

Chapter 5:

6. San Francisco Bay

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General Description

San Francisco Bay is a large (1,240 km²) estuary with a deep central channel, broad lateral shallow bays and intertidal mudflats (Figure 5.6.1), and overall mean depth of approximately 6 m at mean lower low water (MLLW) (Conomos 1979).

The San Francisco Bay-Delta ecosystem comprises two distinct but connected estuary types: North Bay is the tidal estuary of the Sacramento and San Joaquin rivers that carry runoff produced in a 163,000-km² agricultural watershed, and South Bay is a marine lagoon in the densely populated urban watershed between San Francisco, Oakland and Silicon Valley. River discharge is strongly seasonal, with peak discharge from winter storms and spring snowmelt in the Sierra Nevada mountains and low discharge during the dry summer to autumn. The salinity distribution in North Bay changes with seasonal fluctuations in Sacramento–San Joaquin discharge, and



Figure 5.6.1. Two maps of San Francisco Bay. The top map shows the broader location. The bottom map details the estuarine segments. North San Francisco Bay is the estuary between the Sacramento–San Joaquin rivers and the Pacific Ocean at Golden Gate. It comprises lateral shallows in the oligohaline Suisun Bay and mesohaline San Pablo Bay. South Bay is a marine lagoon-type estuary. Central Bay is a deep mixing basin of water originating in the Pacific Ocean, South, and North Bays. Sacramento and San Joaquin River flows are routed through the delta, a complex network of tidal freshwater channels and shallow, open-water habitats. Circles show USGS sampling stations.

salinity in South Bay responds to seasonal fluctuations in river discharge and runoff produced in the local urban watershed (Figure 5.6.2). Wastewater discharge is the primary source of fresh water to South Bay during the dry season.

The tides are mixed semidiurnally with maximum current speed of 1.75 m s^{-1} (Walters et al. 1985) and tidal amplitude of 1.7 m (Conomos 1979) at the Golden Gate. Tidal currents and amplitude are damped as the tidal wave propagates into North Bay, but the tidal range becomes amplified to 2.6 m in the closed South Bay (Conomos

1979). The water column is typically mixed by wind and tidal currents; density (primarily salinity) stratification develops only during neap tides of the wet season, and it breaks down on spring tides, so San Francisco Bay does not experience persistent stratification. Horizontal transports also vary over the neap-spring cycle, with amplification of net residual (baroclinic) currents driven by the horizontal density gradient during neap tides. Residence time varies from days in North Bay during large floods to months in South Bay during the dry season (Walters et al. 1985).

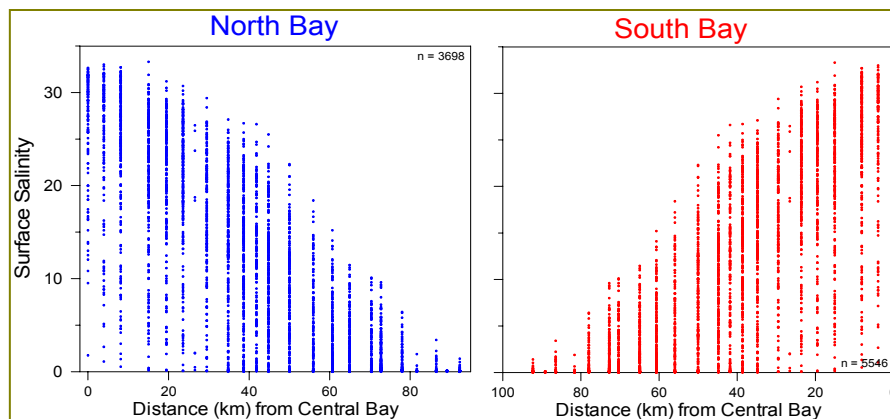


Figure 5.6.2. Surface salinity in North Bay and South Bay vs. distance from Golden Gate. Data shown are all measurements made by USGS from 1969 to 2001.

