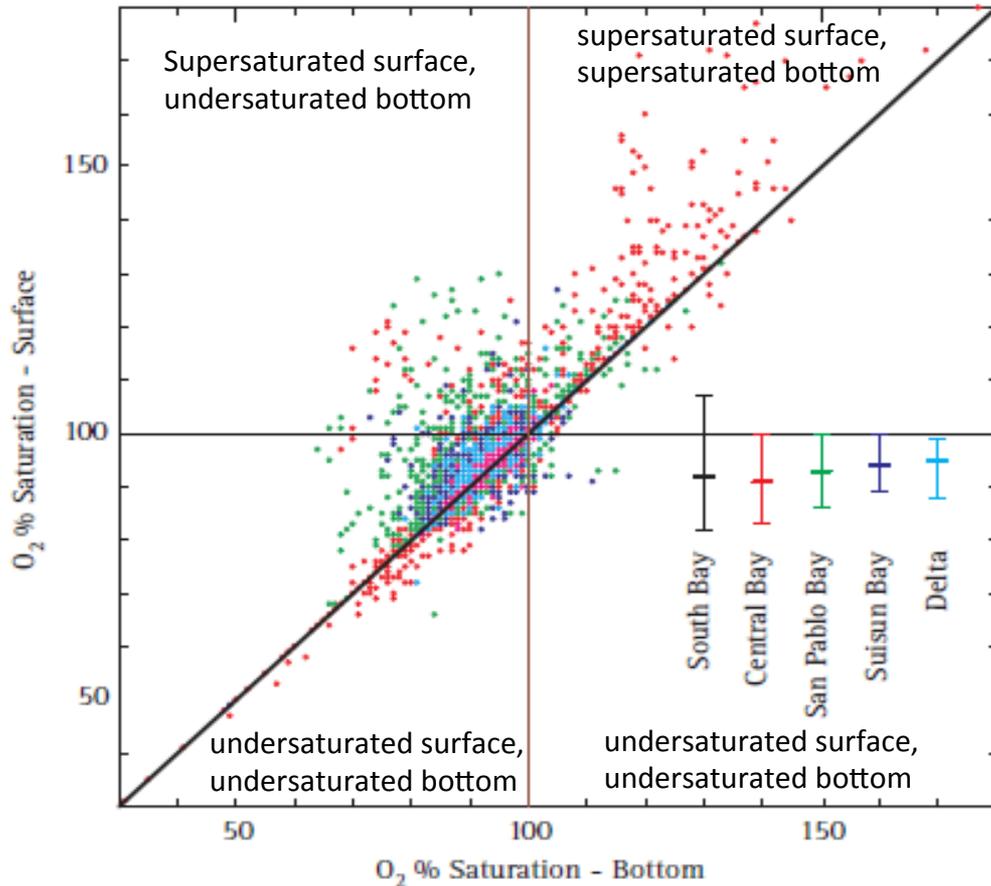


Figure 8.2 DO in deep subtidal areas of SFB.

Source: Kimmerer 2004

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.

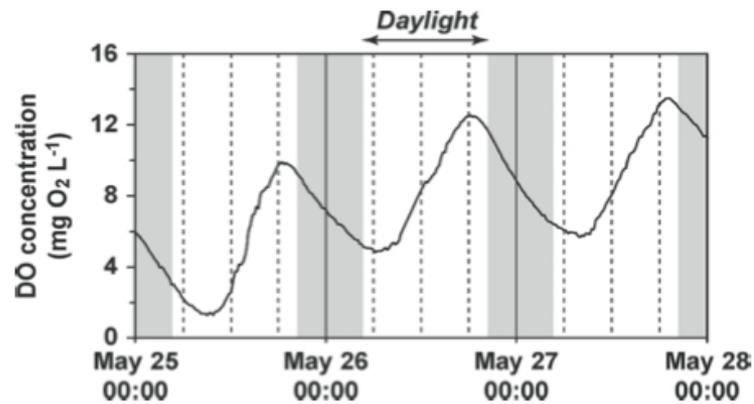


Figure 2. Diel cycles of DO concentration in Pond A18 from May 25 to May 28, 2006.

Figure 8.3 Continuous dissolved oxygen in a LSB salt pond. Source: Thebault et al. 2008

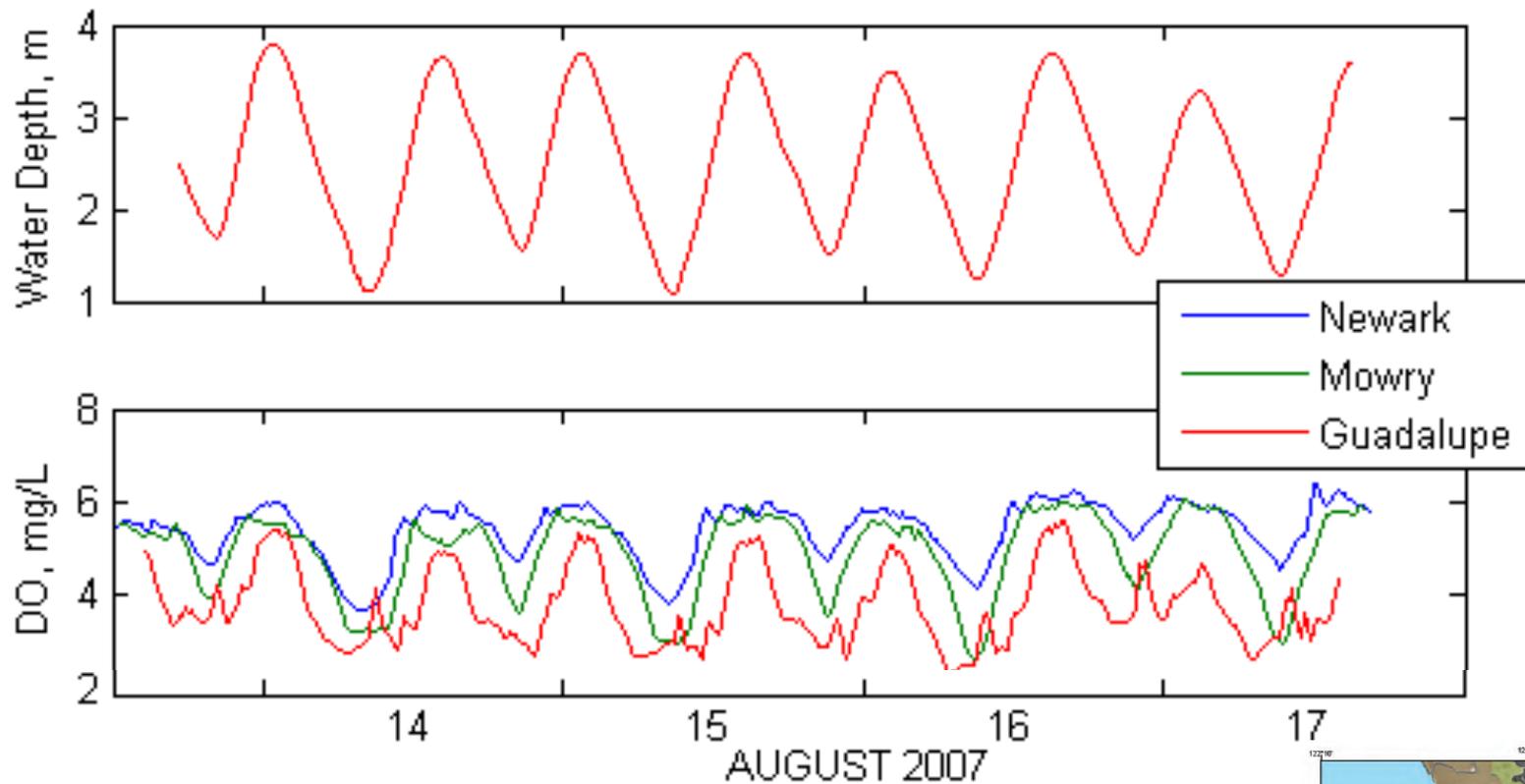
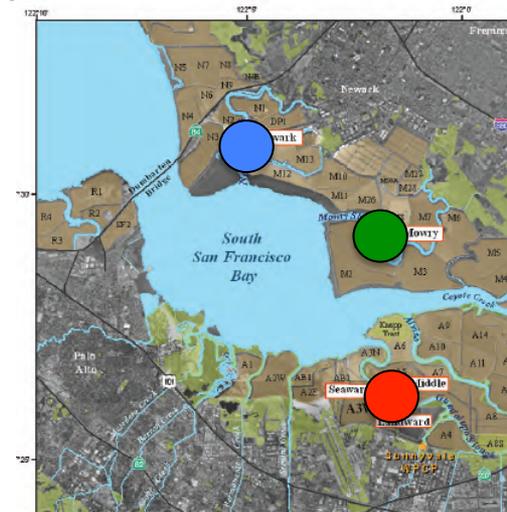


Figure 8.4 Dissolved Oxygen in three slough habitats in Lower South Bay measured using continuous monitoring sensors. Top panel shows water depth. Dissolved oxygen concentrations increase during the flood tide due to water with higher DO from LSB being tidally advected into sloughs. DO concentrations gradually decrease over the outgoing tide interval, likely the result of sediment oxygen demand within the sloughs. Colors of lines correspond to location denoted by circle colors in map. Source: Schellenbarger et al., 2008



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	

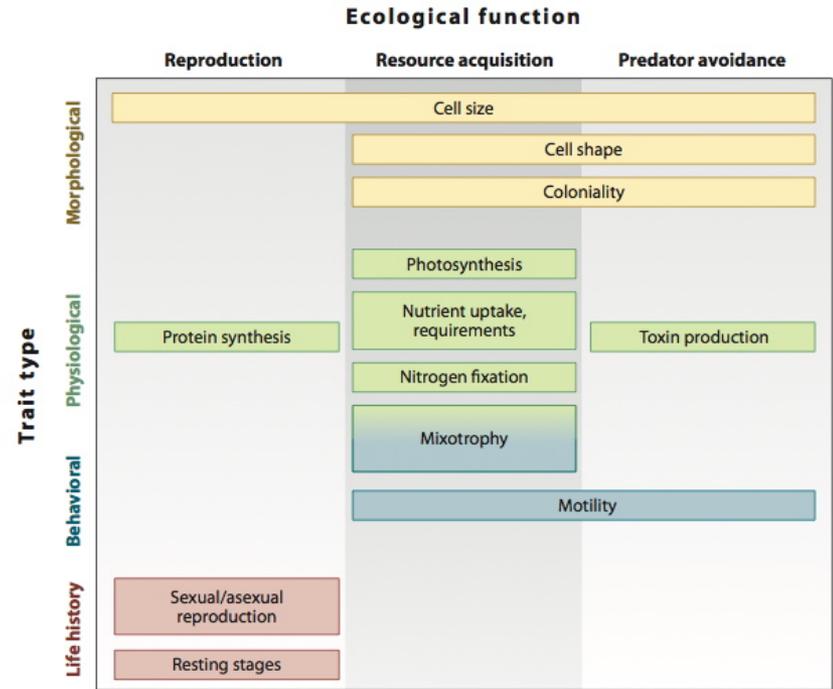


Figure 1

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)

