San Francisco Bay (Suisun Bay) Food Web Index

INDICATOR ANALYSIS AND EVALUATION

A. Overview

San Francisco Bay, the largest estuary on the west coast, supports a variety of lower trophic level species that depict patterns of abundance and composition reflecting estuarine conditions. Physical and chemical factors such as the amounts and timing of freshwater inflows, sediment inputs, and water pollution levels influence the quality and productivity of phytoplankton which fuels aquatic food webs. Zooplankton consume phytoplankton and ultimately support upper trophic levels[1] including fish and bird communities (Figure 1). Factors such as dams and diversions, water pollution and invasive species (not included in this figure) have changed the composition of the lower food web and resulted in an overall decline in productivity.

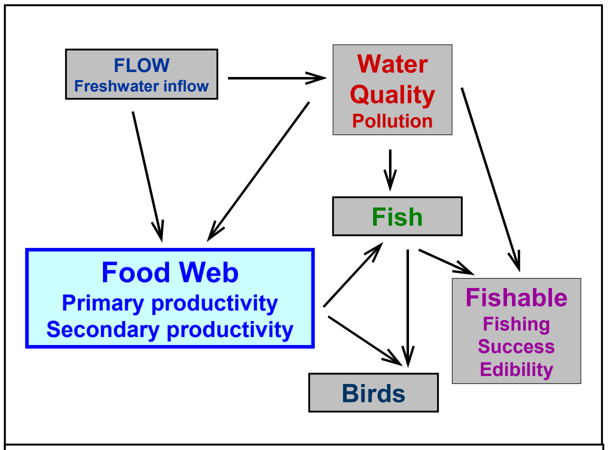

Figure 1: The food web as defined by primary and secondary production is affected by the amounts and timing of freshwater inflow, sediment inputs, pollutants, and invasive species introductions. This in turn affects fish, birds and the human uses that depend on these species.

The San Francisco estuary is actually a series of bays that extend from the confluence of the Sacramento and San Joaquin River systems and their associated shoreline habitats. Unfortunately zooplankton in the Bay are not sampled across the entire region on an annual and seasonal basis. The *Neomysis* Zooplankton Study is the longest term, most comprehensive study, initiated by the California Department of Fish and Game and includes stations from the mouths of the Sacramento and San Joaquin Rivers to San Pablo Bay. The "**Food Web Index"**, assesses the integrity of the lower trophic levels of the pelagic food web. It measures changes in the abundance and composition of the zooplankton that use Suisun Bay, the western most Bay in the San Francisco Bay region for nearly 30 years. It also includes measurements that affect zooplankton productivity including chlorophyll *a*, a widely accepted indicator phytoplankton production in aquatic systems. The indicators include:

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[1] Trophic level - the position an organism occupies in a foodweb. The lower trophic levels refer to plants, occupying the first trophic level, herbivores, the second and perhaps a tertiary level (ie., planktivorous invertebrate or fish).

San Francisco Bay Food Web Index **INDICATORS**	
Phytoplankton (Chlorophyll *a)*	a measure of phytoplankton biomass ("algal production")
Rotifer Abundance	Population abundance of the smallest zooplankton species (commonly measured) that use the Bay
% Native Copepod Abundance	Percentage of total copepods that are known to be native species
Native Mysid, *Neomysis*	Population abundance of a native mysid, ***Neomysis mercedis***, important food for fish
Average Zooplankton "Size"	Annual average weight of zooplankton (copepods and cladocerans) – an indicator of prey for fish

B. Rationale and conceptual model

Phytoplankton and zooplankton species are critical components of the San Francisco Bay Estuary food web. As in most aquatic systems, zooplankton transfer energy from primary (phytoplankton) and bacterial production to higher aquatic invertebrates and fish populations. In the Bay, they are food for key fish species such as Delta smelt, striped bass and juvenile salmon; responding to top-down effects reflecting the health of the bay fish population, in addition to bottom-up effects stemming from changes in phytoplankton and micro-zooplankton production. Zooplankton are early sentinels of ecosystem stress. They are small organisms with short life cycles, which respond more rapidly than fish populations to changing estuarine conditions.

The utilization of biological monitoring in assessing ecosystem integrity has received more attention in recent years. There is increasing interest in adapting the techniques used to develop Indices of Biotic Integrity (IBI) for stream systems to estuarine fauna (Deegan et. al. 1997; Weisberg et. al. 1997) and zooplankton in lakes and wetlands (Loughheed and Fraser 2002; Stemberger et. al. 2001). Also there is movement away from the use of indicator species and the realization that the combination of several metrics improves the robustness of the index and provides multiple lines of evidence, illustrating more readily change due to anthropogenic impacts (Karr and Chu 1996). Despite the long history of zooplankton ecological studies nationally and internationally and the use of phytoplankton and zooplankton biomass measures of indicators of eutrophication, there have been few attempts to develop multimetric zooplankton indexes to measure ecosystem health on regional scales (Loughheed and Fraser 2002; Stemberger et. al. 2001). The techniques used to develop IBI's in other systems can be adapted to develop an index of lower trophic level integrity for the San Francisco Bay Region.

The process of constructing a multimetric index requires a full exploration of available data. Though the exact cause of population fluctuations in abundance and distribution of any taxonomic group may not be readily apparent from field surveys; a well-constructed multimetric index uses a weight of evidence approach by establishing which trends appear to reflect long-term changes due to anthropogenic impacts. For San Francisco Bay, there is literature, summarizing changes in the zooplankton community over time; that provides insights into possible causes of change (e.g., Kimmerer and Orsi, 1996. Orsi and Mecum, 1996). Much of this literature stems from one study, the *Neomysis* Zooplankton Study, initiated by the California Department of Fish and Game that includes stations from the mouths of the Sacramento and San Joaquin Rivers to San Pablo Bay.

The food web indicators address hypotheses about lower trophic level relationships in the San Francisco Estuary. The hypothesized stressor based food web model (Figure 2) depicts generalized Suisun Bay food web relationships. It illustrates how flows in the upper watershed affect sediment transport, light penetration and ultimately primary and secondary production. Meanwhile water quality influences productivity through toxic effects and exotic species through competition and predation. Figure 3 provides additional specificity by showing food web linkages and how these components may have been affected by the stressors listed on the left. These stressors are hypothesized to act in concert to create an unstable food web with declining production at numerous levels. Changes in phytoplankton and zooplankton size structure and composition is measured by evaluating key food web indicators. The Food web index is generalized enough to be useful should alternative hypotheses be developed and can be adapted to other estuarine systems.

Figure 2: The generalized food web on the right, illustrates how flows affect sediment transport, light penetration and ultimately primary and secondary production. Meanwhile water quality influences productivity through toxic effects and exotic species through competition and predation. The Scorecard Indexes are in bold, illustrating their relationship to the Food Web Index.

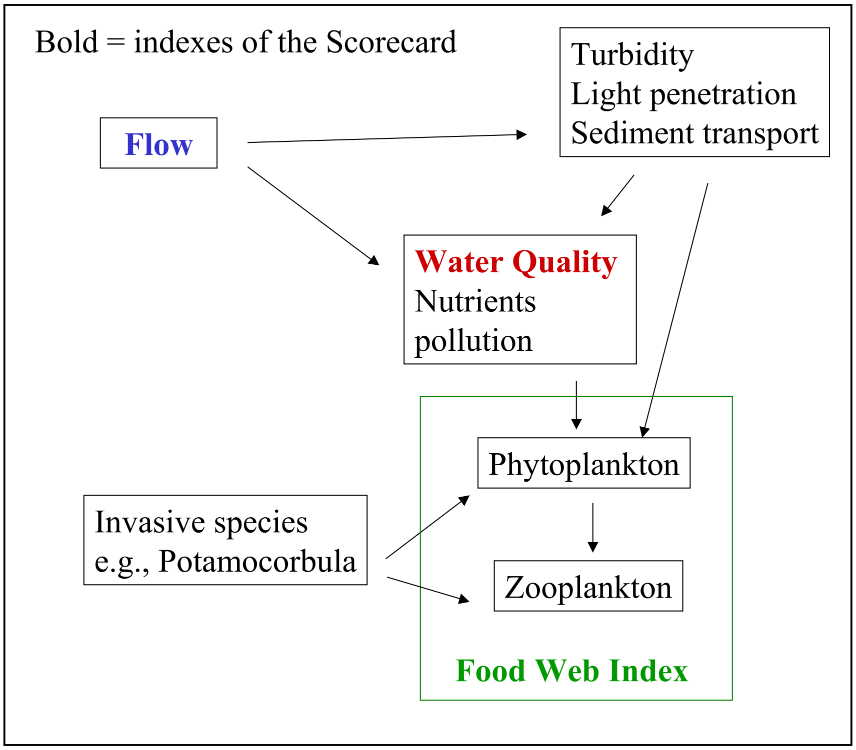
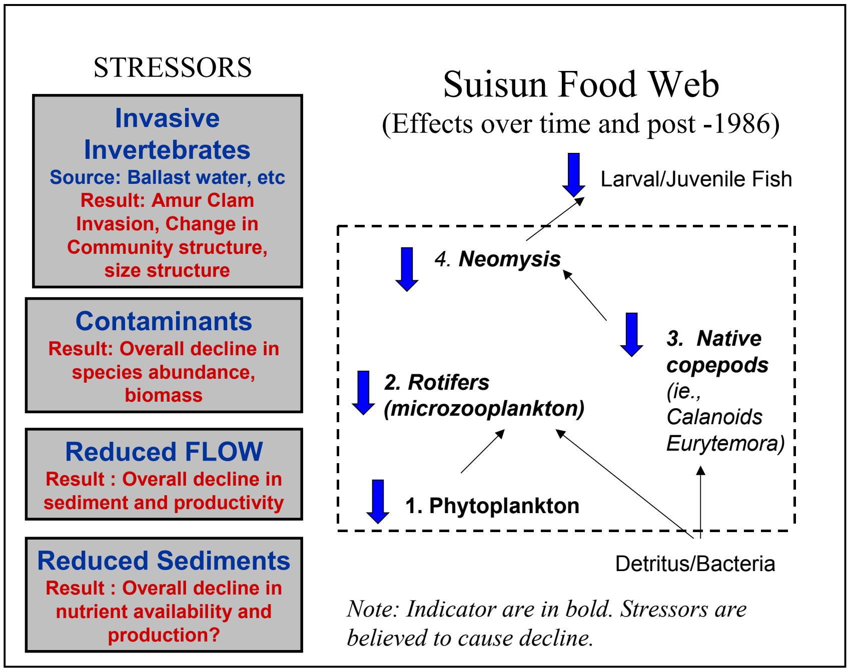