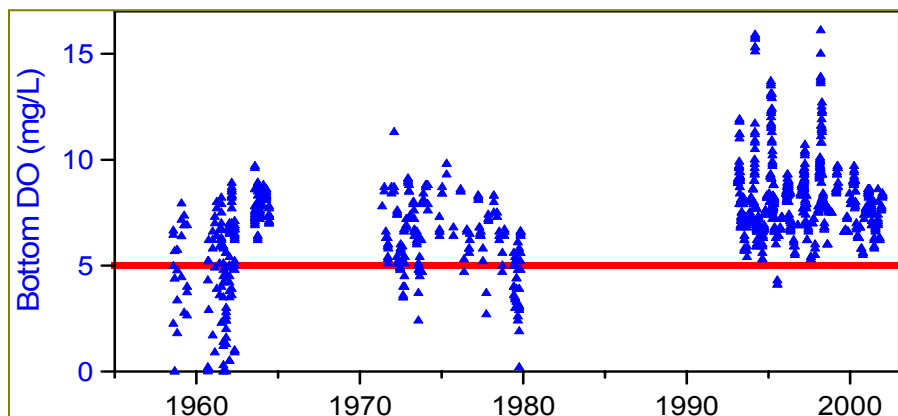


Figure 5.6.3. Near-bottom DO in lower South Bay. Hypoxia disappeared after implementations of advanced wastewater treatment that included nitrification.

Dissolved Oxygen

Through the 1970s, isolated regions of San Francisco Bay experienced seasonal or episodic hypoxia. However, after implementing advanced wastewater treatment mandated by the 1972 CWA, occurrences of hypoxia have been eliminated from South San Francisco Bay (Figure 5.6.3). Seasonal anoxia does develop at one location in the Delta—the deep ship channel at Stockton (Jassby and Van Nieuwenhuyse 2005).

Turbidity and Light

North San Francisco Bay receives > 1 metric ton of sediments yearly from the Sacramento and San Joaquin Rivers (McKee et al. 2006), and South Bay receives sediments from urban runoff delivered by

Nutrients in Estuaries

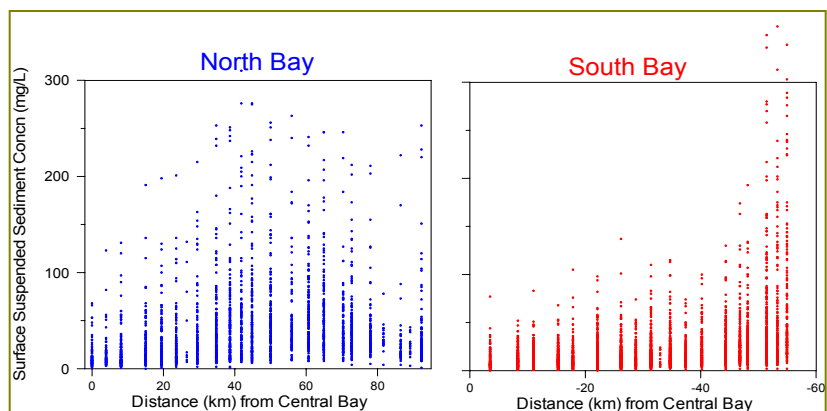


Figure 5.6.4. Surface suspended sediment concentrations in North Bay and South Bay versus distance from Golden Gate. Data shown are all measurements made by USGS 1969–2001.

local streams. Sediments delivered during the wet season are redistributed by tidal and wind-driven currents during the dry season, so there is strong seasonality in the concentration and spatial distribution of suspended sediments. Distributions along the North Bay salinity gradient reflect accumulation of sediments in a mid-estuary turbidity maximum, and distributions along South Bay reflect the large source from urban runoff in the southernmost basin (Figure 5.6.4).

As a result of large river inputs, shallow depth and continual resuspension from winds and tides, San Francisco Bay has high concentrations of suspended sediments and high turbidity that limit phytoplankton photosynthesis and growth rates. From the long-term measurements, the mean photic depths in the channels of North and South Bay are 1.4 m and 2.1 m, respectively. Turbidity is substantially higher in the lateral subtidal shallows subjected to wind-wave resuspension (Cloern et al. 1985; May et al. 2003).

Nutrients

San Francisco Bay is highly enriched in N and P, a result of riverine inputs from a large agricultural watershed and wastewater discharge from > 6 million people (Smith and Hollibaugh 2006). Overall distributions of DIN (= NH_4^+ +

$\text{NO}_3^- + \text{NO}_2^-$) and P (as PO_4^{3-}) do not show consistent strong spatial patterns along the salinity gradient (Figures 5.6.5, 5.6.6). However, distributions of $\text{Si}(\text{OH})_4$ reveal the strong freshwater source of this nutrient (Figure 5.6.7).