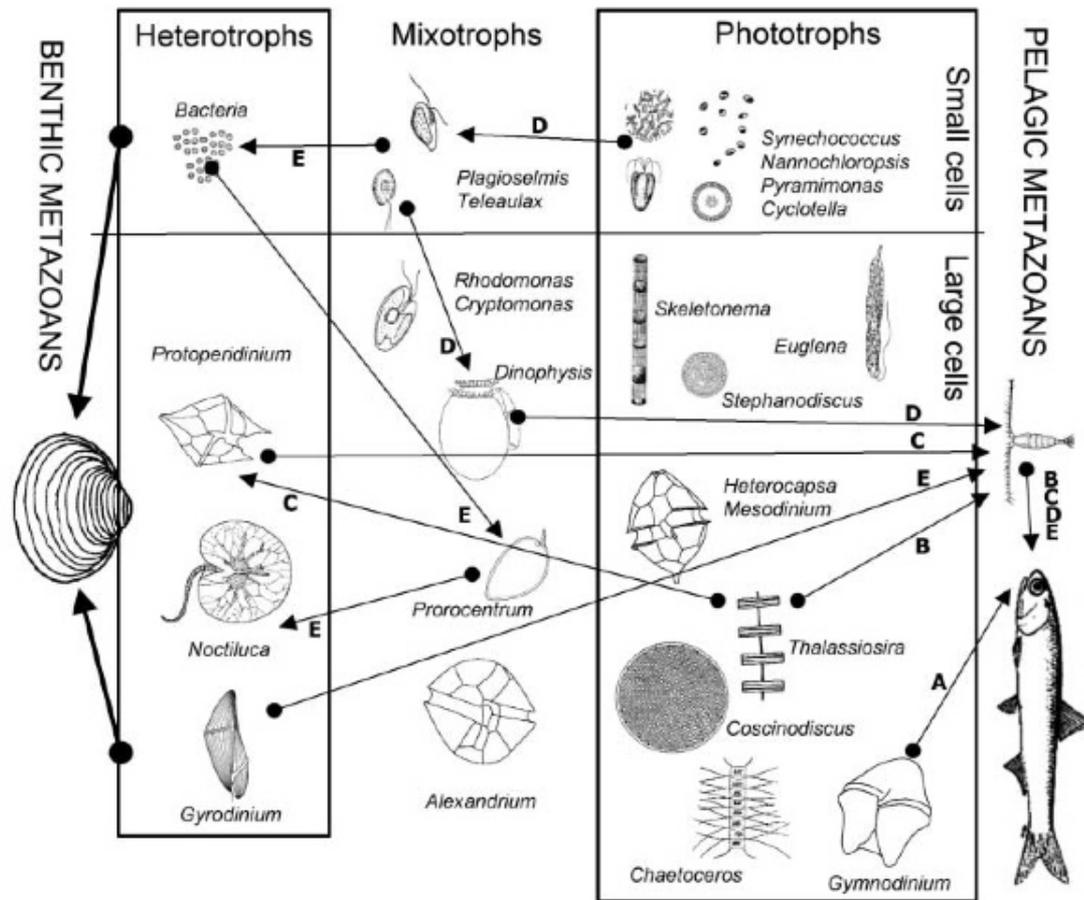
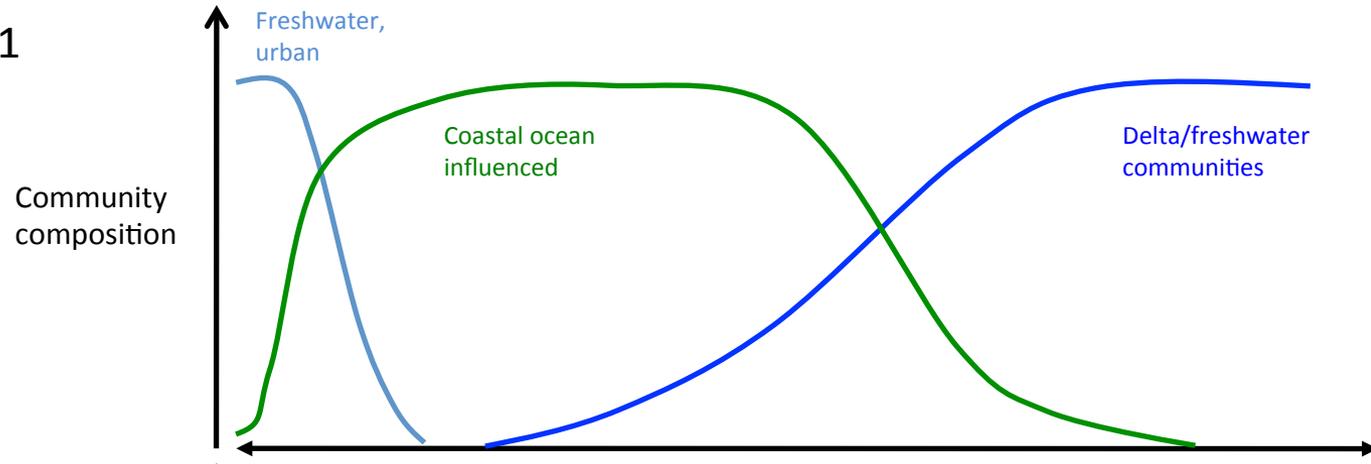


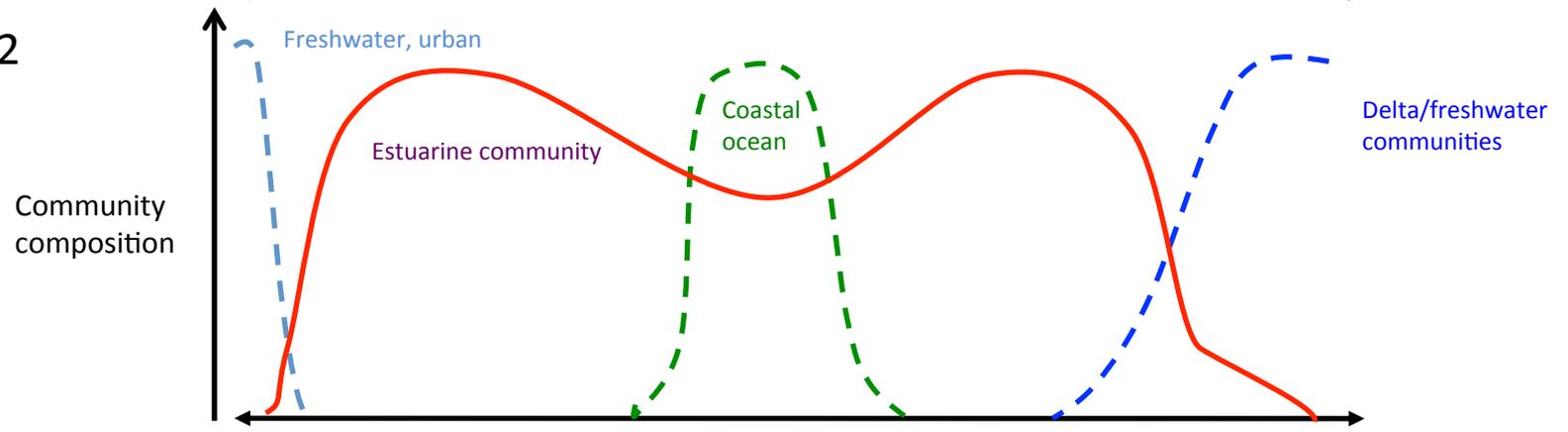
Fig. 7. Phytoplankton classification by size (small cells <math>< 15 \mu\text{m}</math>) and nutritional mode that influence pathways through which energy and essential biochemicals are supplied to benthic metazoans (e.g. bivalve mollusks) and pelagic metazoans (e.g. copepods and anchovies). Trophic 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)

Figure 9.2. From Cloern and Dufford (2005).

Scenario 1



Scenario 2



Scenario 3

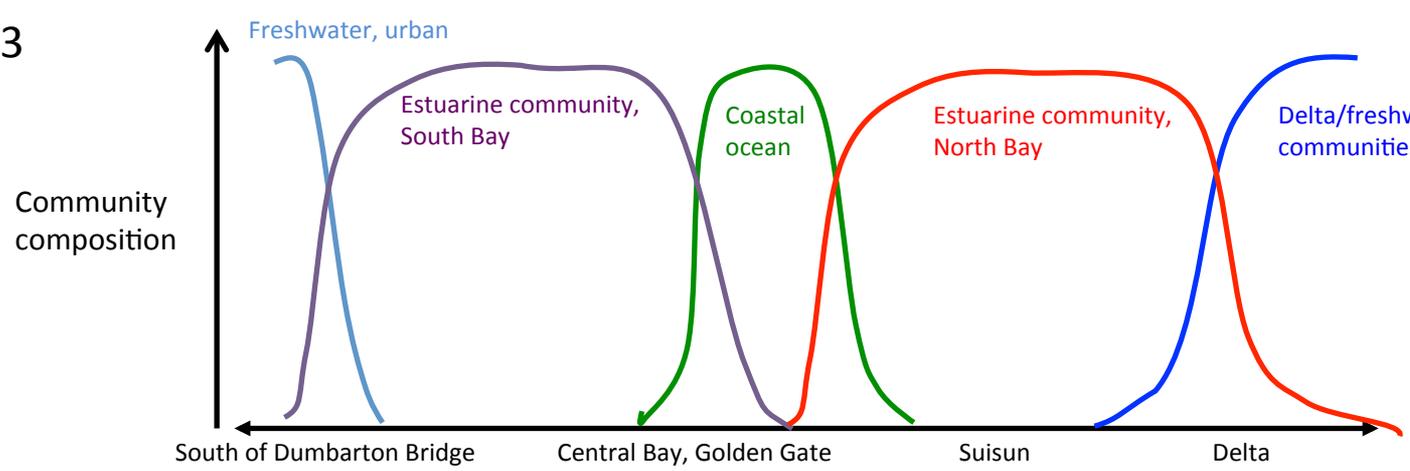


Figure 9.3 Conceptualization of 3 scenarios of spatial variability in phytoplankton assemblage