Figure 3: The boxes on the left of this figure, illustrate the primary stressors that have impacted the Suisun Bay food web and the hypothesized result. These are ongoing problems throughout the Bay; however, some stressors have depicted spikes in their effect, such as the invasion of *Potamocorbula*, the exotic clam in 1986. The hypothesized cumulative effects of these stressors on the food web is illustrated as a decline in each of the components (blue arrows).



In addition to improving our understanding of lower trophic food web structure, the monitoring of pelagic zooplankton populations provides important information about the status of native zooplankton species. For example, in Suisun Bay, *Neomysis mercedis* is one of the largest components of the zooplankton fauna, and is highly regarded as an excellent food source for many fish species, including Delta smelt and striped bass. The Habitat Goals process also identified this species as an important indicator species. The food web index measures changes in the abundance of *Neomysis mercedis* because of its role as a key component of the historic food web.

Zooplankton monitoring also provides important information on the status of *non-native plankton* species. In the Bay Area, non-native species introductions have changed the marine environment so much that scientists despair of ever returning the Bay to its original condition. New species arrive not only in ballast water, but on fouled ship hulls, and through aquaculture, bait fish shipments, and deliberate introductions of species used for food in other parts of the world or originally acquired for aquarium use (Bay Area Monitor, March-April 2003). In June 1999, the Port of Oakland became the first major US West Coast container port to restrict the discharge of ballast water originating in foreign ports, a measure taken to decrease the introduction of potentially invasive, non-native species to the waters of San Francisco Bay *(Bay Area Monitor, December-January 2003).* Many of the invaders are components of the pelagic plankton during some or all of their life cycle. The zooplankton index measures changes in the abundance of native species as one measure of the efficacy of the implementation of ballast water and other regulations affecting planktonic non-native species.

C. Data Sources:

<u>Chlorophyll and Zooplankton</u>: The chlorophyll and zooplankton data for the Food Web Index are collected by the *Neomysis* and Zooplankton Sampling Program conducted in Suisun Bay once per month in January and February and twice per month from March to November. The zooplankton portion of this survey has occurred since 1974 using a Clarke-Bumpus net and a pump –and the *Neomysis* sampling began in 1972. Chlorophyll measurements are also included in the study; however, chlorophyll was not sampled until 1976 (Orsi, metadata Accessed 2003 http://www.iep.ca.gov/neozoop/doc.html). Sampling methods and processing is discussed in more depth in Orsi and Mecum 1996. To minimize interpolation of this data set between sites that are not routinely sampled, six long term stations (see Figure 4a – orange points in box) that were sampled approximately biweekly in Suisun Bay to the west Delta were chosen for this analysis.

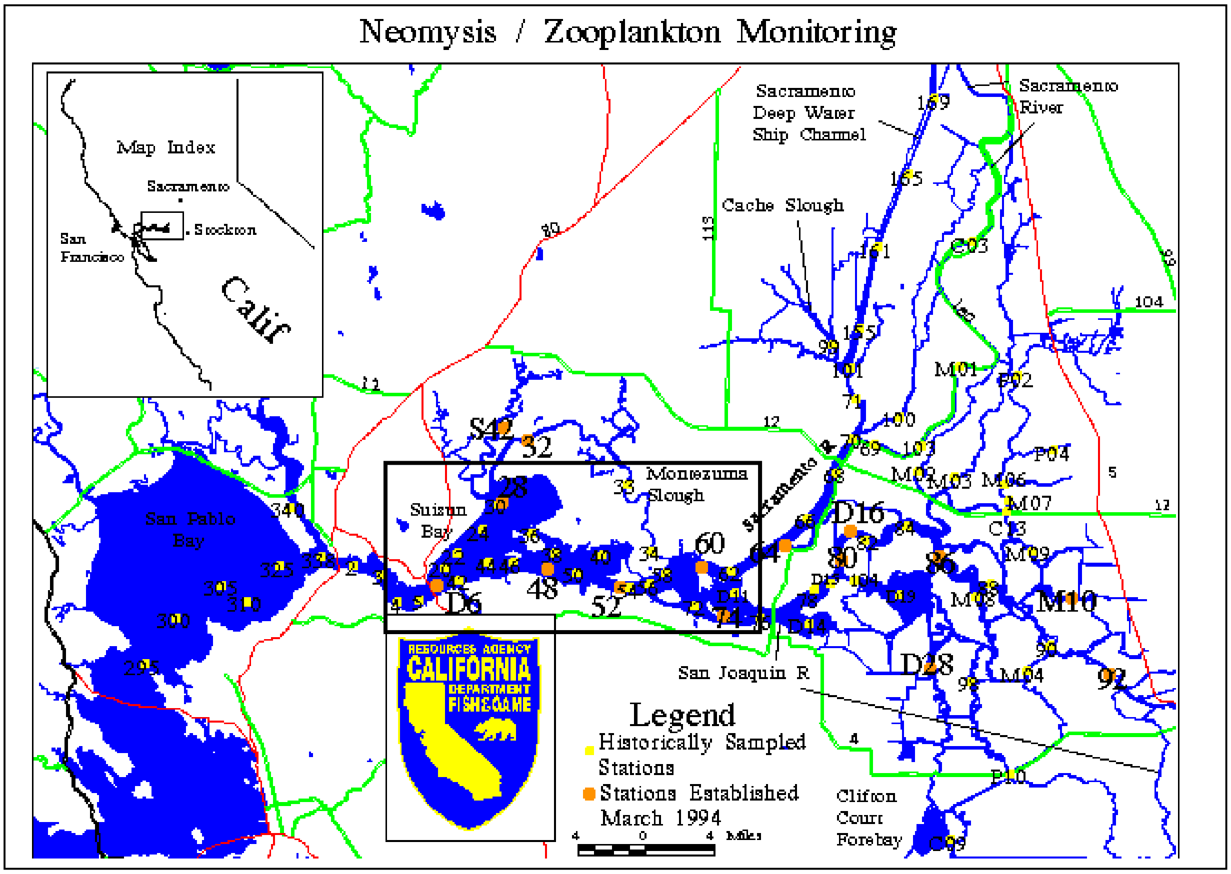


Figure 4a: The *Neomysis* and Zooplankton Sampling Program performed by the Department of Fish and Game (Interagency Ecological Program) samples the Estuary throughout the year. Orange dots included in the boxed area represent long term monitoring stations used in this analysis. *Figure courtesy of the Department of Fish and Game.*

Field and zooplankton data provided by Lee Mecum of the Department of Fish and Game were input into Microsoft Access and queries were constructed to explore abundance and trends of chlorophyll *a*, several taxanomic groups and specific species. Weight estimates for selected species was also obtained from Jim Orsi, (Department of Fish and Game retired). Indicators were chosen upon evaluation of the data and available literature. Indicator selection criteria are explained more fully in the Scorecard Overview; but generally indicators were selected based on their ecological and management relevance, statistical responsiveness to anthropogenic stress, their ability to summarize influences and be understood, and their ability to be tracked and maintained over an historical time frame into the future.

Potamocorbula: Benthic data from the Department of Water Resources' Environmental Monitoring Program, Benthic Survey was used to obtain historical trends for *Potamocorbula,* a species that has been shown to have major impacts on estuarine productivity (Kimmerer and Orsi 1996; Thompson 2000). The survey has been conducted from 1975 to the present. The number of stations sampled per year has varied over the course of the survey, as some stations were dropped from the sampling program and others added over time. Currently five stations are monitored in Suisun to San Pablo Bay, on a regular basis. D4 and D7 have been sampled since the program was initiated (See Figure 4b). These stations were queried using ACCESS to construct a long-term trend for *Potamocorbula*. The database was also queried for trends in other benthic species to ensure that this species depicted the most significant historical trend.