Figures 5.6.5 to 5.6.7 compare dissolved inorganic nutrient concentrations along the salinity gradient against one index of potential limitation of phytoplankton

growth: a value taken as twice the half-saturation constants for algal growth ($K_P = 0.15 \mu\text{M-P}$, $K_N = K_{\text{Si}} = 1.5 \mu\text{M-N or Si}$). On the basis of this index, dissolved inorganic nutrient concentrations are virtually always well above those that limit algal growth in North Bay. Potential P limitation is extremely rare (only 2 of 1,264 measurements), but potential N and Si limitation occur episodically in South Bay during unusually large spring diatom blooms (Cloern 1996).

Although the 12-year data set shows no obvious pattern for DIN versus salinity, the winter data (when biological activity is low) for NO_3^- , NH_4^+ , and $\text{Si}(\text{OH})_4$ all show a strong inverse relationship to salinity (Figure 5.6.8). The major source of the nutrients in North San Francisco Bay is in the freshwater inputs at the head of the estuary.

Recent studies show the anthropogenically altered composition of DIN (relative contribution of NH_4^+ and NO_3^-) may have resulted in decreased primary production. Measurements of NO_3^- and NH_4^+ uptake made from 1999 to 2003 with the stable isotopic tracer ^{15}N revealed that NO_3^- uptake rarely occurs in the North Bay, a result of high ambient NH_4^+ concentrations that inhibit uptake of NO_3^- by the phytoplankton (Figure 5.6.9 upper panel).

High NH_4^+ inputs to the estuary resulted from the conver-

sion of sewage treatment from primary to secondary in the early 1980s with the result that now spring phytoplankton blooms occur only in years when NH_4^+ concentrations decline to about $4 \mu\text{M-N}$ or less (Dugdale et al. 2007) and the available NO_3^- can then be taken up at

higher rates than for NH_4^+ (Figure 5.6.9 lower panel) with maximal levels of chlorophyll *a* accumulation. For blooms to occur in North Bay, favorable irradiance conditions are required to reduce NH_4^+ concentrations to non-inhibiting levels and then allow rapid NO_3^- uptake. Because NO_3^-

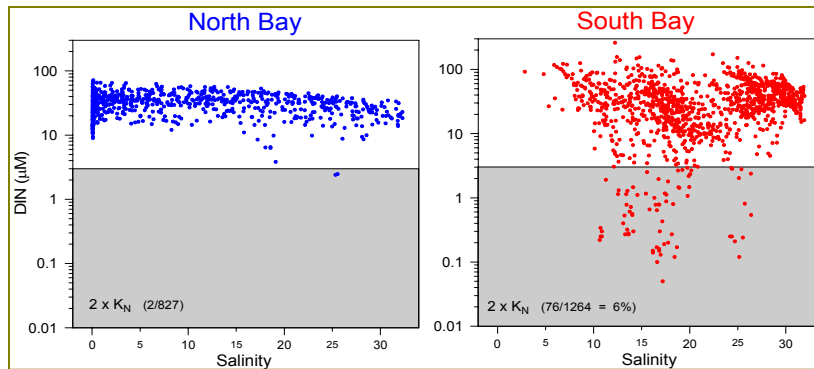


Figure 5.6.5. Near-surface DIN concentration versus salinity in North and South Bay. Data shown are all measurements made by USGS, 1988–2000. The gray rectangle indicates potential N limitation.

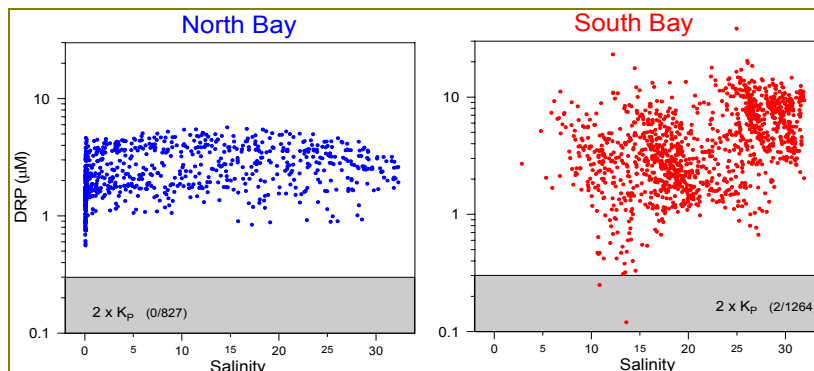


Figure 5.6.6. Near-surface DRP (PO_4^{3-}) concentration versus salinity in North and South Bay. Data shown are all measurements made by USGS, 1988–2000. The gray rectangle indicates potential P limitation.