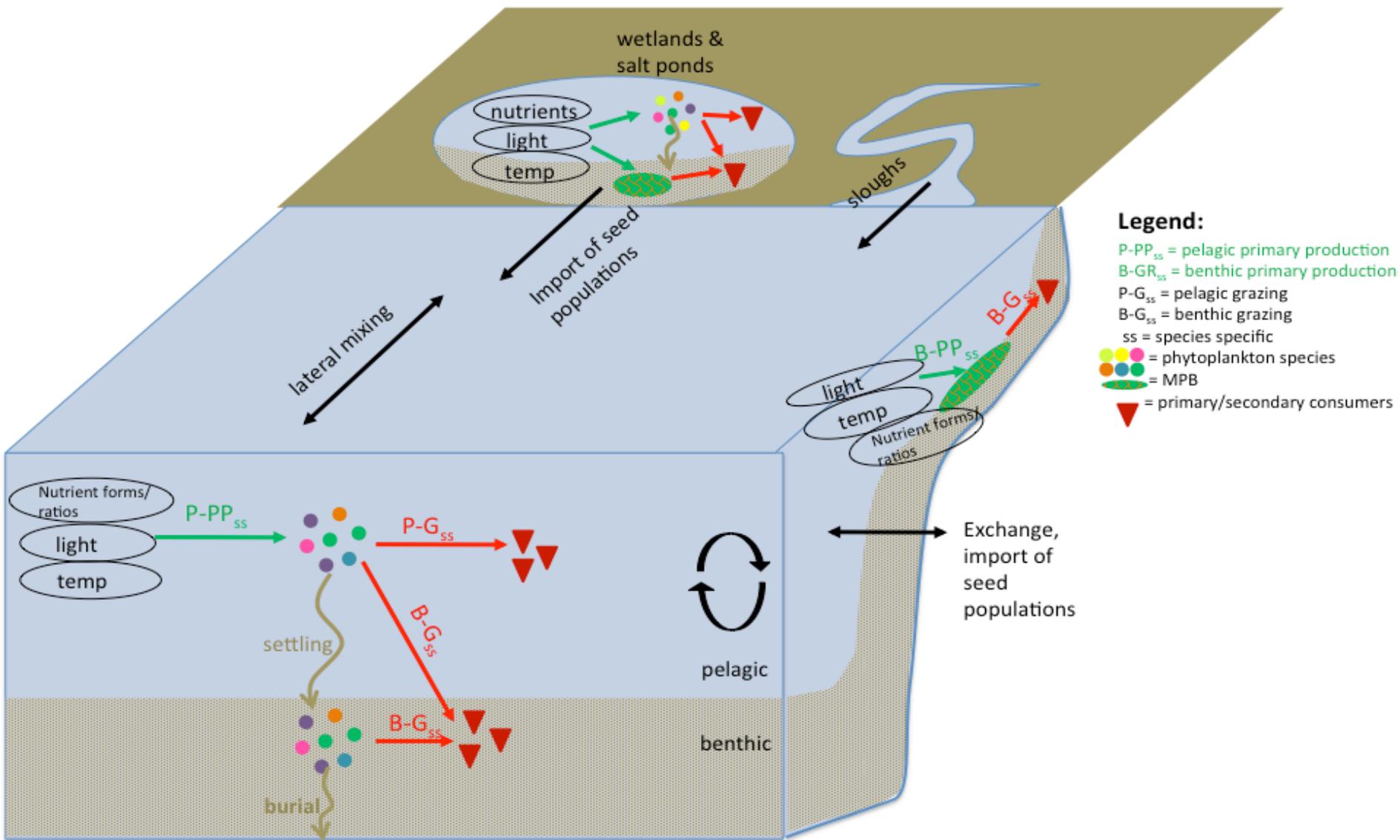


Figure 9.4. A. Conceptual model of phytoplankton community composition and processes affecting it.

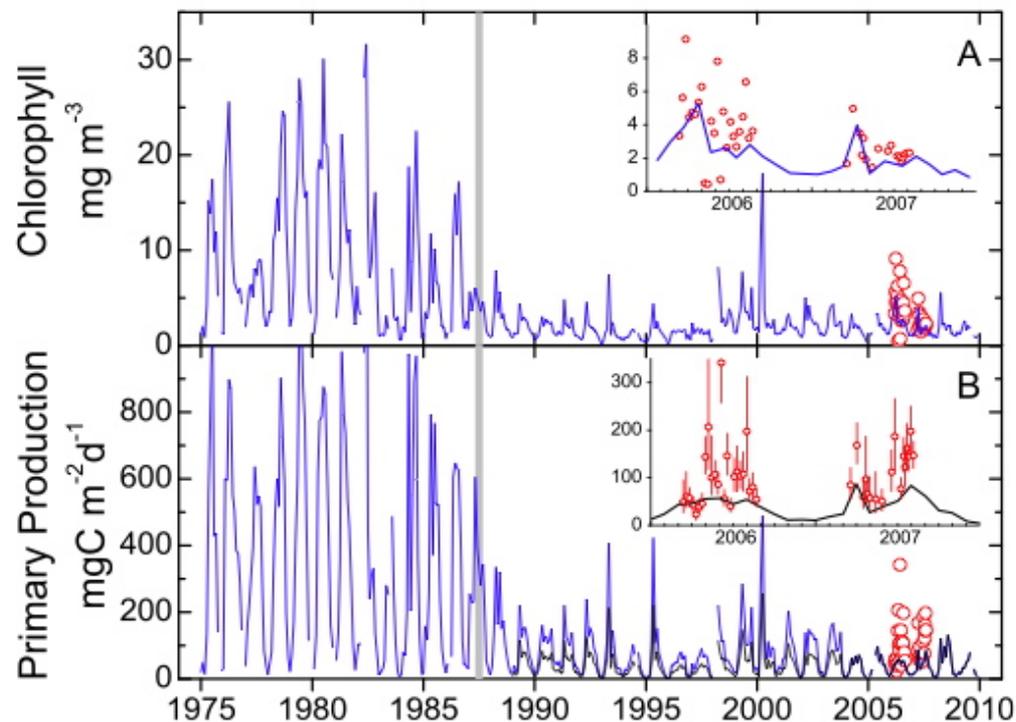


Fig. 9 Chlorophyll concentration (*A*) and estimated primary production (*B*) in this study and from a long-term monitoring program. *Insets* show data for 2006–2007 only. *A Lines* monthly means of chlorophyll from the Interagency Ecological Program environmental monitoring (Sommer et al. 2007) for 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

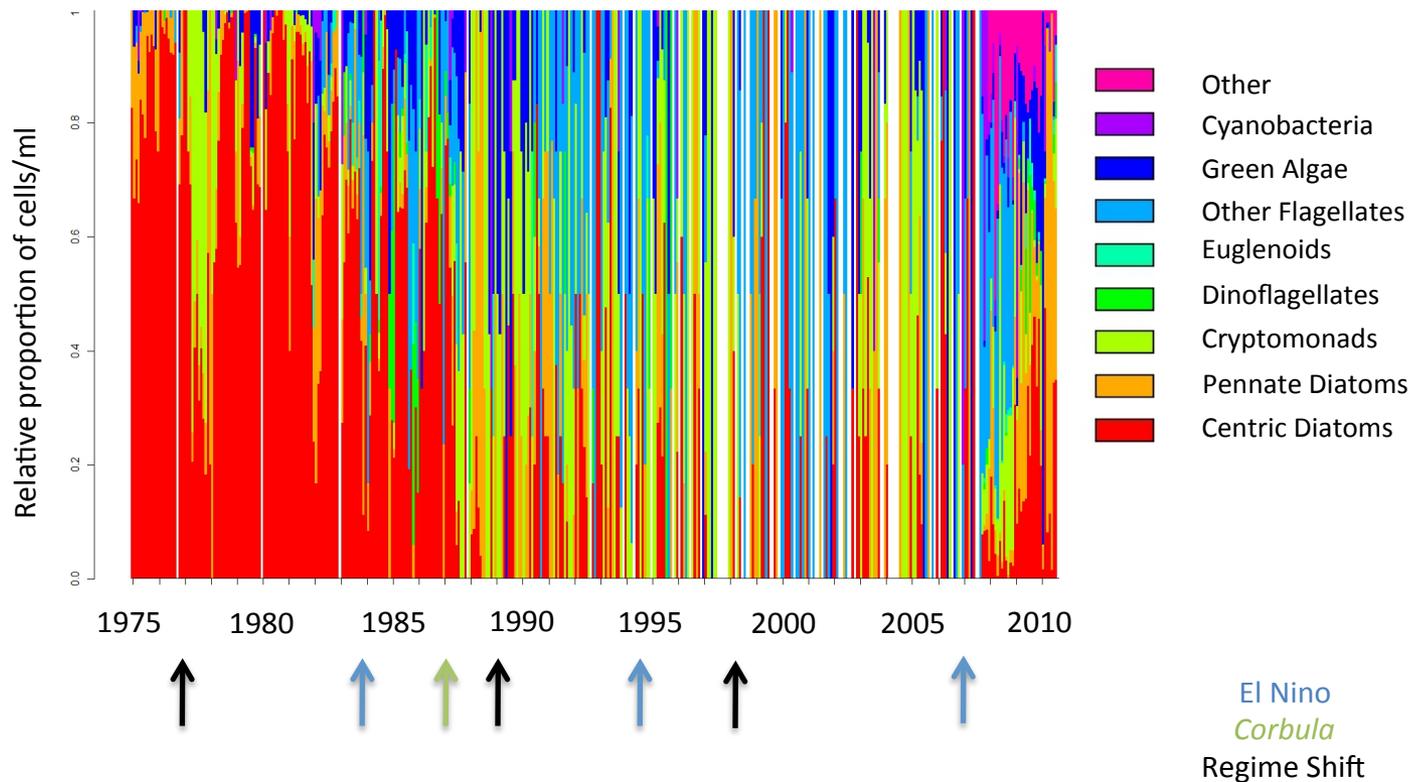


Figure 9.6. Time series of phytoplankton community composition, 1975-2007, from IEP/DWR staton D7 in Grizzly Bay. Regime Shifts based on Overland et al. 2008, Progress in Oceanography.