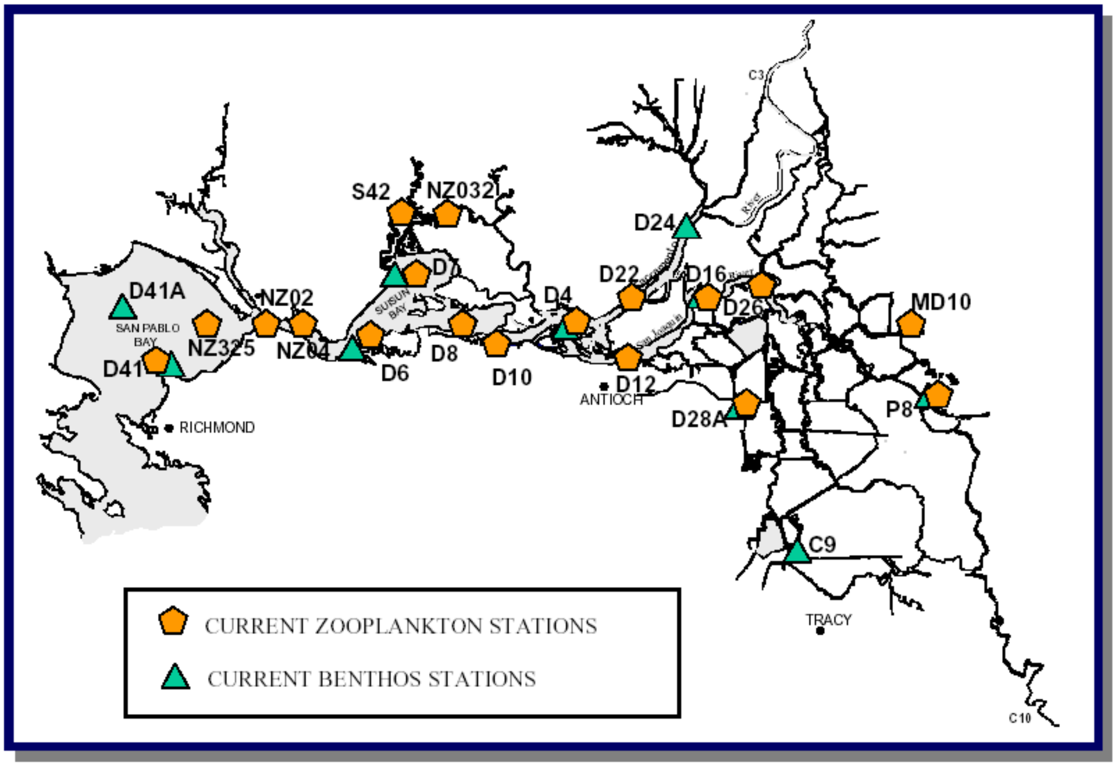


Figure 4b: Suisun region and San Pablo Bay benthic monitoring stations were included in the analysis: D4, D6, D7,D41A and D41. Stations, D4 and D7 were the only stations sampled since the program began in 1975. (Figure courtesy of the Department of Water Resources.)

D. Indicator Analysis:

1. Phytoplankton

Chlorophyll *a* is a measure of phytoplankton biomass. Phytoplankton are microscopic single-celled algae that drift with the currents in estuarine aquatic habitats. They are an important high-quality source of energy to consumers, primarily small herbivorous zooplankton. Phytoplankton growth tends to be limited by light, temperature, nutrients, grazing, and high levels of contaminants. Problems can result from large changes in phytoplankton abundance. For example, excessive reproduction of phytoplankton, usually caused by enhanced levels of nutrients, results in algal blooms. These blooms can exert a high oxygen demand through nocturnal respiration and decomposition following phytoplankton cell death. The oxygen depletion of the water accompanying excessive blooms can suffocate other aquatic organisms and generally degrade the environment. Conversely, a shortage of phytoplankton depletes the food supply of primary and higher consumers such as zooplankton, oysters, shrimp, fish, and birds.

In San Francisco Bay as a whole, algal blooms are generally not considered as problematic as the shortage of phytoplankton to fuel the food web. Because the Bay is turbid, zooplankton, mysid shrimp and clams are usually food limited (Cloern 1996).
In Suisun and San Pablo Bay, where the most information is available, this is particularly true.

Methods and Calculations:

The phytoplankton indicator is the average annual Chlorophyll *a* measured in ug/l. Chlorophyll *a* was measured by filtering samples and extracting chlorophyll from phytoplankton cells collected on a filter. Additional information on chlorophyll for other parts of the Bay was obtained from published literature sources (see below).

Results:

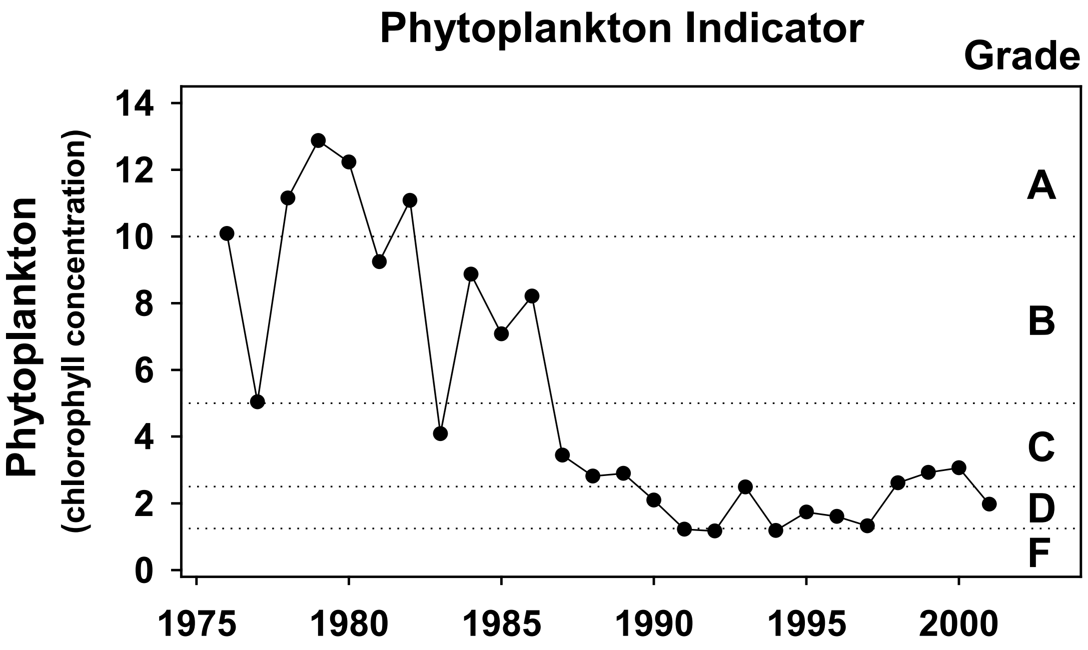


Figure 5. Phytoplankton Indicator from 1976-2001 as determined from chlorophyll measurements taken by the California Department of Fish and Game, concurrent with the *Neomysis* Zooplankton Survey. Average annual chlorophyll levels were 10.27 ug/l from 1976-1980 compared to 2.38 ug/l from 1997-2001. This represents a five-fold decrease in chlorophyll.

		Trends	
Chlorophyll *a*	Grade	Long term 1976-2001	Short-term recent 5 year
In 2001, chlorophyll < 23% of mean 1976-1980 values	D	↓ declining	↔ stable, but low levels

Key Findings:

Average chlorophyll levels were 10.27 ug/l from 1976-1980 compared to 2.38 ug/l from 1997 -2001. This represents a five-fold decrease in chlorophyll *a*.

As Figure 5 above illustrates chlorophyll *a* has declined significantly ($p < .05$) from the late 1970's to the most recent five-year period (1997-2001). This pattern was also substantiated by an analysis of USGS data (see figure 6 below from Cloern (2003). The annual averages from the last five years of sampling, shows chlorophyll at slightly fluctuating but low levels.

Declines in chlorophyll in Suisun Bay were pronounced after 1987 and appear to be correlated with the introduction of *Potamocorbula,* the invasive overbite clam.

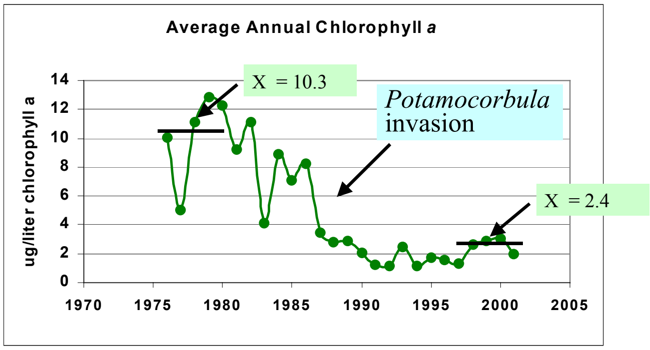


Figure 5a. Changes in the Chlorophyll *a* Indicator from 1976-2001 as determined from chlorophyll measurements taken by the Department of Fish and Game, concurrent with the Neomysis Zooplankton Survey. Average chlorophyll levels were 10.27 ug/l from 1976-1980 compared to 2.38 ug/l from 1997-2001. This represents a five-fold decrease in chlorophyll.

The beginning of the decline in chlorophyll *a* may have slightly predated the *Potamocorbula* invasion (Figure 5a); however benthic measurements during this period were not available. The two incidents are highly correlated and experiments with *Potamocorbula* note filtration rates high enough to filter the water column several times in a day at current population estimates (Thompson, 2000). Continued monitoring and analysis are needed to indicate whether other factors are responsible for the chlorophyll decline and whether the trend can be reversed.

Potamocorbula, an invasive benthic clam has increased dramatically since 1986 and remains at high densities.