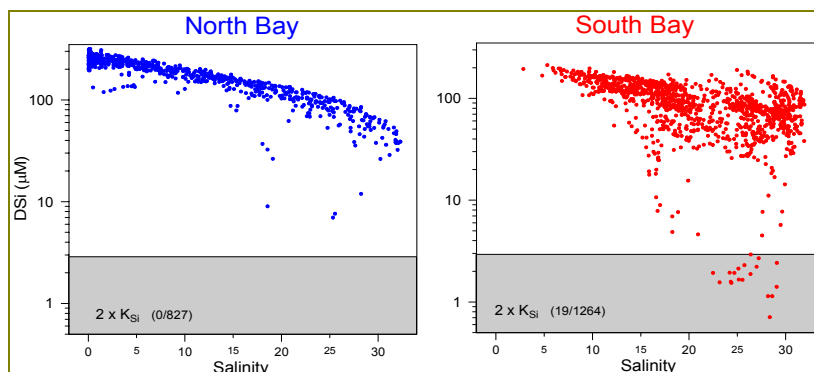


Figure 5.6.7. Near-surface $\text{Si}(\text{OH})_4$ (DSi) concentration versus salinity in North and South Bay. Data shown are all measurements made by USGS, 1988–2000. The gray rectangle indicates potential Si limitation.

is present in concentrations higher than NH_4^+ by a factor of up to 10, phytoplankton or chlorophyll *a* accumulation on NH_4^+ only will be comparatively weak. Growth rates on NH_4^+ are also only 50 percent of that on NO_3^- in those measurements (Figure 5.6.9). The high NH_4^+ concentrations reduce the frequency and size of blooms and the rate of primary production (Dugdale et al. 2007), a condition that becomes more severe as NH_4^+ increases toward the head of the estuary (Figure 5.6.8).

Chlorophyll and Primary Production

The Sacramento-San Joaquin Delta and North and South San Francisco Bay have each experienced large and ecologically important changes in chlorophyll *a* concentrations and seasonal patterns over the past three decades. As a result of a multidecadal trend of chlorophyll *a* decrease, primary production in the delta is very low ($\sim 75 \text{ g C m}^{-2}$) and declined > 40 percent between 1975 and 1995 (Jassby et al. 2002). Low primary production is considered a contributing factor to declining stocks of zooplankton and planktivorous fish, including native species listed as threatened or endangered, and the CALFED Ecosystem Restoration Program is considering actions to aug-