Freshwater Niche

Generalists

Open Ocean Niche

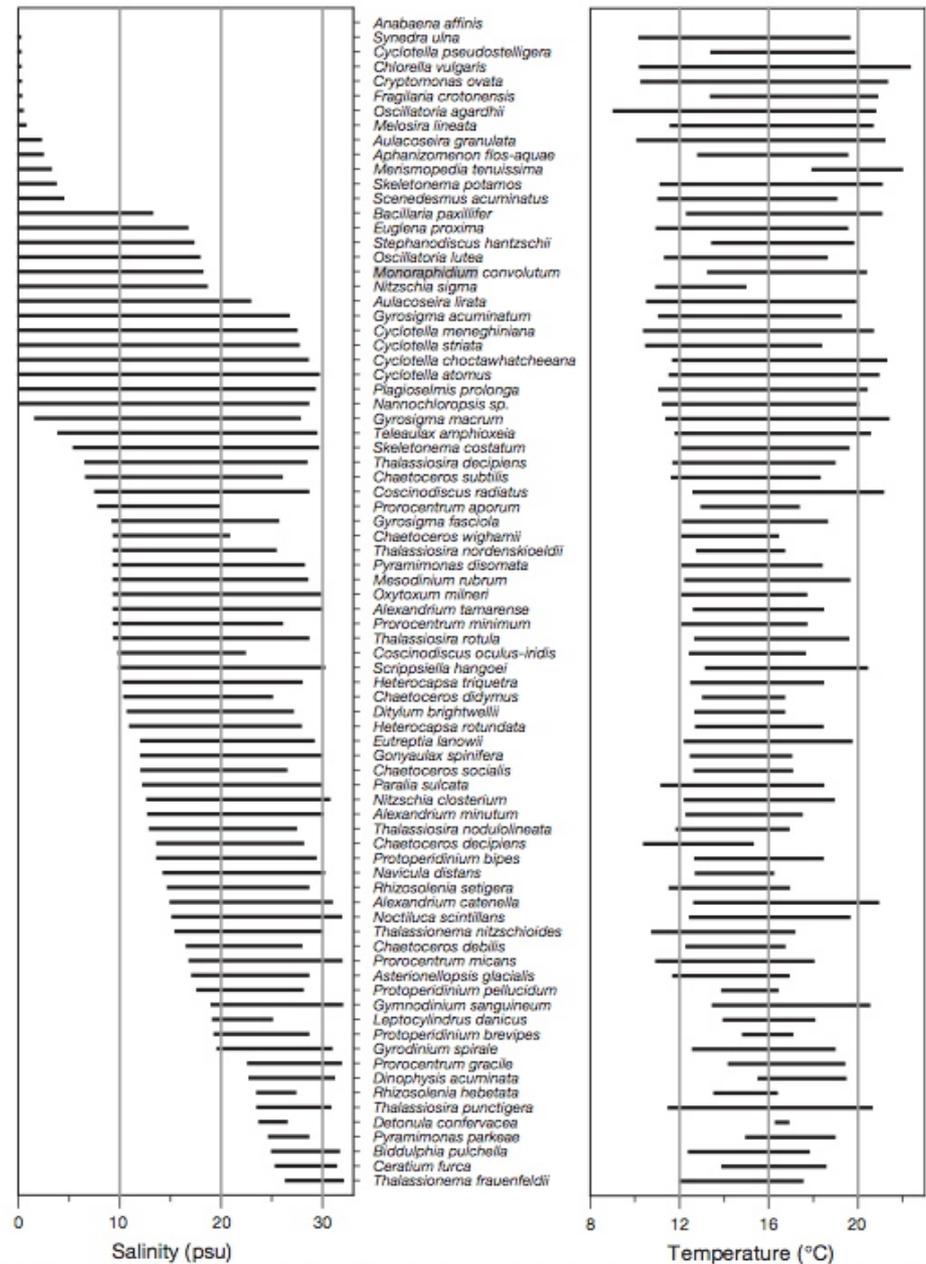


Figure 9.7. From Cloern and Dufford 2005.

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)

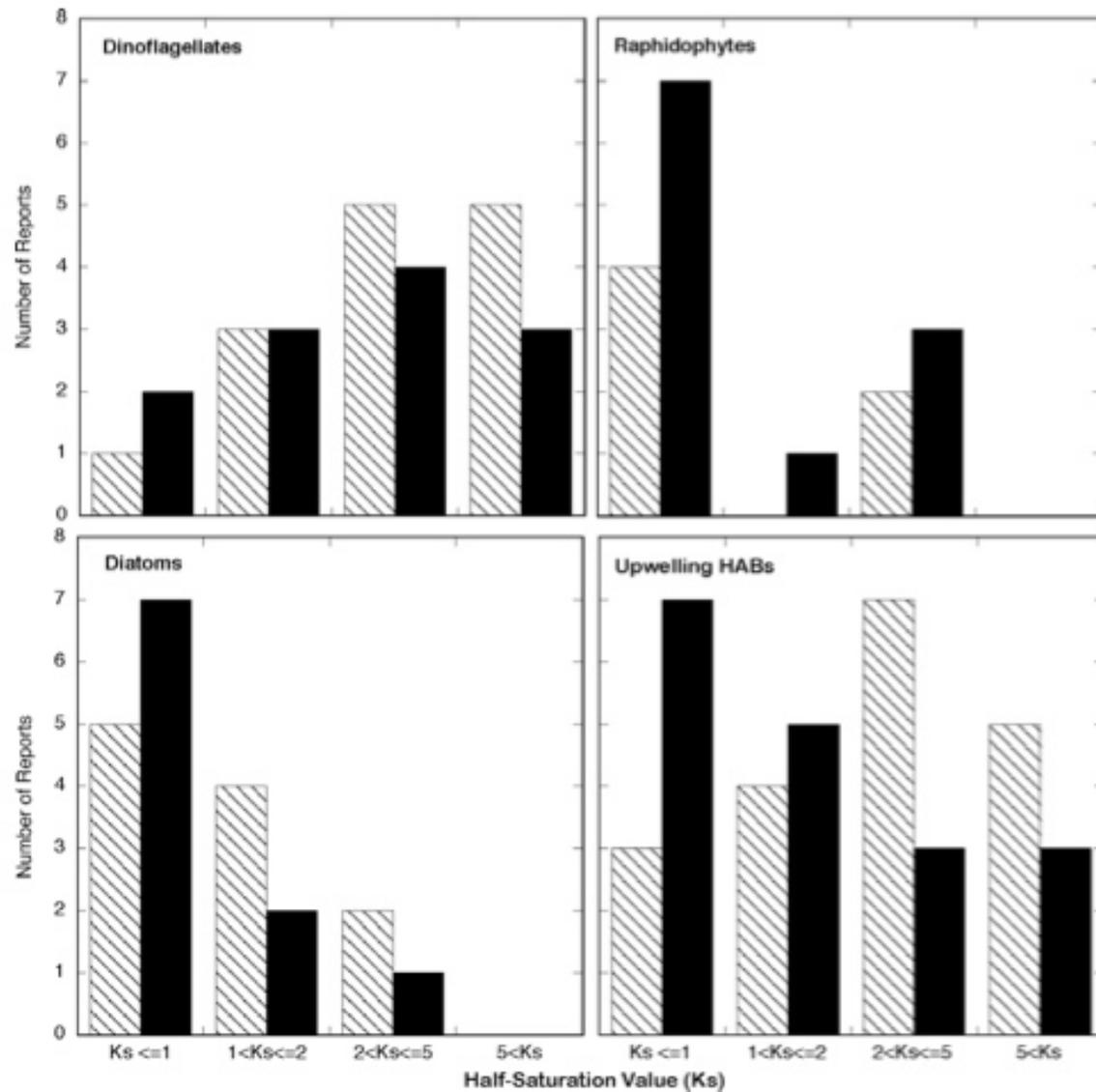


Fig. 1. Kinetics values for nitrate (solid bars) and ammonium (hashed bars) were binned based on the half-saturation (K_s) value using the same categories as Smayda (2000) for Dinoflagellates, Raphidophytes, Diatoms, and Upwelling HABs. Data were obtained from Smayda (1997, 2000), Kudela and Cochlan (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 9.8. A summary of nitrogen kinetics responses reported in the literature for major algal groups, as reported in Kudela et al. 2010.

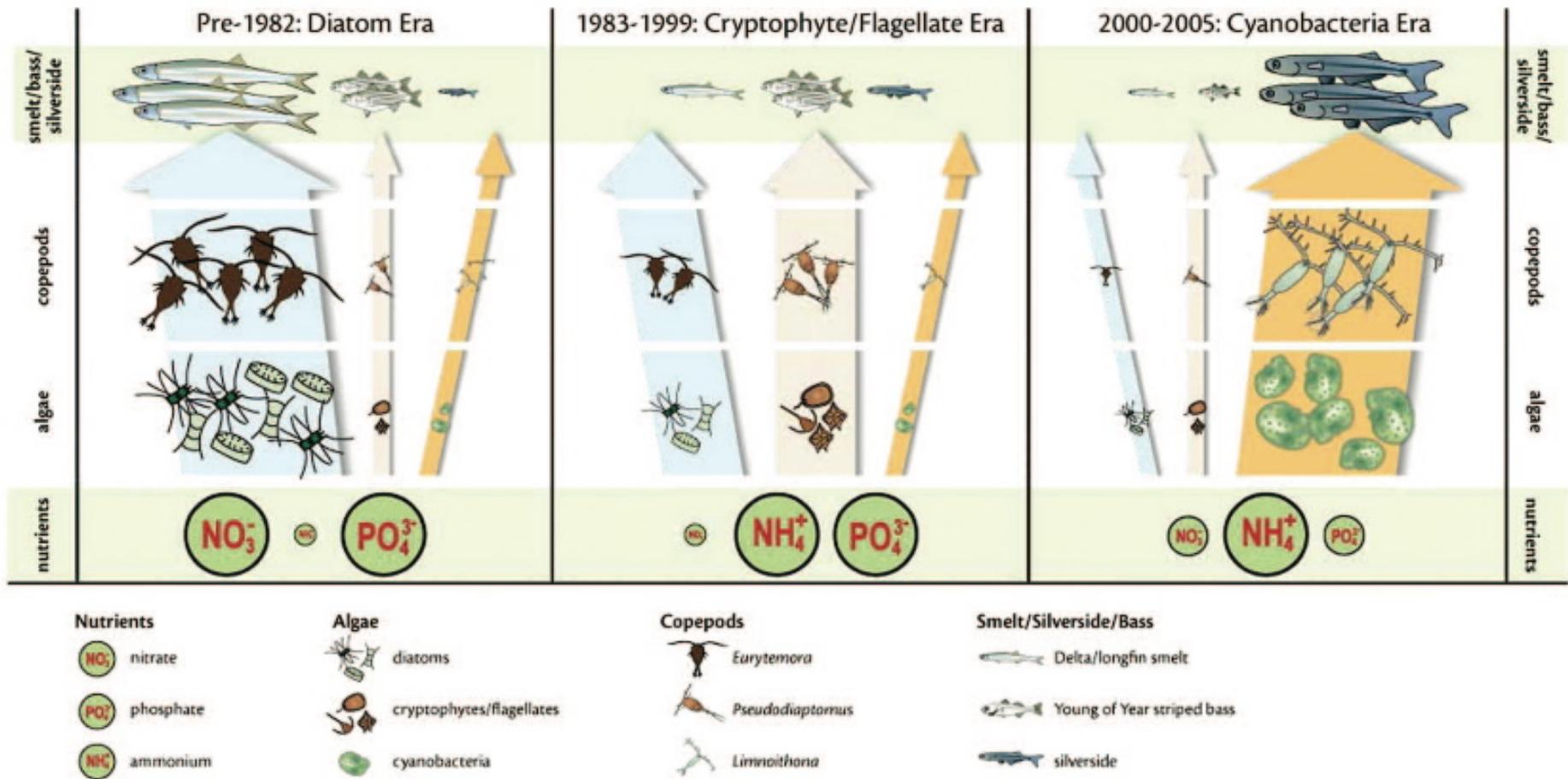


Figure 23 Conceptual diagram of some of the hypothesized changes in the food chain from phytoplankton to fish that have occurred in the Sacramento-San Joaquin Estuary over the past 30 years. Each of these hypothesized food chains has different dominant nitrogen forms or amounts relative to phosphorus. This conceptual model is intended simply to highlight some of the major flows of energy and materials and does not include all organisms, pathways or flows. The size of the symbols is meant to infer relative importance.

Figure 9.9. A conceptual model of food web changes triggered by shifts in phytoplankton community composition. Prior to 1982, the form of N and the N:P ratio favored diatom blooms. From 1983-1999, increasing ammonium inputs shifted the community towards cryptophytes and flagellates. From 2000-2005, another shift towards cyanobacteria was triggered by a reduction in the N:P ratio. From Glibert 2010.