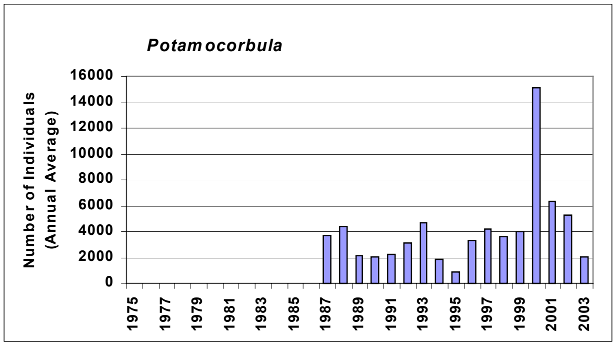


Figure 6: The Amur or overbite clam, Potamocorbula invaded the estuary in 1986. The number of individuals per sample has remained at high levels despite subsequent high flow events. Benthic data courtesy of Department of Water Resources Environmental Monitoring Program.

Benthic communities change with natural disturbances, such as high flow events and changing salinity conditions. However, natural disturbances can be intensified by anthropogenic disturbances that enhance invasion opportunities. For example, a high flow event is believed to have reduced the native clam population in the mid 1980's (Cohen and Carlton, 1998; Kimmerer and Orsi 1996). Following this event a severe drought occurred which was further enhanced reduce flow into Suisun Bay by water exports from the Delta. The denuded areas combined with brackish conditions, helped *Potamocorbula amurensis* invade areas where native clams once resided. *Potamocorbula* remains at very high densities and is believed to have had a significant impact on the pelagic food web.

San Francisco Bay is not very productive compared to most estuarine systems.

Production in Suisun Bay is low compared to most estuaries. The NOAA Coastal Assessment Framework process (1999) consulted with a core group of scientists to develop a scoring system to rank the eutrophication status of the nation's estuaries. Chlorophyll *a* is considered one of the three primary symptoms of eutrophication. Maximum surface water concentrations of >60ug/l chlorophyll are considered hypereutrophic, 20-60ug/l is high, 5-20 ug/l is medium, and 0-5 is low. The range of maximum chlorophyll values ranged from 20-67 ug/l during the first five years of the Suisun Bay study and from 5-30 ug/l during the latter five years. As the figure 6 shows, Suisun Bay has gone from a high level trophic status to a low to medium condition in the last three decades.

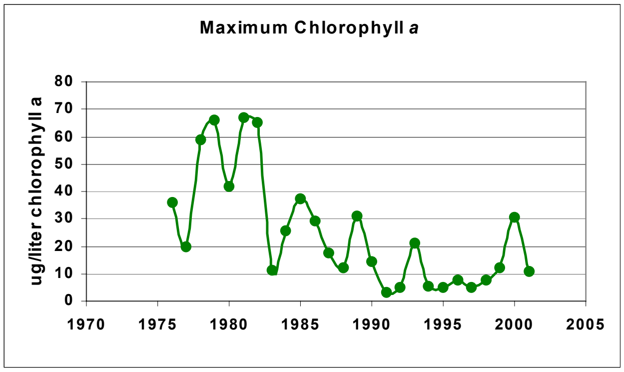


Figure 7: Maximum chlorophyll levels also declined during the sampling period. Maximum levels of chlorophyll represent times when there are blooms. Since 1986, the maximum chlorophyll never exceeds 35 ug/l, which is considered mesotrophic by most estuarine standards. Generally values are in the low range.

San Francisco Bay is a highly turbid system so phytoplankton production is predominantly a function of light (Cole and Cloern 1984, 1987, Cloern 1996). Recently investigators have pointed to the possibility that declining levels of sediment could affect primary production (See Habitat Index-mudflats; Williams 2003). If sediment levels decline to such a degree that light becomes less limiting to phytoplankton growth rates, primary production could increase. However, in the brackish portions of the Bay where *Potamocorbula* is abundant, this shift may not necessarily surpass the ability of *Potamocorbula* to graze phytoplankton and limit primary production to the pelagic food web. This relationship is complex for it depends on multiple interacting factors.

Chlorophyll patterns in the estuary vary by sub-region and location.

Though there was a decline in Suisun Bay and San Pablo Bay productivity, this has not been observed throughout all portions of the Bay. Suisun Bay exhibited a decline in chlorophyll (Figures 5,7); however, other portions of the Bay are generally more stable (Kimmerer, 2003). In the South Bay for example, Cloern (2003) noted a shift in a twenty- year pattern of spring blooms to a bloom during the spring and in the fall to winter period.

Harmful algal blooms are a major problem in many estuaries around the world and may be on the rise nationwide (Coastlines 1998); however, to date the San Francisco Estuary has been affected infrequently (Kimmerer, *2003*).

Generally noxious algal blooms have not been a major problem in San Francisco Bay; however, there have been infrequent incidents of red tide that have caused shellfish fishery closures. In September 2002, 'red tide' caused by a species (*Heterosigma akashiwo,* was discovered. This species has never been observed before and its presence is reason for concern because it is associated with fish kills in Puget Sound and other coastal ecosystems (Cloern 2003). Causes of the bloom in San Francisco Bay are a mystery, but satellite imagery suggests that it may have originated offshore (Cloern 2003). In Suisun Bay and the Delta, blue green algae are the cause of harmful algal blooms (Lehman, pers. comm.). This phenomenon has not been well investigated, but could affect food web productivity in some unforeseen ways.

Evaluation and Grading:

Estimated average annual chlorophyll level for 1976-1980 (10.27) was set as the lower bound for the upper reference condition. We used the annual chlorophyll estimate, as this is believed to be a better determinant of overall annual biomass available to zooplankton and fish predation. For grading, the A-B break point was set at the 10 and each lower grade increment was set at 50% of the grade above. It should be noted that this upper baseline; could be an underestimate of historical chlorophyll levels prior to European habitation and the removal of the vast tule marshes that once existed. Also, if chlorophyll levels begin to approach high levels, a grading curve that takes into account extreme eutrophication should be instituted. Levels higher than 10, especially sudden changes could be signs of eutrophication and harmful algal blooms.

Reference condition	**Average chlorophyll (ug per liter)**	**Rationale for reference conditions**	**Ecological condition**	**Grade point**	**Grade**
Upper	>10	The average of the annual average chlorophyll measurements between 1976-1980 (10.3ug/l) is the upper reference condition. For grading, the A-B break point was set at the 10. Each lower grade increment was set at 50% of the grade above.	Excellent	4	A
	>5		Good	3	B
	>2.5		Fair	2	C
	>1.25		Poor	1	D
Lower	> 0		Very poor	0	F

2. Rotifer Abundance

Rotifers are the smallest zooplankton that are regularly sampled and are important components of the food web. Rotifers exert significant grazing pressure on phytoplankton; and more rotifers as components of the plankton could lead to higher trophic efficiencies. High assimilation efficiencies enable rotifers to convert a significant amount of food to animal biomass, passing higher levels of food up the food chain than larger macrocrustaceans (Bogdan and Gilbert 1982; Starkweather 1980, 1987). In addition, rotifers serve as good indicators of environmental water quality in laboratory investigations (Sladecek 1983); however, the extent to which the Suisun Bay plankton populations are impaired due to water quality has not been well studied.

Methods and Calculations:

The rotifer abundance indicator measures the composite population abundance of rotifers in the Bay. Abundance was calculated as [(# of individuals collected)/(cubic meter)] as annual means over the 28-year study. Mean annual abundance for the first five years of sampling were compared to annual means to obtain annual scores.

Results:

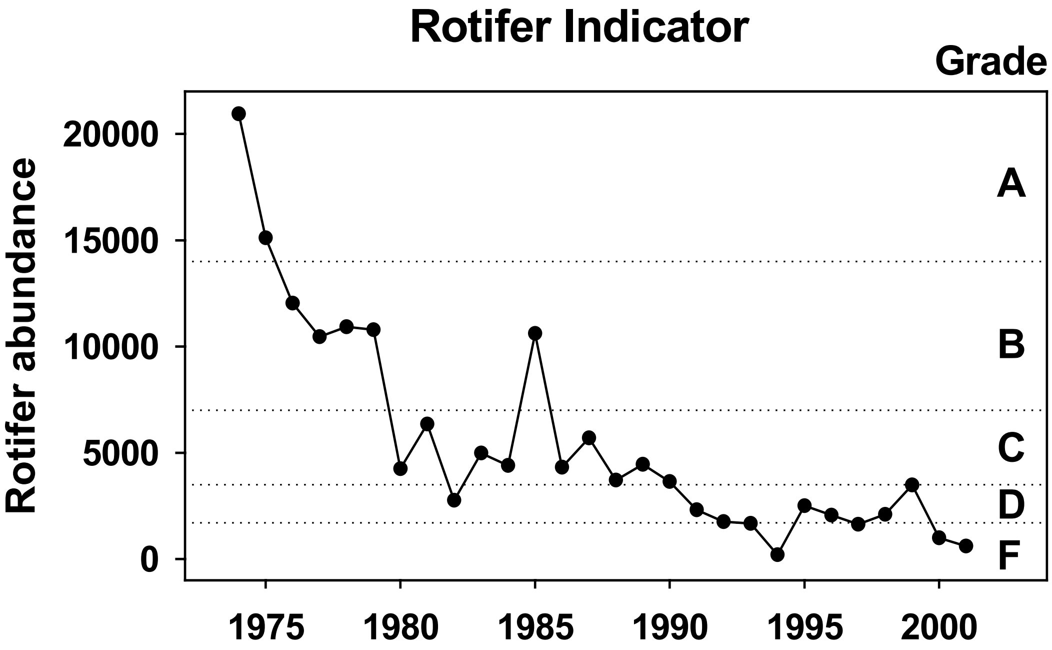


Figure 8: The Rotifer abundance Indicator measures the population size (individuals per cubic meter) of rotifer species collected by the CDFG Neomysis Zooplankton Survey, from 1974 to 2001. Rotifers, the smallest zooplankton routinely measured declined during the sampling period. During the last five years, the average number of Rotifers is less than 1.5% percent of the mean during the early sampling period (1974-1979).