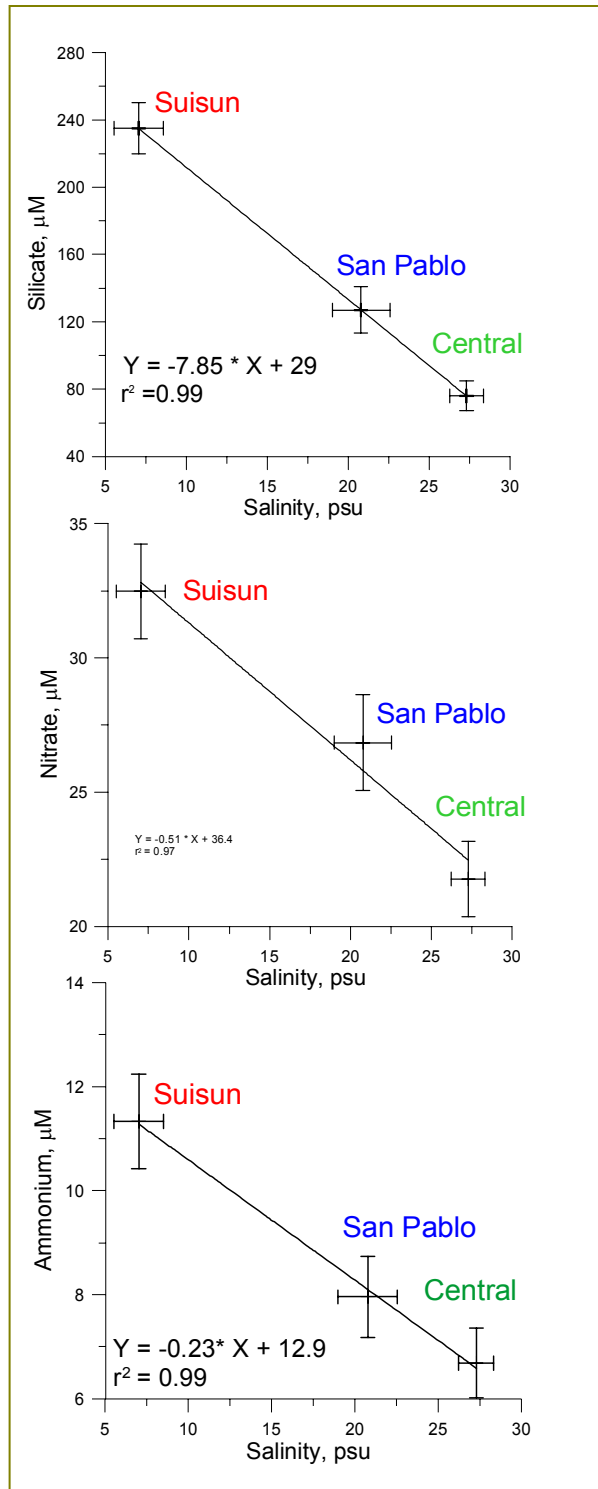


Figure 5.6.8. Mean nutrient concentrations, μM (\pm standard error of mean) for Suisun, San Pablo and Central bays versus mean salinity for 1999–2003 for the winter months (December, January, February): (top panel) $\text{Si}(\text{OH})_4$, (center) NO_3^- , (bottom) NH_4^+ showing higher concentrations at the head of the bay. From Wilkerson et al. 2006.

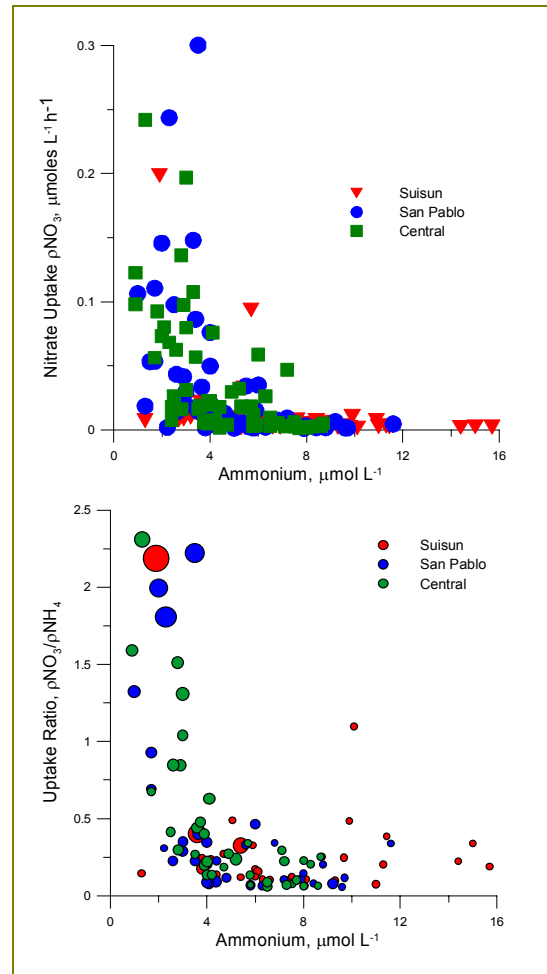


Figure 5.6.9. (Top panel) Saturated NO_3^- uptake, μNO_3^- , $\mu\text{M h}^{-1}$ versus NH_4^+ concentration, $\mu\text{M-N}$ for Suisun, San Pablo and Central Bays and (bottom) ratio of saturated NO_3^- to NH_4^+ uptake, $\text{pNO}_3^-:\text{pNH}_4^+$ versus NH_4^+ . The points in the graph are shown as bubbles that indicate higher chlorophyll a concentrations with high NO_3^- uptake and low NH_4^+ values. From Dugdale et al. 2007.

ment the phytoplankton food supply to consumers (Lopez et al. 2006). Management goals to amplify phytoplankton production in the nutrient-rich delta provide an instructive contrast to management goals of reducing phytoplankton biomass in estuaries where nutrient enrichment has stimulated excessive algal production.