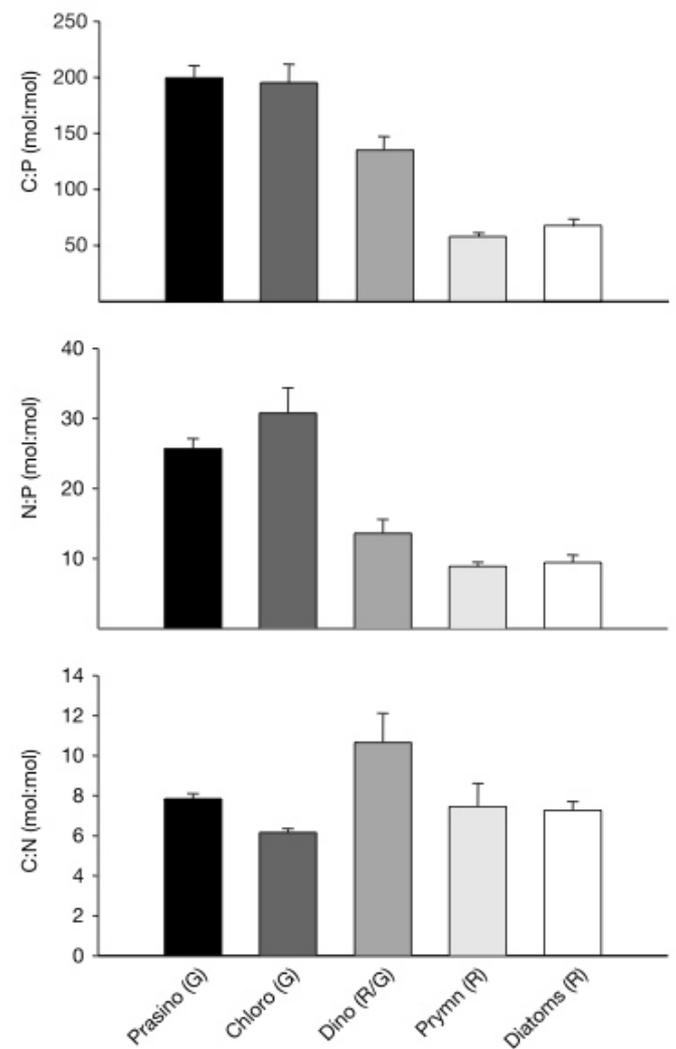


Figure 1 C:N:P composition varies between phyla and superfamilies. Phytoplankton C:P, N:P and C:N (mol:mol) ratios are grouped phylogenetically—Prasinophyceae (Prasino) and Chlorophyceae (Chloro) are members of the green (G) plastid superfamily whereas Dinophyceae (Dino), Prymnesiophyceae (Prymn) and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

Figure 9.10. Intrinsic C:P, N:P, and C:N ratios for major phytoplankton groupings. From Quigg et al. 2003.

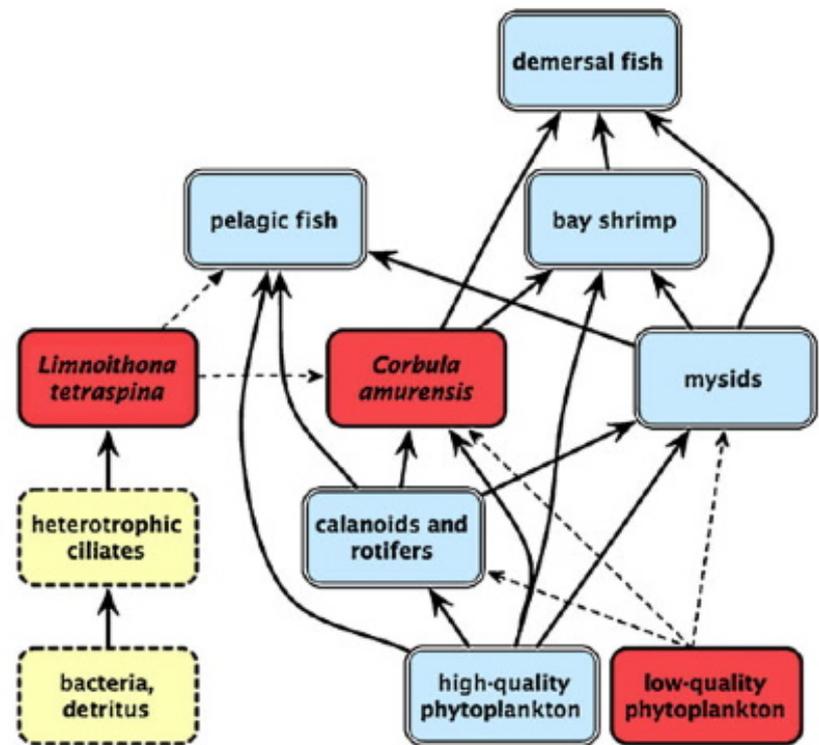


Fig. 11 Trophic interactions of the pelagic food web in the upper San Francisco Estuary at the “suisun” subregion. *Arrows* indicate major energy flow based on gut content analysis or literature data. *Solid lines* represent strong and *dashed lines* weak trophic interactions. *Box colors* reflect long-term 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 for demersal fish and bay shrimp are adapted from Kimmerer (2006)

Figure 9.11. Shifts in phytoplankton community composition are associated with shifts in grazing pressure.

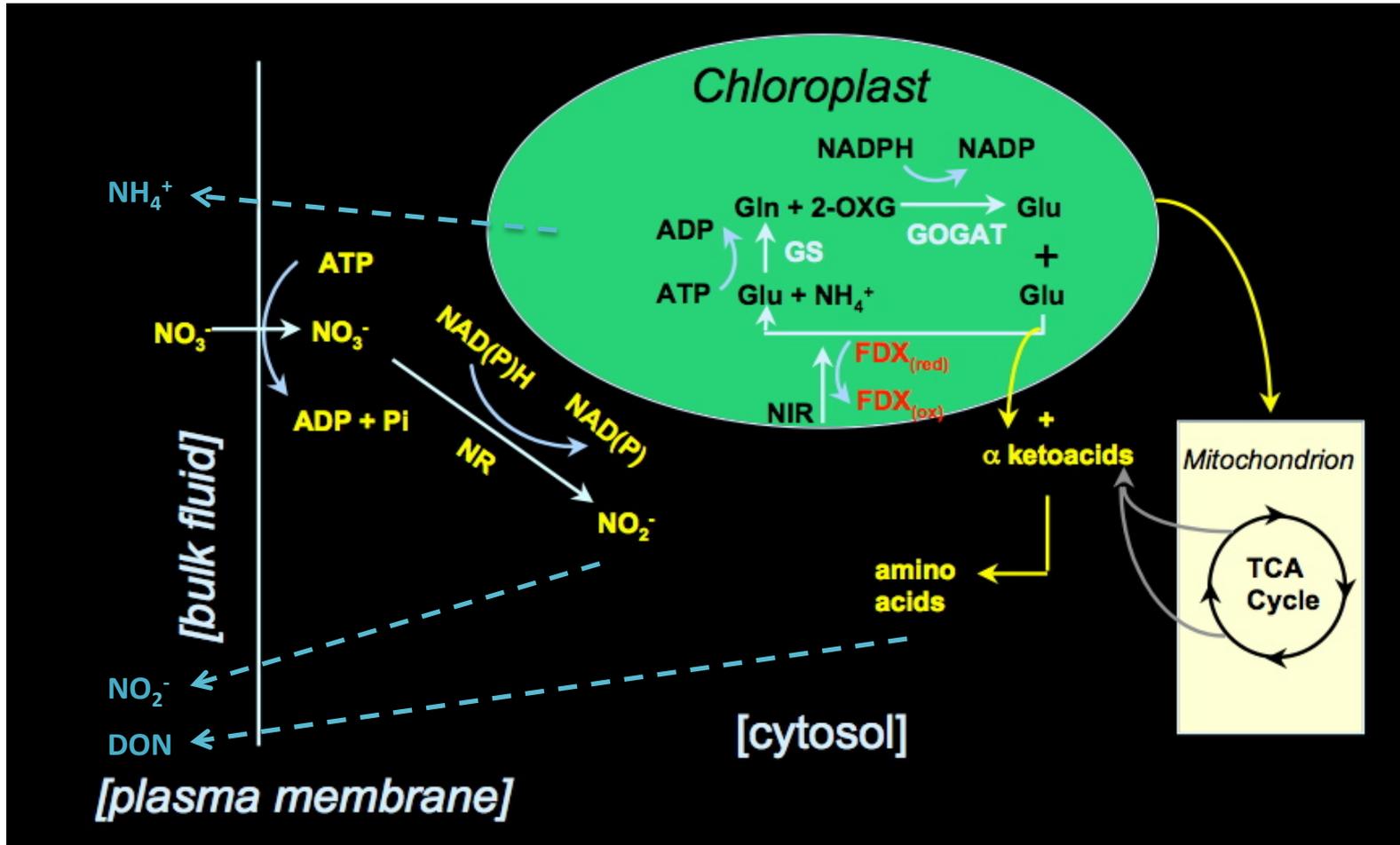
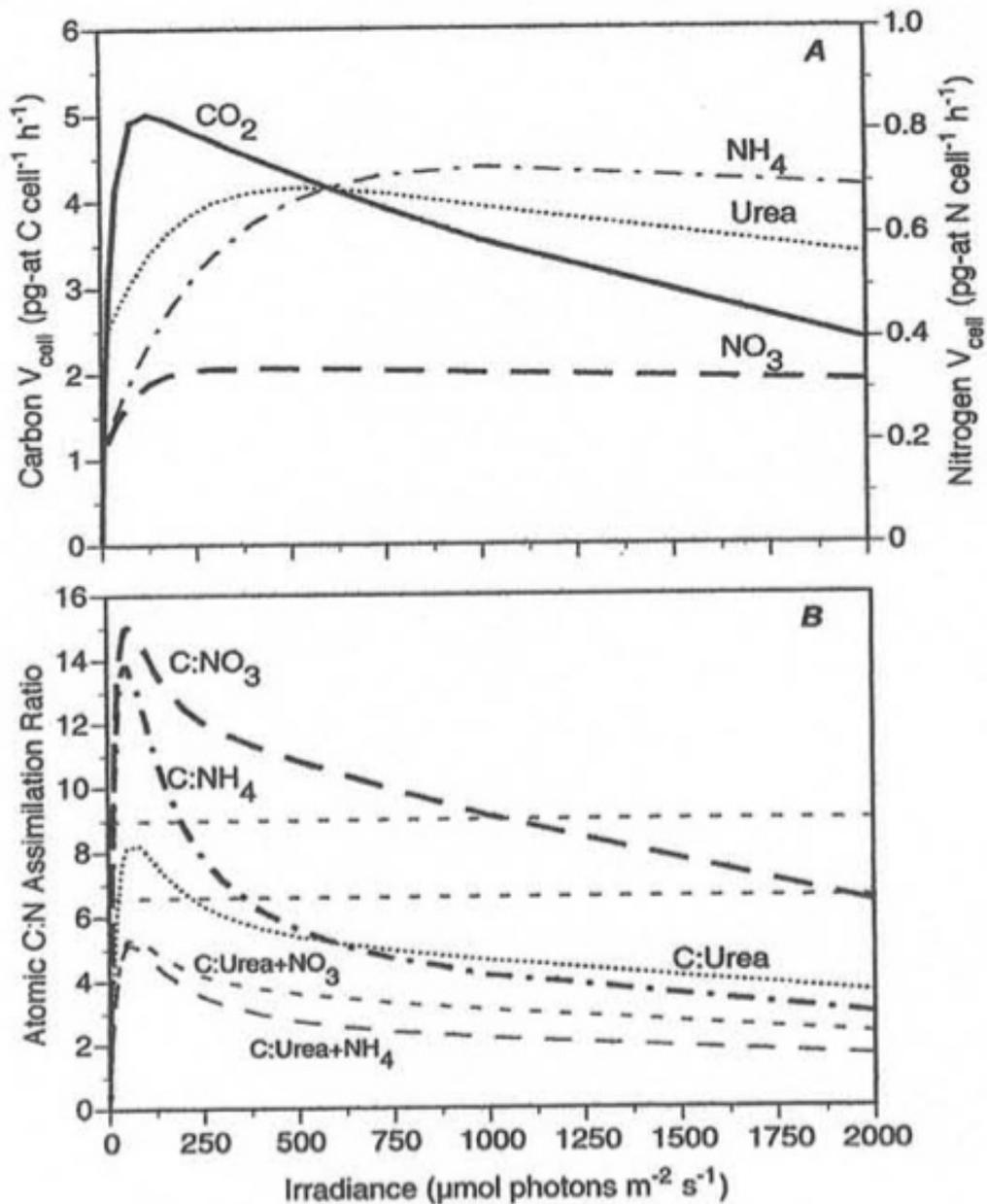
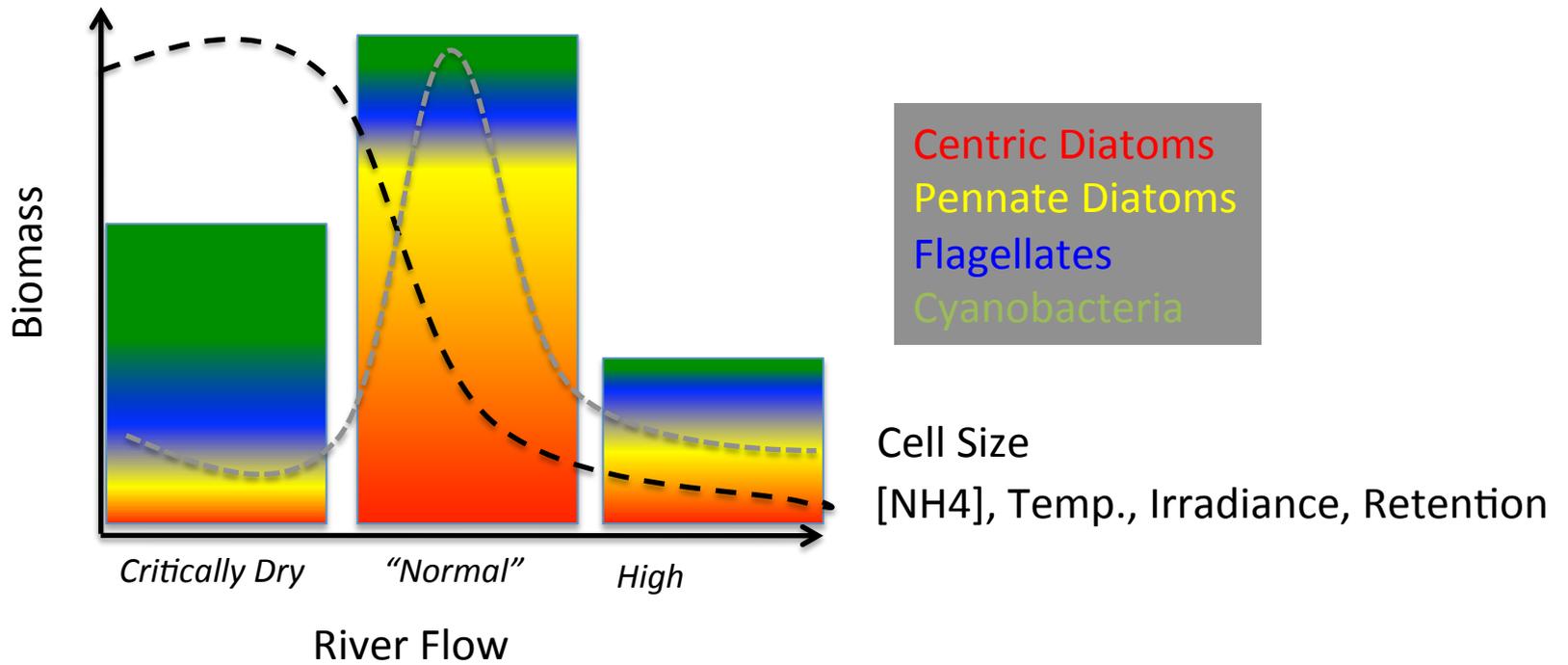