Rotifers	Grade	Trends Long term 1976-2001	 Short-term recent 5 year
In 2001, Rotifers are 1.5% of mean 1974-1979 values	F	↓ declining	↓ declining

Key Findings:

Annual average abundance during the recent five-year period is less than 10% of levels during the first sampling period 25 to 30 years ago.

During the past five years (1997-2001), the average abundance of rotifers of 1024 (number of individuals per cubic meter) is less than 10% of the average rotifer abundance measured during the same survey in 1971-1975.

Abundance of rotifers has declined steadily

The abundance of rotifers declined steadily ($R^2=0.665$, $p<0.001$) during the sampling period. At its low point in 1994, abundance was 101 individual per cubic meter, compared to 20,942 in 1974, the first year of the Zooplankton survey. This period was followed by a decline in fish abundance in Suisun Bay (see Fish Index) and was preceded by increased diversion of water from the rivers that flow into the Bay and a prolonged drought (1987-1992) (see Bay Flow Index).

Since its low point in 1994, Rotifer populations have not increased

Since its low point, rotifer abundance has not significantly increased (regression, $p>0.98$). Rotifer abundance is correlated with declining chlorophyll *a* levels in Suisun Bay indicating a general decline in productivity over the system during the 25-year period for which data is available. The decline was pronounced in the early years of the study, and may have been further exacerbated by the invasion of a voracious Asian clam, *Potamocorbula* in 1986. In addition, Jassby (2002) noted a steady decline in Delta phytoplankton during winter months prior to the invasion of *Potamocorbula.*

Rotifer abundance decline in Suisun Bay is system-wide

Rotifer abundance has declined at a fairly consistent rate across the six long-term Suisun Bay stations. The only station in which the decline in rotifers was delayed was in the shallow water station, NZ32. There are several hypotheses for this pattern including: 1) productivity in the shallow water region is higher and buffered from effects stemming from changes in production due to Sacramento River and Delta freshwater flow,

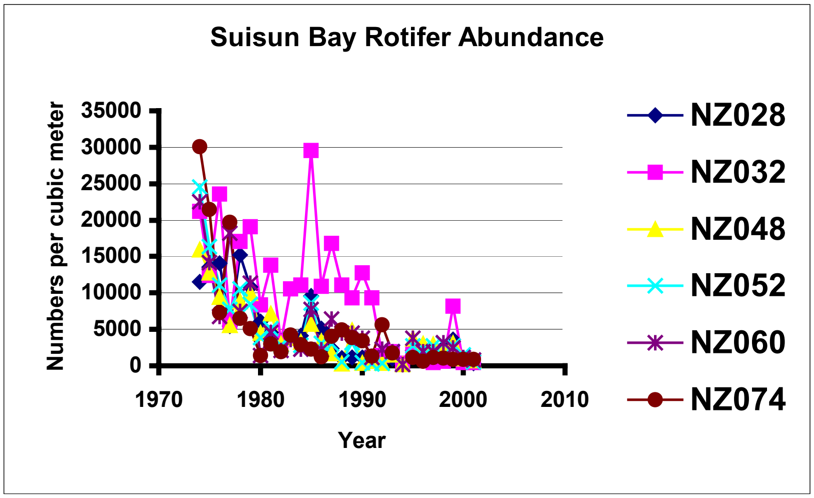


Figure 9: Long-term Suisun Bay stations depict system-wide rotifer trends in Suisun Bay. The only station in which the decline in rotifers was delayed relative to other stations was at NZ32, the shallow water station.

2) *Potamocorbula,* the Asian clam invaded this area much later than in the deeper water sections of the bay 3) the area served as a refuge from higher invertebrate predation while the various invertebrate predators reacted to the increased level of competition due to lowering food resources. Additional research is needed to test these hypotheses.

Evaluation and Grading:

Mean annual abundance for 1974-1979 (13894 rotifers/cubic meter) is the "upper bound" reference condition for evaluating the index, representing less degraded conditions. Each lower grade increment was set at 50% of the grade above, with the last category extending to 0 abundance. This upper baseline probably underestimates the rotifers present prior to the 1974 when the zooplankton measurements were initiated.

Reference condition	Abundance (# per cubic meter)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	>14,000	Estimated abundance of rotifers for 1974-1979 (13894 rotifers/cubic meter, mean) was set as lower bound for the upper reference condition. For grading, the A-B break point was set at the 14,000 individuals per cubic meter. Each lower grade increment was set at 50% of the grade above.	Excellent	4	A
	7,000-14,000		Good	3	B
	3500-7000		Fair	2	C
	1750- 3500		Poor	1	D
Lower	<1750		Very poor	0	F

3. Percent native copepod species

The relative proportions of native and non-native species found in an ecosystem is an important indicator of ecosystem health (May and Brown, 2002). The Bay-Delta zooplankton fauna is dominated by invasive species, mostly from Asia (Orsi and Mecum 1994, Kimmerer 2000,2002). Some of these exotic species have short-lived population increases and eventually are almost eliminated from the ecosystem over time. Others have become well established. The dominance of introduced species from Asia led Orsi and Ohtsuka (1999) to describe the fauna of this region as an "eastern Asian fauna". When sampling began, a single brackish-water copepod, *Eurytemora affinis*, dominated the fauna of the San Francisco Estuary, however, its origin is not known (Lee 1999). Orsi and Ohtsuka (1999) hypothesized that the younger and simpler composition of the San Francisco Estuary zooplankton community provided opportunities for the Asian zooplankton species to become established. Because introductions continue and non-natives continue to influence zooplankton population structure, it is important to track the relative abundance of native copepod species over time.

Methods and Calculations:

As an indicator of the level of invasion, we calculated the percent of native copepod individuals compared to total individuals at six Suisun Bay long-term monitoring stations. Many zooplankton species persist at low numbers so the relative abundance of non-native individuals is likely a better determinant than percent native species of their impacts on community structure and food web stability. *(See Table 1, below for a list of species designations.*) Cladoceran and rotifers are classified only to the genus level and are considered cosmopolitan, so they were not included in this analysis. As noted above, some copepod species origins are uncertain (e.g., *Eurytemora affinis*) and have been here so long that they were considered native species for this analysis.

Table 1: San Francisco Bay Copepod Species

Copepod Species	Phylum/Class	Native/Exotic	Actual taxonomic name
Acartia spp	Calanoid Copepod	N	Acartia spp
Acartiella sinensis	Calanoid Copepod	E	Acartiella sinensis
Diaptomus spp	Calanoid Copepod	N	Diaptomus spp
Eurytemora affinis	Calanoid Copepod	N	Eurytemora affinis
Pseudodiaptomus spp	Calanoid Copepod	N	Pseudodiaptomus spp
Pseudodiaptous forbesi	Calanoid Copepod	E	Pseudodiaptous forbesi
Pseudodiaptomus marinus	Calanoid Copepod	E	Pseudodiaptomus marinus
Sinocalanus doerrii	Calanoid Copepod	E	Sinocalanus doerrii
Tortanus dextrilobatus	Calanoid Copepod	E	Tortanus dextrilobatus
Acanthocyclops vernalis	Cyclopoid Copepod	U	Acanthocyclops vernalis
Acanthocyclops/Cyclops spp	Cyclopoid Copepod	U	Acanthocyclops/Cyclops spp
Limnoithona spp	Cyclopoid Copepod	E	Limnoithona spp
Oithona spp	Cyclopoid Copepod	U	Oithona spp
Oithona davisae	Cyclopoid Copepod	E	Oithona davisae
Oithona similis	Cyclopoid Copepod	E	Oithona similis

Note: U = Unidentified, Note Limnothona spp.- not identified to species level

Results:

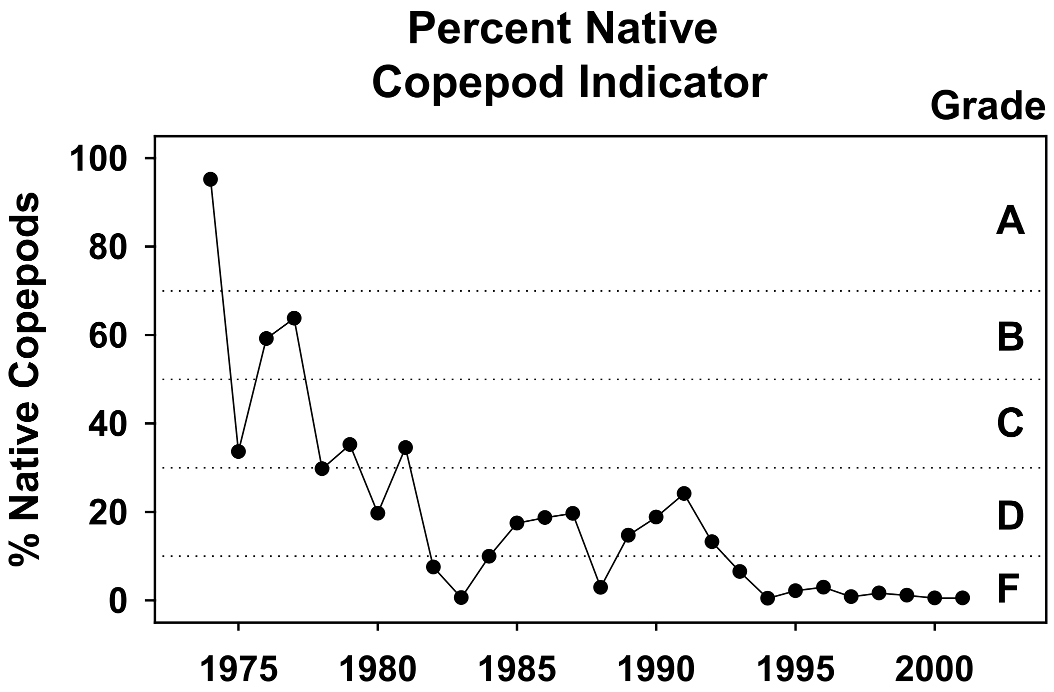


Figure 10: The Percent Native Copepod Indicator measures the percent of copepod individuals in Suisun Bay that are non-native. In 2001, native copepod individuals were less than 1% of the mean of 1974-1979 values (56%). Data source: California Department of Fish and Game, *Neomysis* and Zooplankton survey.