The phytoplankton seasonal cycle in the oligohaline North Bay (Suisun Bay) was historically characterized by

a large summer bloom, with variations of the annual cycle by hydrologic extremes such as the record high discharge of 1983 and record drought of 1977 (Figure 5.6.10). That pattern ended abruptly in 1987 as Suisun Bay became rapidly and densely colonized by the non-native clam *Corbula amurensis*. Phytoplankton primary production was low ($\sim 100 \text{ g C m}^{-2}$) in Suisun Bay before that invasion, but it was reduced five-fold after the non-native filter feeder prevented development of the summer bloom (Alpine and Cloern 1992). Reduced primary production has led to collapse of the pelagic food web, with near extinction of the estuarine copepod *Eurytemora affinis* and native mysid *Neomysis mercedis* (Orsi and Mecum 1996).

Uptake rates of NH_4^+ in Suisun Bay are lower than in the other two northern embayments. The presence of a chemical toxin has been suggested by experiments in which inoculated phytoplankton failed to grow in Suisun water but grew in San Pablo and Central Bay water. The low NH_4^+ uptake rates combined with the highest NH_4^+ concentrations in the North Bay, indicate a low probability of a bloom in Suisun Bay.

The seasonal pattern in South Bay has historically (1977 to 1998) been characterized by a spring (March to April)

bloom followed by persistent low chlorophyll *a* and high nutrient concentrations. This pattern changed in 1999 when new autumn-winter blooms occurred and a trend of increasing autumn-winter chlorophyll *a* began (Figure 5.6.11). The underlying cause(s) of the regime change in South Bay is unknown, but the contemporaneous trends of phytoplankton decrease in North Bay and increase in South Bay illustrate the complexity of estuarine phytoplankton dynamics and their nonuniform response to nutrient enrichment.

Phytoplankton Blooms and Species Composition

Phytoplankton biomass in San Francisco Bay is overwhelmingly (> 80 percent) dominated by diatoms, primarily because of their importance during spring blooms (Cloern and Dufford 2005). Spring blooms are episodes of population growth by marine taxa, many of which develop in the adjacent California Current upwelling system, such as *Coscinodiscus* spp., *Thalassiosira* spp., *Chaetoceros* spp. and *Skeletonema* spp. Other common diatom taxa include benthic forms, such as *Paralia sulcata*, *Gyrosigma* spp. and *Pleurosigma* spp., indicating suspension into the plankton of cells produced on the mudflats. Dinoflagellates (e.g., *Akashiwo sanguinea*, *Heterocapsa triquetra*, *Prorocentrum minimum*, *Alexan-*

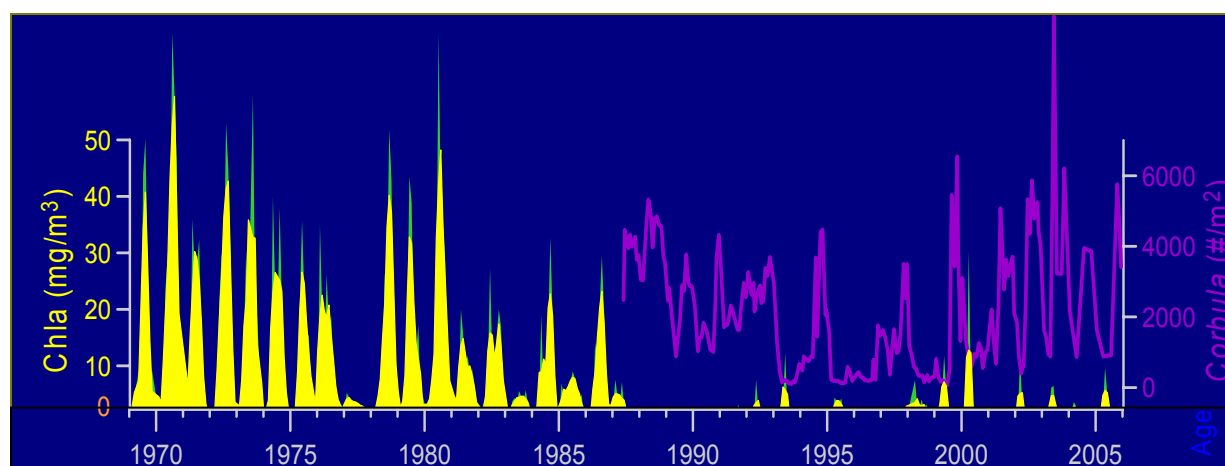


Figure 5.6.10. Time series of chlorophyll *a* concentration (yellow) and abundance of the alien clam *Corbula amurensis* (purple) in Suisun Bay. Data are from the Interagency Ecological Program (<http://bdat.ca.gov/>).