Figure 9.12. After carbon assimilation, nitrogen assimilation is the largest sink for photo-reductant. ATP and NADPH are used for membrane transport, nitrate reductase, nitrite reductase, and ammonium assimilation. Under low light conditions it may be energetically favorable to use reduced N compounds. Conversely, under rapidly changing light conditions and in cold temperatures, N reduction can be used as a sink for electrons, resulting in production and efflux of nitrite, ammonium, and DON (dashed lines).

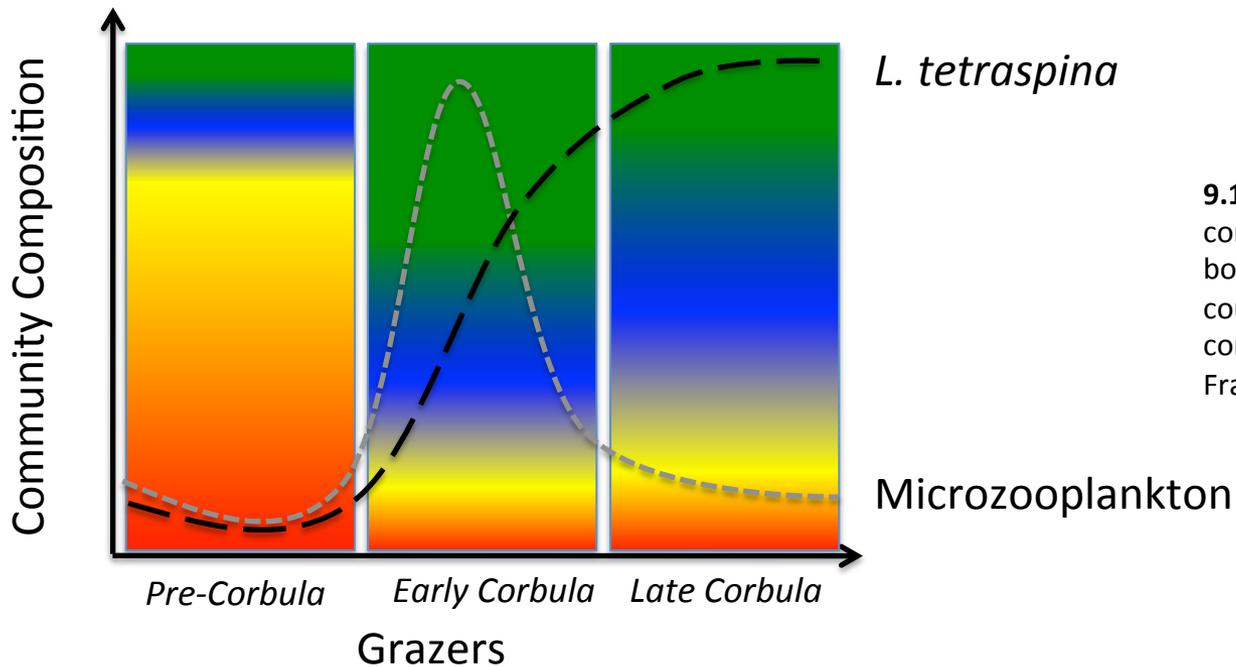
Figure 9.13. The interactive effects of light, nutrient assimilation, and the energetic requirements for N-metabolism (see Figure 9.12) can result in unexpected patterns of nutrient utilization. Panel A shows uptake versus irradiance for a red tide comprised of the dinoflagellate *Lingulodinium polyedrum*, indicating more efficient utilization of ammonium and urea compared to nitrate. Panel B shows 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 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$) 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 $\text{NO}_3 > \text{NH}_4 > \text{Urea}$ (based on K_s values). At the time of collection, ambient nutrients were approximately at the K_s value or higher throughout the water column. From Kudela and Cochlan, 2000.



A.



B.



9.14. Two (overly) simple conceptual models of how (A) bottom-up or (B) top-down control could reconcile the trends in community composition for San Francisco Bay.

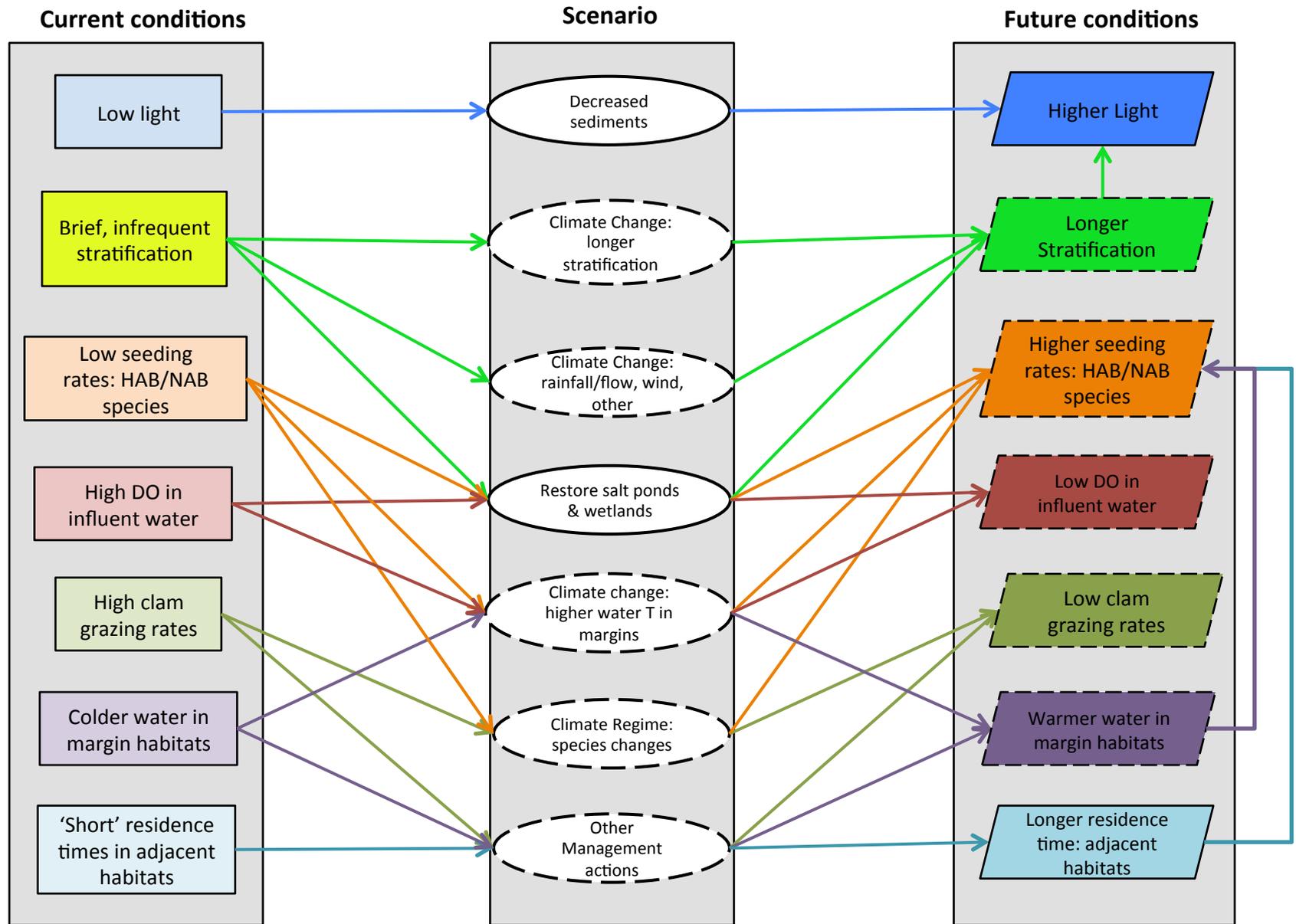


Figure 11.1 On the left, Current Conditions within SFB that have thus far provided resistance to harmful effects of high nutrient loads. In the middle, potential environmental or management scenarios that could create future conditions with weaker resistance to nutrient-related impairment. Likelihood 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