Percent Native Copepod Individuals	Grade	Trends	
		Long term 1976-2001	Short-term recent 5 year
In 2001, Native species are less than 0.5% of the mean 1974-1978 values	F	↓ declining	↓ declining

Key findings:

Annual average abundance of native copepod individuals has decreased dramatically

In the early 1970's, Suisun Bay was already an invaded ecosystem; however, during the past twenty-five years the situation has worsened (Figure 10). During the last five years (1997-2001), the average abundance of non-native species (number of native copepod individuals/total copepods) was 0.9% percent compared to 56% percent during the first five years of the *Neomysis* Zooplankton Survey from 1974-1979.

Current numbers of exotic Copepod species are dominated by a small non-native copepod, *Limnoithona tetraspina*.

The above calculation includes two non-native *Limnoithona* species. *Limnoithona sinensis* disappeared from the estuary at about the time that *L. tetraspina* became abundant (Orsi and Ohtsuka 1999). *Limnoithona tetraspina* species have increased radically and currently dominate the number of exotic zooplankton species in the system. Even without the inclusion of *Limnoithona* in the percent native copepod calculation, the declining trend in native species is apparent (Figure 11).

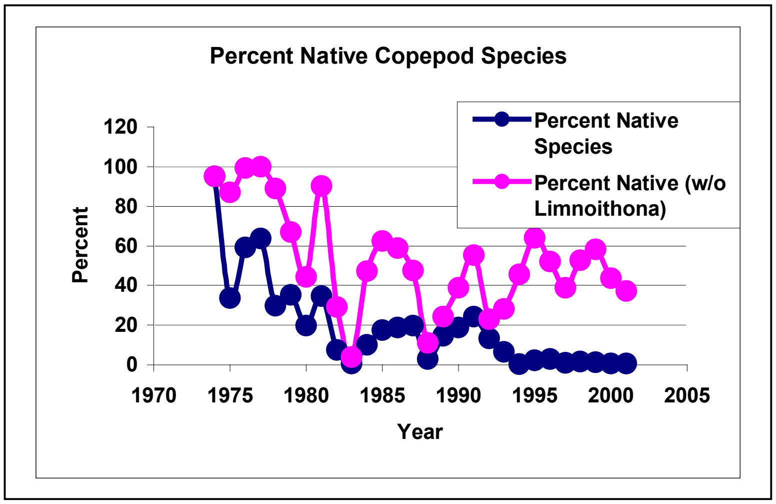


Figure 11: Percent native species with and without the dominant and invasive cyclopoid copepod, *Limnoithona*. Notice that without this invader, the percent natives is significantly higher at 40%, indicating that *Limnoithona* species make up a substantial portion of the copepod community.

Evaluation and Grading:

The Percent Native Copepod Species Indicator can range from 100%, indicating that all of the zooplankton individuals collected were native to the Bay to 0%, indicating that all of the copepod zooplankton species collected were non-natives. Because of its importance as a port, the Bay has become highly invaded, largely due to ballast water exchanges. One hundred percent native species abundance represents the non-degraded condition; however, because the system is so highly invaded, and it is unlikely that the ecosystem will ever return to its non-degraded state, 70% native species abundance was set as the break point for the A-B grade. Each break point represents an additional 20% loss in native copepod individuals. The grading scale for the Percent Native Copepod Species is shown below.

Reference condition	Percent Native Copepod Abundance	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	>70%	70 % native copepod species abundance was set as the lower bound for the upper reference condition. Each grade point break point is set at 20% below the previous reference condition.	Excellent	4	A
	>50%		Good	3	B
	>30%		Fair	2	C
	>10%		Poor	1	D
Lower	>0 %		Very poor	0	F

4. Abundance of native Mysid shrimp (*Neomysis mercedis*)

Historically, *Neomysis,* a large euryhaline mysid shrimp species, was considered an integral part of the invertebrate community and important fish food. It was eaten by bay shrimp (*Crangon franciscorum*) and many fish species including delta smelt and striped bass ((Obrebski et al. 1992; Herbold et al. 1992; Kimmerer 1992;Orsi and Mecum 1994). *Neomysis* consumes phytoplankton and rotifers when young and shifts to copepods, such as the calanoid copepod, *Eurytemora affinis* as adults. It is the only planktonic invertebrate considered in the Bayland Habitat Goals process as a keystone indicator species (Habitat Goals 2000).

The population depicted high but variable levels until 1987 when the population experienced a precipitous decline. This decline was coincident with increased population levels of *Potamocorbula amurensis, which* rapidly invaded the upper estuary and appears to compete with *Neomysis* for phytoplankton resources (Kimmerer 2002). In recent years *Neomysis* continues to exist at extremely low densities. Another factor that is likely affecting *Neomysis* abundance is competition with another mysid species, *Acanthomysis bowmanii*, which appears to have replaced *Neomysis* but exists at significantly lower levels (Orsi and Mecum 1994).

Methods and Calculations:

The Neomysis indicator is the average annual abundance of *Neomysis mercedis* per cubic meter.

Results:

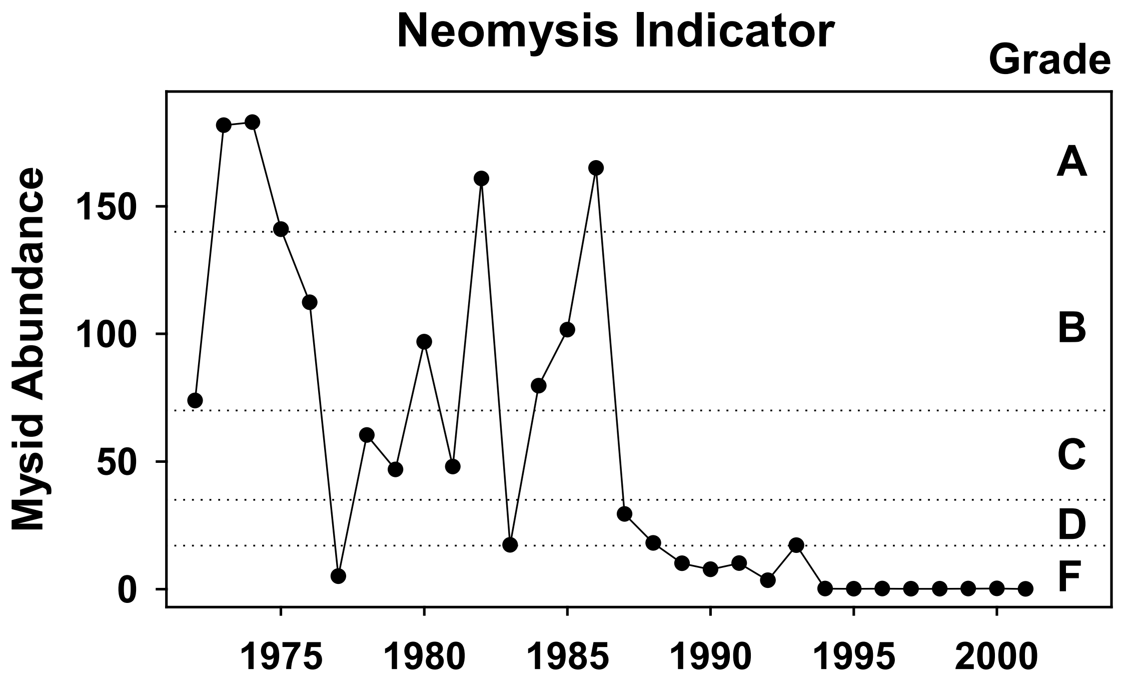


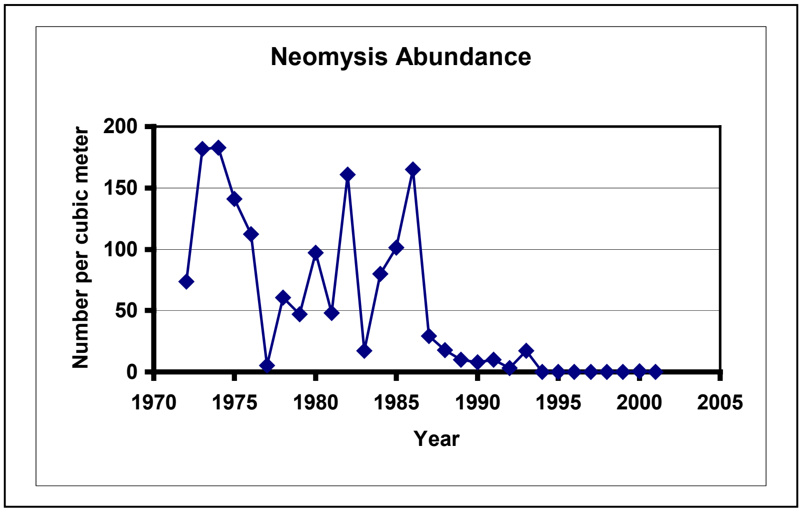
Figure12: This indicator measures Neomysis abundance per cubic meter during the sampling period. The decline of Neomysis coincided with the introduction of exotic Amur clam, *Potamorcorbula* in 1986. During the last five years, the average number of *Neomysis* is less than 0.1 percent of the mean during the early sampling period (1974-1979). Data source: California Department of Fish and Game, *Neomysis* and Zooplankton survey.