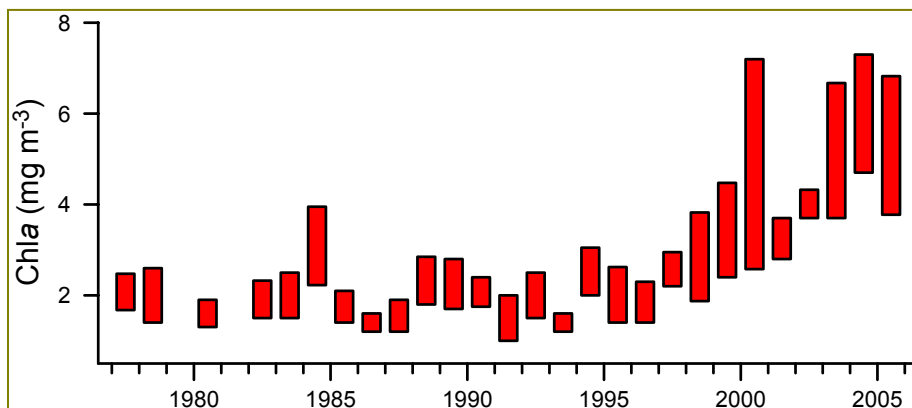


Figure 5.6.11. Interquartile ranges of surface chlorophyll a in South Bay during August–December, showing significant trends of increase after 1998.

drium spp. and *Protoperdinium* spp.) compose 11 percent of overall phytoplankton biomass, and some of those taxa are also commonly found in the California current following relaxation of upwelling. Cryptophytes, which compose 5 percent of overall biomass, are widely distributed in time and space but do not dominate blooms. Picocyanobacteria, primarily *Synechococcus*, constitute a small component of phytoplankton biomass in San Francisco Bay, consistent with the generality that phytoplankton biomass is dominated by large cells in high-nutrient pelagic habitats (Ning et al. 2000). Cole et al. (1986) measured size-fractionated biomass and primary production every 2 weeks at a shallow and deep site in Suisun, San Pablo and South bays and determined large cells to be the most important fraction of phytoplankton across the estuary. Wilkerson et al. (2006) measured fractionated chlorophyll *a* and N productivity and similarly found phytoplankton in San Francisco Bay to be mostly cells > 5 μm and > 10 μm in diameter.

The plankton of San Francisco Bay includes many species that have produced toxic or harmful blooms elsewhere, but there are no documented occurrences of HAB events causing human illness or mortality of fish or shellfish. Visible blooms of *Mesodinium rubrum* occur during years of high runoff (Cloern et al. 1994), but they are benign and perhaps beneficial to consumers. Episodic red tides of *Heterosigma akashiwo*, *Alexandrium* spp.,

and *Akashiwo sanguinea* have been observed in recent years, but each seems to have been triggered by events in the coastal Pacific that propagated into the estuary. Evidence suggests that water and habitat quality in the freshwater delta have been impaired in recent years by blooms of the toxic cyanobacterium *Microcystis*

aeruginosa (Lehman et al. 2005).

Benthic Primary Producers

As a contrast to many estuaries of the U.S. East Coast, San Francisco Bay does not provide habitat for SAV because of its high turbidity and muddy, mobile bottom. However, intertidal mudflats provide large habitat surface for benthic microalgae. Primary production by that community has not been measured systematically, but estimates based on habitat area and seasonal rate measurements indicate that the benthic microalgae contribute about one-third of total primary production in San Francisco Bay (Jassby et al. 1993; Guarini et al. 2002).