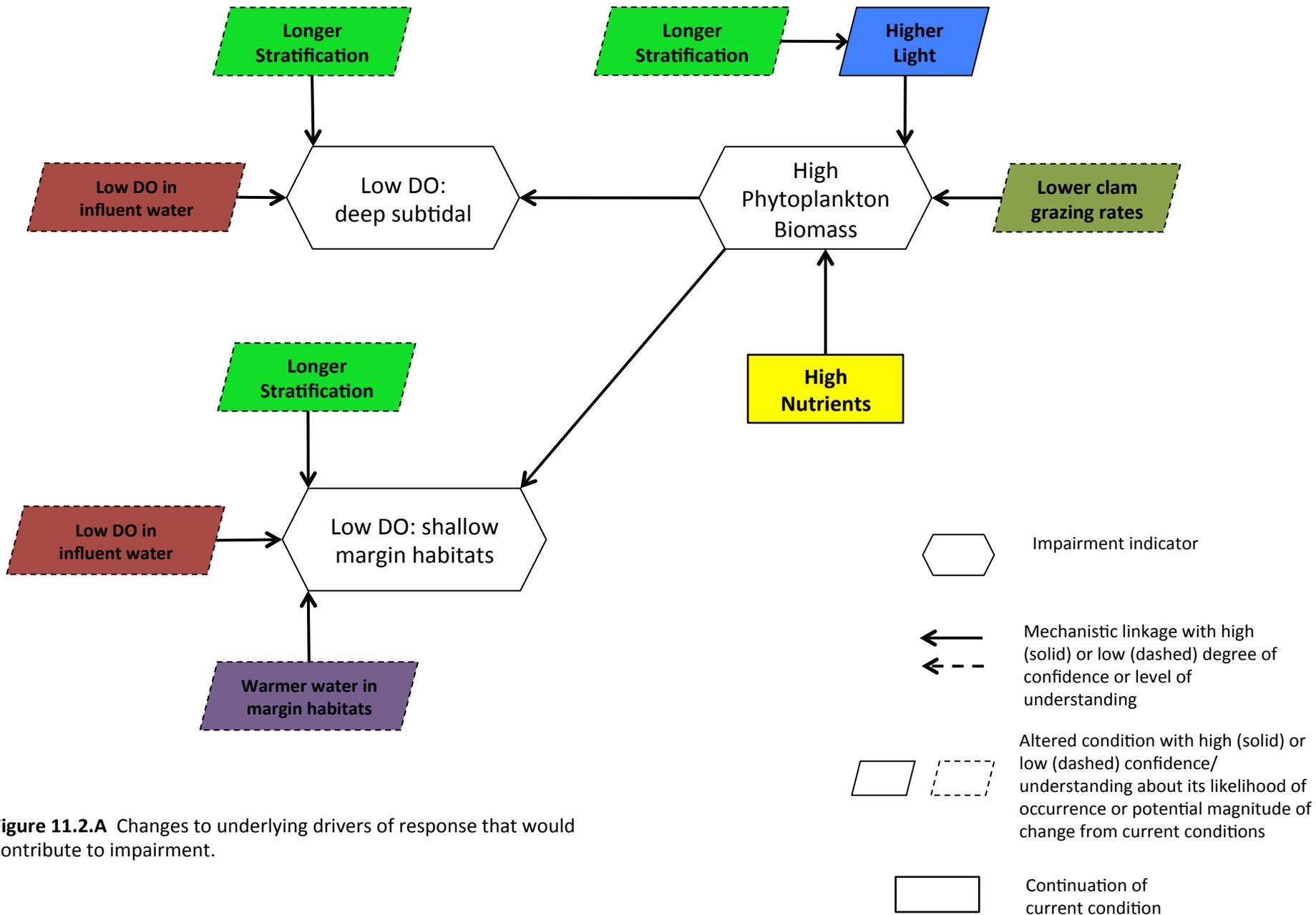


Figure 11.2.A Changes to underlying drivers of response that would contribute to impairment.

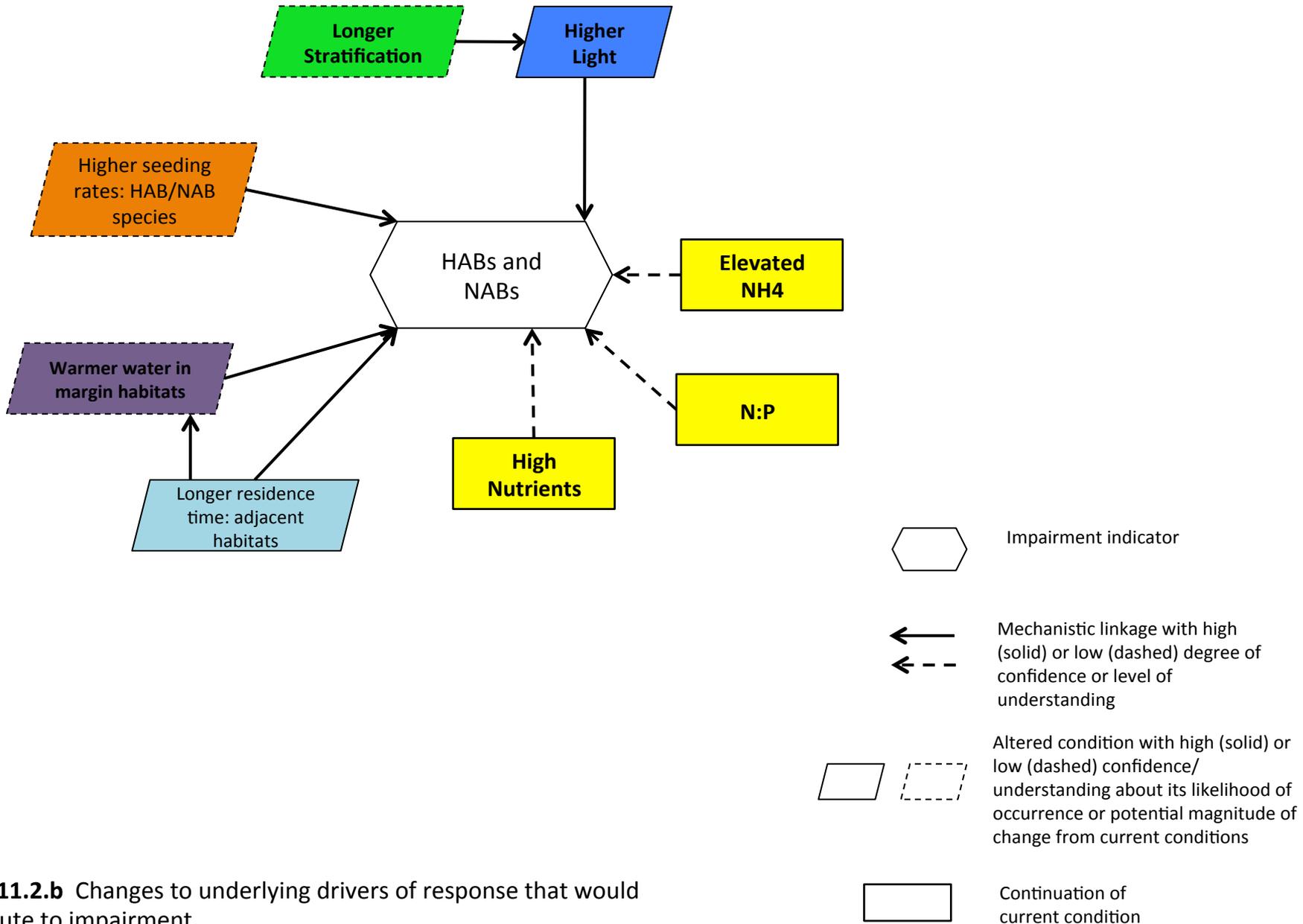


Figure 11.2.b Changes to underlying drivers of response that would contribute to impairment.