		Trends	
Neomysis	Grade	Long term 1976-2001	Short-term recent 5 year
In 2001, Neomysis individuals < 0.1% of mean 1972-1976 values	F	↓ declining	extremely low abundance

Key Findings:

Annual average abundance of Neomysis is less than 0.1% of levels during the first sampling period 25 to 30 years ago.

During the past five years (1997-2001), the average abundance of *Neomysis* of 0.13 per cubic meter is less than 0.1% of *Neomysis* abundance measured during the same survey from 1972-1976. In addition, the mean annual Neomysis abundance during the period after 1986 when the Asian clam, *Potamocorbula amurensis* invaded the estuary is significantly lower than levels measured during the previous period 1972-1986 (Mann-Whitney, p<0.001).



Abundance of *Neomysis* declined precipitously in 1987

During the sampling period, between 1974 to 2001, *Neomysis* abundance declined (R^2=0.51, p<0.001). Abundance declined precipitously in 1987 to a low of 30, but has declined further through 2002. Levels are barely detectable and levels such as 0.33 in 1994 and 0.12 per cubic meter in 2001 are common. This period coincides with decreased levels of rotifers and calanoids, and is followed by a decline in fish abundance in Suisun Bay (see Fish Index).

Since its low point in 1987, *Neomysis* populations have remained at very low numbers

Since 1987, Neomysis abundance has not significantly increased (regression, p> --) and numbers are extremely low. The population should be monitored as it may be a candidate for localized extinction.

Evaluation and Grading:

Estimated mean abundance of *Neomysis* for 1972-1976 (138.3 individuals/cubic meter) was set as the lower bound for the upper reference condition. The mean for the recent time period (1998-2001) is 0.12 individuals per cubic meter. Each subsequent category represents an even linear distribution between the upper bound and zero abundance.

Reference condition	*Neomysis* Abundance (number per cubic meter)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	>138	Estimated mean abundance of *Neomysis* for 1972-1976 was set as the lower bound for the upper reference condition. Each subsequent category is set below the mean with the last category extending to 0 abundance.	Excellent	4	A
	>110		Good	3	B
	>56		Fair	2	C
	>28		Poor	1	D
Lower	>0		Very poor	0	F

5. Average Zooplankton "Size" (Copepods and Cladocerans)

Larger zooplankton are more visible to fish, so size is an important indicator of their accessibility to planktivore predation. Recent studies also indicate that increases in predation or other stressors frequently result in shifts toward smaller bodied species (Kerr and Dickey, 2001). In the early years of the Neomysis- Zooplankton study, large native Calanoid copepods and large Cladocerans dominated the plankton. These large visible species are generally considered important fish prey. A decline in the abundance of large sized zooplankton and increase in smaller sized species can indicate a change in the availability of copepod and cladocerans as resources to planktivorous fish and may have impacts up the food chain. A decline in the average size of zooplankton may also indicate an increase in the number of lower trophic levels, which could result in lower energy transfer rates to the fish community. At the very least a large change in average size, is a sign of shifts in zooplankton community composition, a possible sign of ecosystem instability.

Methods and Calculations:

At the time of this analysis, size class information for the zooplankton species was not available; however, rough estimates of weight (ug/liter per individual) were obtained from Jim Orsi (See Table 2 for weight estimates). Consequently average weight was used as a surrogate of size. This information was entered into the Access database, and multiplied by the density for each taxon to develop a surrogate estimate of the change in size spectra of the zooplankton community per station and year. Because macro-zooplankton (calanoid and cyclopoid copepods and cladocerans) are believed to be important food for larval fish species, we focused our calculation of size spectra to changes in these taxa. The indicator is calculated as:

$$\Sigma\ (u\text{g/individual} \ * \ \#\ \text{individuals/cubic meter}) = \text{average } u\text{g/cubic meter.}$$

We also used weight estimates to investigate whether total biomass had declined during the sampling period.

Results:

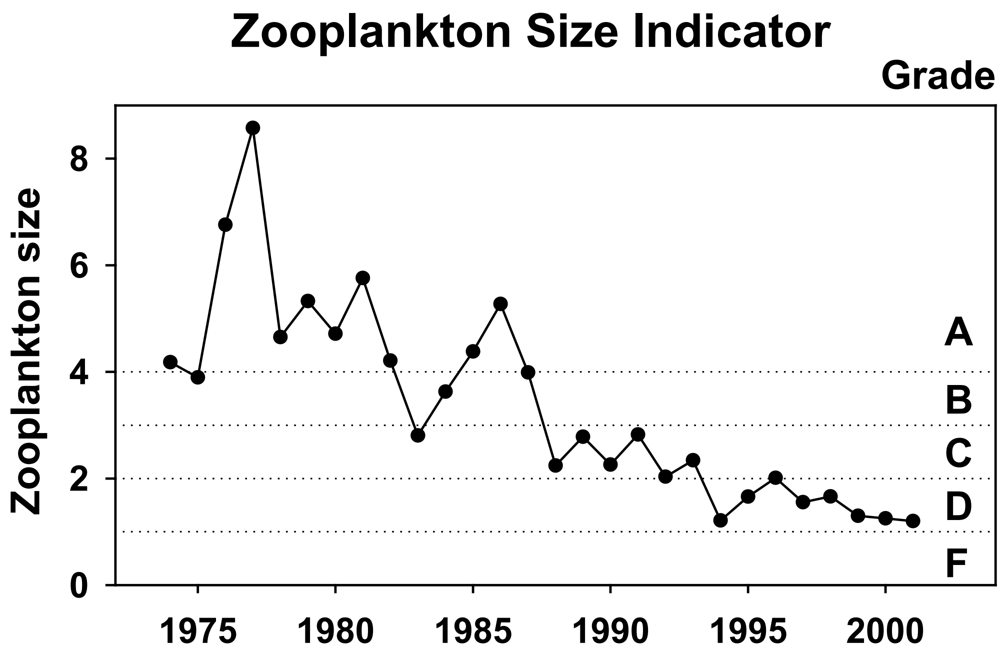


Figure 13: The Average Size indicator measures the change in average weight of individuals in Suisun Bay from 1974-2001. Weight is used as a surrogate of size and the average weight per individual declines steadily over the sampling period. This is due to a decline in large native copeopods and cladocerans and increase in small non-native cyclopoids. The average weight in 2001 represents a 4-fold decline in size from the mean weight during the first five years of the study. CDFG, *Neomysis* and Zooplankton survey and James Orsi.

Average weight per individual	Grade	Trends	
		Long term 1976-2001	Short-term recent 5 year
In 2001, the average weight per individual is one fifth of the average weight during 1974-1978.	F	↓ declining	↓ declining

Key findings:

The size of the copepod and cladoceran community decreased five-fold during the sampling period.

The average weight per individual declined steadily over the sampling period (see figure 12). The average weight of zooplankton from the six stations in Suisun Bay sampled during 2001 represents a 5-fold decline in size from the mean levels during the first five years of the study. The mean of the first five years of sampling: 5.6 *ug*. fell to 1.2 *ug*. in 2001. The mean during the past five years was 1.4 *ug* and declined from a high of 1.7 *ug*, reflecting a continuing increase in *Limnoithona* copepod species.

Biomass did not decline during the sampling period.

Though we expected to see a decline in biomass during the sampling period, our preliminary estimates of biomass for all taxa for which weights were available, did not depict a statistically significant decline. This result is somewhat surprising given the decline in chlorophyll and requires additional investigation.

Evaluation and Grading:

The mean weight of 5.6 ug. per individual copepod and cladoceran taxa for the first five-year sampling period , 1972-1976 was used as a guide to set the lower bound for the upper reference condition at 4.0 ug. The bottom range of the scale was set at zero, which is clearly lower than the metric will ever go. The mean for the recent time period (1998 - 2001) was 1.2, which received a score of 1 or a grade of D. Each subsequent category represents an even linear distribution between the upper bound and zero abundance. Mysids were not included in this analysis; however, if they were, would cause an even more significant shift in this metric because of its large size relative to *Acanthomysis bowmanii.*

Reference condition	**"Size" Average annual weight (*ug*) per individual**	**Rationale for reference conditions**	**Ecological condition**	**Grade point**	**Grade**
Upper	>4	The lower bound for the upper reference condition was set at 4 *ug*. Each subsequent category is set below the mean with the last category extending to 0 abundance.	Excellent	4	A
	>3		Good	3	B
	>2		Fair	2	C
	>1		Poor	1	D
Lower	>0		Very poor	0	F

6. Food Web Index

The San Francisco Bay Food Web Index aggregates the results of the Phytoplankton (Chlorophyll *a)*, Rotifer Abundance, Native Copepod Abundance, Native Mysid (Neomysid) Abundance, and Average Zooplankton Size (Figure 14).
Table 1 shows the grades of each of the Indicators for the Food Web Index. The Index grade and the score are derived from the "grade point average" of the component indicators.