Long-Term Changes

San Francisco Bay has been described as the world's *most invaded estuary* with more than 230 nonnative species (Cohen and Carlton 1998), many of which have caused major ecological disturbance. The biomass of benthic invertebrates is dominated by nonnative species (Nichols et al. 1986), the mesozooplankton community has been transformed by nonnative species several times over the past three decades (Kimmerer and Orsi 1996; Hooff and Bollens 2004), and competition/predation by introduced freshwater fish is a contributing factor to the long-term declines of native species in the delta and Suisun Bay (http://science.calwater.ca.gov/pod/pod_synthesis.html). Sustainability of native fauna

has also been compromised by habitat loss, inputs of toxic contaminants (emerging pesticides such as pyrethroids, selenium, heavy metals), legacy contaminants (PCBs, mercury), and water diversions that export up to 80 percent of the freshwater inflow to the Delta and San Francisco Bay. Those stressors and their interactions have caused decreased abundance and complexity of indigenous biological communities in San Francisco Bay and its river delta. Although nutrient enrichment has clearly caused comparable disturbance of other estuaries around the world, and San Francisco Bay has clearly become enriched with N and P as a result of human activities, the ecological consequences of enriching this estuary are not well established. However, a correlation appears between increased NH_4^+ concentration with reduced primary productivity, observed also in the Delaware Estuary (Yoshiyama and Sharp 2006). The recent occurrences of dinoflagellate red tides, altered seasonality of phytoplankton and significant trends of chlorophyll a increase in South Bay suggest the possibility that the estuary's apparent resistance to the harmful consequences of enrichment might be changing.

Summary of Ecosystem Impacts

San Francisco Bay presents a valuable contrast to other nutrient-enriched estuaries because its phytoplankton biomass is highly variable in time and space, but only some of that variability can be attributed to changing nutrient availability. The persistence of high nutrient concentrations during the past decades of phytoplankton increase in South Bay and decrease in North Bay implies that phytoplankton dynamics in this estuary are driven by processes other than simple nutrient regulation of growth rate. However, the persistent high nutrient concentrations are in part the result of increased NH_4^+ concentrations, reducing phytoplankton use of NO_3^- and reducing phytoplankton growth rates. In considering anthropogenic impacts on estuaries, it is important to distinguish between what might be called intrinsic limitations, i.e., that which would be in place and controlling ecosystem

characteristics historically, and anthropogenic factors superimposed on intrinsic limitations. For example, the well-demonstrated intrinsic limitation in San Francisco Bay is the ambient turbidity and its effect on the irradiance field, relegating the estuary to a low position in the productivity hierarchy of estuaries. The high NH_4^+ concentrations that probably resulted from changes in treatment practices impose a further reduction in primary productivity and increased variability.

Sustained research in San Francisco Bay has documented the importance of (1) top-down control by benthic suspension feeders (Cloern 1982; Lopez et al. 2006); (2) salinity stratification on neap tides that induces blooms by retaining phytoplankton cells in a high-light, high-nutrient, surface layer and isolating them from benthic consumers (Cloern 1991); (3) net, tidal-residual currents that transport phytoplankton between habitats that function as net sources and sinks of algal biomass (Lucas et al. 1999); (4) connectivity to the Pacific Ocean as a source of phytoplankton cells that can seed blooms within the estuary (Cloern et al. 2005); (5) high turbidity as a constraint on phytoplankton growth rate such that the large pool of dissolved inorganic nutrients is not fully assimilated into biomass (Alpine and Cloern 1988; Cloern 1999); and (6) interactions between the diel light and semidiurnal tidal cycles that determine whether light exposure is sufficient to sustain blooms (Lucas and Cloern 2002). Recent studies have documented (1) the importance of high NH_4^+ inputs in reducing the frequency and intensity of spring blooms through inhibition of NO_3^- uptake; (2) the necessity for periods of favorable irradiance conditions about 5 days for bloom initiation; and (3) the suggestion that in Suisun Bay, primary productivity is additionally impaired by undetermined chemical inhibitors.

San Francisco Bay receives comparable areal loadings of N and even larger loadings of P than the Chesapeake Bay, but it has much lower phytoplankton biomass and primary production. That contrast exemplifies the vari-

ability across estuaries in their response to nutrient enrichment (Cloern 2001), it also highlights the importance of studying and managing eutrophication in the context of all processes that regulate the efficiency with which estuarine ecosystems convert exogenous nutrients into algal biomass.

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