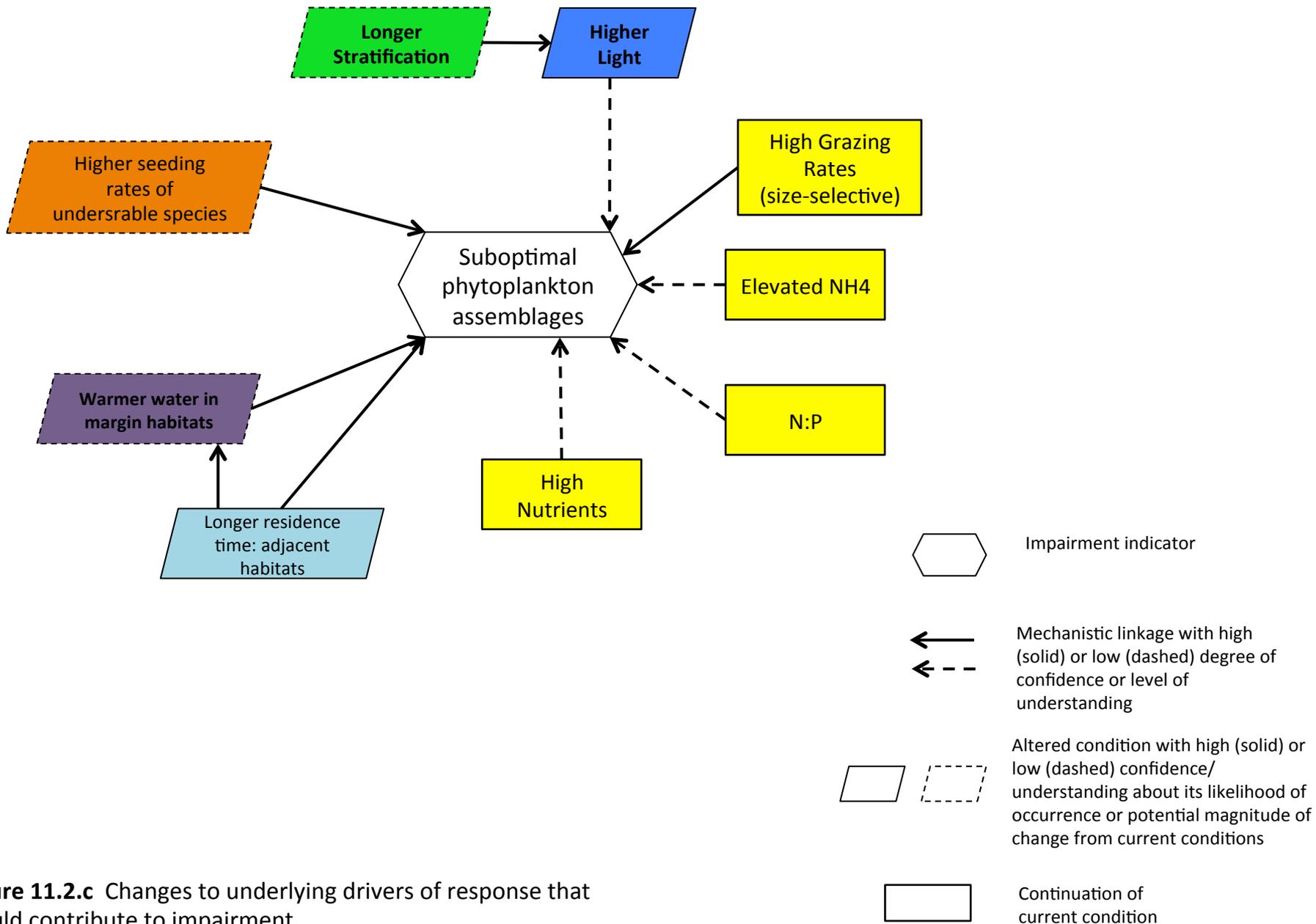
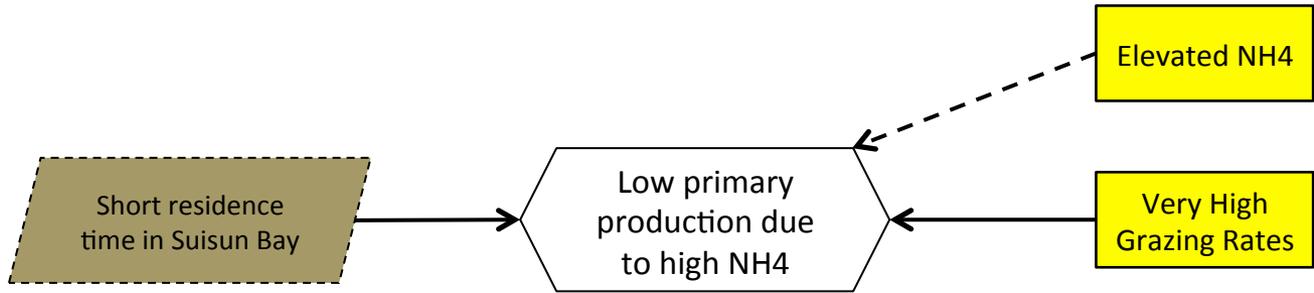
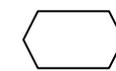
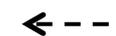


Figure 11.2.c Changes to underlying drivers of response that would contribute to impairment.



 Impairment indicator

 Mechanistic linkage with high degree of confidence or level of understanding
 Mechanistic linkage with low degree of confidence or level of understanding

 Altered condition with high confidence/understanding about its likelihood of occurrence or potential magnitude of change from current conditions
 Altered condition with low confidence/understanding about its likelihood of occurrence or potential magnitude of change from current conditions

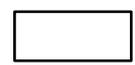
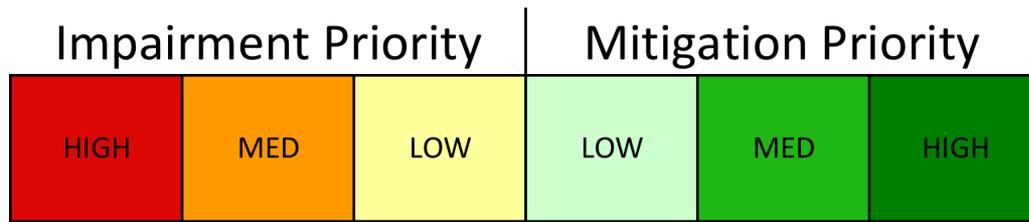
 Continuation of current condition

Figure 11.2.d Changes to underlying drivers of response that would contribute to impairment.



		Current Understanding			
		4 (Higher)	3	2	1 (Lower)
Effect magnitude	1 (Lower)	LOW	LOW	LOW	MED
	2	LOW	LOW	MED	MED
	3	HIGH	HIGH	HIGH	HIGH
	4 (Higher)	HIGH	HIGH	HIGH	HIGH

		Current Understanding			
		4 (Higher)	3	2	1 (Lower)
Effect magnitude	1 (Lower)	LOW	LOW	LOW	MED
	2	LOW	LOW	MED	MED
	3	MED	MED	HIGH	HIGH
	4 (Higher)	HIGH	HIGH	HIGH	HIGH

Figure 11.3 Prioritization scheme for impairment and mitigation scenarios. The ranking of LOW, MED, or HIGH is assigned based on the potential magnitude of the effect and the current level of understanding. The rank indicates the level of priority that should be given to gathering additional information. The rank is not necessarily an indication of the magnitude of the effect alone, or the probability that it will occur.

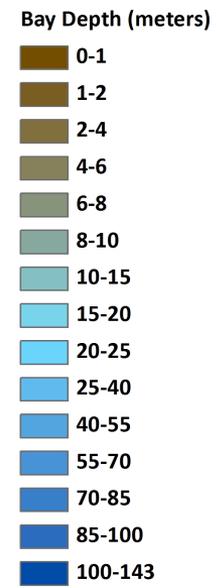
CURRENT TRENDS

	LSB	SOU	CEN	SAN	SUI
High biomass, Deep	●	●			
Low DO, Deep subtidal					
Margins low DO	●	●			
HABs	●	●	●	●	●
NABs	●	●	●	●	●
Low biomass					●
Phyto Comm Comp	●	●	●	●	●
other foodweb effects					

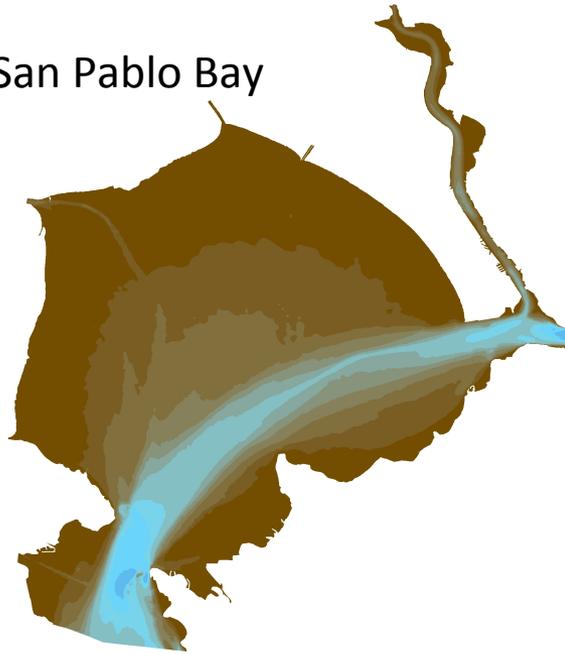
Figure 11.4 Prioritization of impairment pathways for further consideration by subembayment based on current trends alone. Black circles indicate further prioritization (see Section 11.4) of issues that should receive near-term attention.



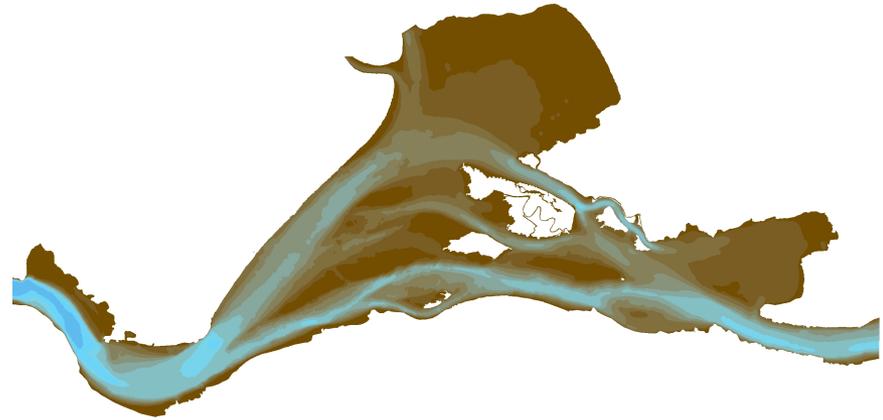
Figure 11.5 Full set of subbayment-indicator-scenario combinations. Black circles indicate highest near-term priority combinations



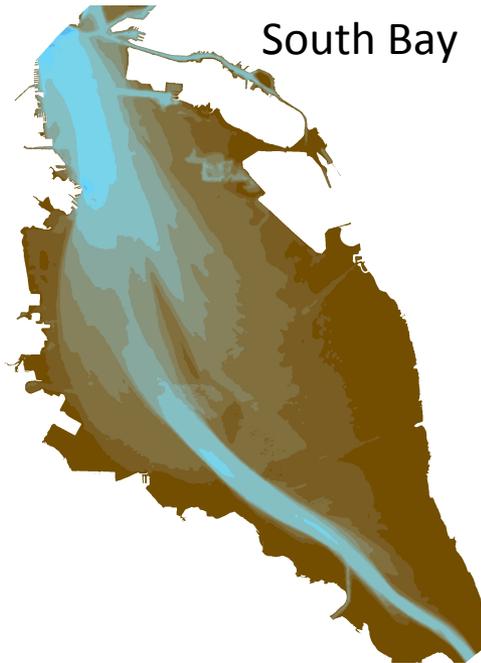
San Pablo Bay



Suisun Bay



Central Bay



South Bay

Lower South Bay

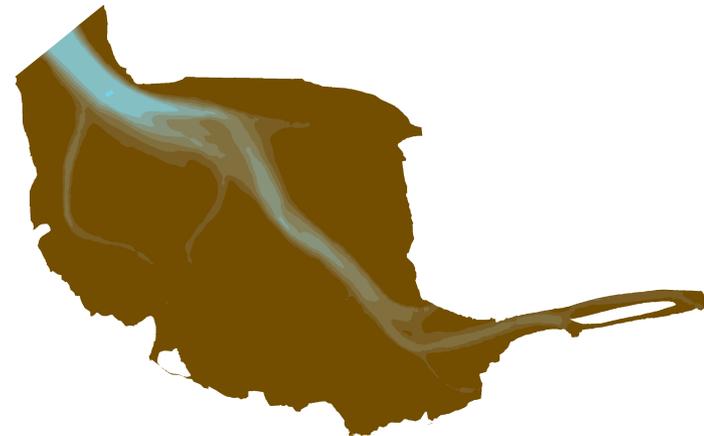


Figure A.1 Major Bay segments and their bathymetry. Note that the subembayments are drawn at different scales.