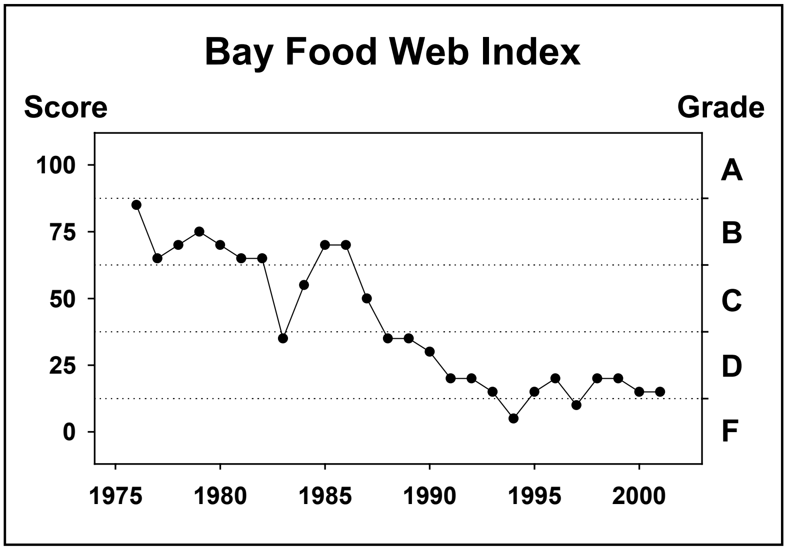


Figure 14: The Food Web Index aggregates the results of the phytoplankton, rotifer, native copepods, neomysis and zooplankton size indicators for Suisun Bay.

Table 1. Results, grades and grade points for the four indicators used to calculate the Food Web Index for 2001.

Indicator	2001 Result	Grade	Grade point
Phytoplankton (Chlorophyll *a)*	Suisun Bay levels less than 20% of 1976-1980 levels	D	**1** (out of 4)
Rotifers	Abundance less than 2% of 1974-79 levels in Suisun Bay	F	**0** (out or 4)
Percent Native Copepod Abundance	Less than 1% of species are native in Suisun Bay	F	**0** (out of 4)
Neomysis abundance	Currently Neomysis are extremely rare	F	**0** (out of 4)
Size	Average size is less than 20 percent of that in 1974-1979	D	1 **(out of 4)**
	Index Grade Point Average	F	**0.4**
Food Web Index Score =			**10 (out of 100)**

The Food Web Index declined precipitously between 1986 and 2001 (regression, $p<0.01$). (Figure 14). Though there was some decline in the index between the mid 70's and mid 80's, the decline was most pronounces after the introduction of *Potamocorbula* in 1986, which indicates that this factor may be the most important factor causing the decline.

The average score in the mid 1970's (1976-1980) was 68, significantly greater than the average score measured for the 1997 -2001 period, 13 (t-test, $p<0.01$). The decline in the Food web Index is fairly consistent among all of the indicators and was most pronounced for the zooplankton abundance indicators (rotifers, native copepods, and mysids (*Neomysis*).

Ecological and Management Implications:

In San Francisco Bay, like many threatened ecosystems, people tend to pay the most attention to the species that are endangered, harvested, or simply most charismatic, such as wild salmon or the great water birds. But it is the humbler species, from bacteria and algae to planktonic plants and animals that serve as the foundation of the Bay's complex food web. Changes in the abundance and species composition of these primary producers and consumers can have profound impacts on the structure and composition of aquatic communities, and in some cases may be the crucial factors affecting the success of the more visible species of the Bay.

Phytoplankton growth is controlled by many factors, including light, water depth and transparency, freshwater inflow and circulation patterns, and availability of nutrients. The massive alterations of natural inflow to the Bay from the construction of the Central Valley's water supply and flood management system and reductions in nutrient inputs from the wholesale conversion of wetland and floodplain habitats during the past 150 years undoubtedly had huge impacts on food web dynamics and productivity that are now impossible to quantify. An exception to this general trend is that some aspects of productivity may have benefited from nutrient-rich sewage discharges into the Bay and may now be declining as a result of improvements in wastewater collection and treatment. Not surprisingly, the food web has changed dramatically in the northern reaches of the Bay, which are most strongly influenced by springtime freshwater inflow and large seasonal and inter-annual variations in salinity (see Freshwater Inflow Index).

Changes in the percent of native species were observed in the first few years of sampling and are testament to the highly invaded nature of this estuary. The recent declines in phytoplankton production coincided with an extreme wet period, with an extraordinarily high flushing flow event which may have eliminated resident native clams from bottom sediments, followed by a sharp decline in Bay inflow as upstream diversions skyrocketed and the 1987-1992 drought began. These conditions may have facilitated the rapid colonization of the Bay's upper reaches by the alien *Potamocorbula* clam (Figure 15), which consumes phytoplankton faster than phytoplankton can reproduce. This exotic clam is now a major component of the highly altered Suisun Bay food web. The clam also bioaccumulates selenium, a trace element that is toxic at very low levels, at higher rates than native filter feeders, increasing the risk of bio-magnification of this and other

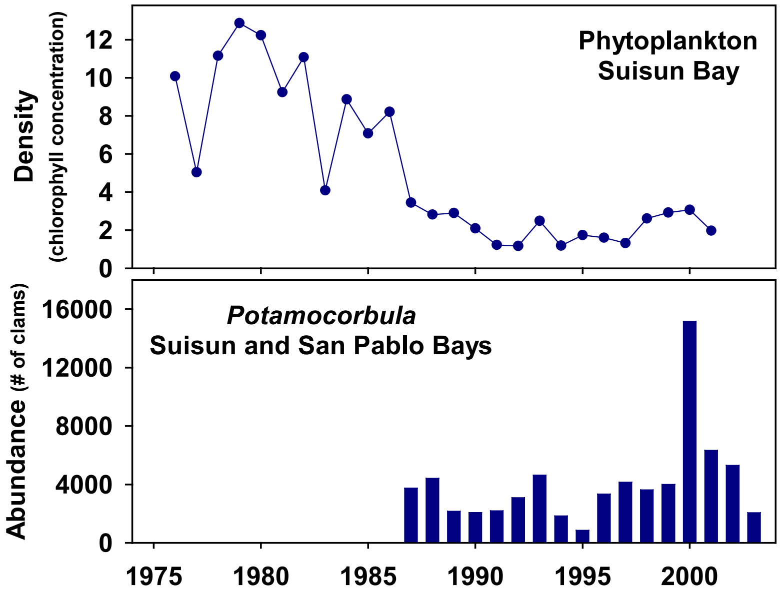


Figure 15. Establishment of the filter-feeding alien clam, *Potamocorbula*, decimated phytoplankton production in northern San Francisco Bay.

contaminants in fish and birds. Current management initiatives to increase Bay inflow (see Stewardship Index) and expand wetland habitat (see Habitat Index) may help simulate some of the conditions that improve primary production and favor native food web species. However, these actions may be too modest to make a measurable difference as long as highly efficient alien filter feeders continue to dominate the bottom community. New water supply projects under consideration in the Delta and Central Valley that would expand the ability to store and convey upstream runoff could also negate any efforts to improve Bay inflow conditions.

Data Gaps and Availability:

This analysis emphasized specific issues regarding data availability and interpretation of lower trophic level processes. Problems that were identified in the study of lower trophic level processes include 1) gaps in the spatial coverage of the monitoring programs that address these processes and 2) the lack of attention to analyses and synthesis of the data coming from existing programs and 3) the lack of data available prior to the mid seventies. The IEP, USGS and RMP program each sample different portions of the estuary; however, these programs are not coordinated and differ in their sampling frequency. There is a need to take a careful look at coordinating these programs and sampling in a consistent way. This problem is about to be solved for the zooplankton sampling effort, DWR’s Environmental Monitoring Program just completed a review (add website); and zooplankton is going to be monitored in a more consistent fashion across the region allowing that funds are made available for this effort.

The second issue can be illustrated by taking a closer look at the benthic sampling efforts. At present, IEP monitors benthos from the Delta to San Pablo Bay, but the San Pablo station data has not always been collected. USGS samples benthic invertebrates from Rio Vista to the South Bay; however, due to current funding priorities, the group is very behind in their analyses (Frances, personal comm.). The Regional Monitoring Program also monitors and evaluates benthic fauna; however, this sampling effort is on a quarterly basis and is not long-term. To date, the results of these efforts have not been compared and these agencies should step up their efforts to process and analyze existing samples so that the data is available for important syntheses.

Though the San Francisco Bay sampling programs are very well developed compared to those in some estuaries, these programs still began after humans had made substantial changes in the estuary and so can be considered relatively recent in their temporal scope. Presently, the only way to obtain a more complete picture of pre-1974 conditions is through paleoecological studies. Efforts should be made to investigate the feasibility of establishing such a research program.

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