State of San Francisco Bay 2011
Appendix E

LIVING RESOURCES - Shrimp and Crab Indicators
Technical Appendix

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I. Background and Rationale

The San Francisco Estuary is important habitat for several shrimp and crab species, including Bay shrimp, which once supported an extensive commercial fishery in the Bay, and Dungeness crab, an icon of San Francisco's Fisherman's Wharf. Even today, California's commercial crab fishery relies heavily on crabs that rear in the Bay, feeding and growing in the estuary's brackish waters and tidal marshes for the first year or two of their lives before migrating to the ocean to mature and breed.

Abundance and distribution of shrimp and crabs in the Bay is affected by environmental conditions in the estuary and in the nearby ocean, and different species use different regions of the estuary. Estuarine species like the Bay shrimp, which prefer low salinity waters, are strongly influenced by the amounts and timing of freshwater inflows (Kimmerer 2002). Other species restricted to higher salinity habitats closer to the Golden Gate may be more affected by environmental conditions in the nearby ocean. Thus, while measures of shrimp and crab abundance, distribution and species composition within the Bay can be useful biological indicators for environmental conditions in the estuary, they must be interpreted carefully because they may also be affected by the ocean conditions outside the Bay (Cloern et al., 2007, 2010).

The State of San Francisco Bay 2011 report uses several indicators to assess the condition of the shrimp and crab communities in the San Francisco Estuary. The simplest ones measure abundance, or "how many?" shrimp and crabs does the estuary support. For shrimp, this measurement is also made for the different regions of estuary, from Central Bay near the Golden Gate, which is essentially a marine environment, to Suisun Bay, which is strongly affected by freshwater inflows from the Sacramento and San Joaquin Rivers. Another indicator for shrimp compares the abundance and distribution of species that prefer low salinity waters to those that prefer saltier waters. For both shrimp and crabs, other indicators measure species composition and the prevalence of non-native species in the estuary.

II. Data Source

All of the indicators were calculated using data from the California Department of Fish and Game (CDFG) Bay Study surveys, conducted every year since 1980.[1] The Bay Study collects crabs and shrimp using an otter trawl, which is towed near the bottom and selectively captures shrimp, crabs and demersal fishes that utilize bottom and near-bottom habitats. Each year, the survey samples the same 35 fixed stations in the estuary. These stations are relatively evenly distributed throughout the estuary, among the four sub-regions of the estuary (South, Central, San Pablo and Suisun Bays), and among channel and shoal habitats, and they are sampled once per month for most months of the year.[2] Information on sampling stations, locations and total number of surveys conducted each year in each of the four sub-regions is shown in Figure 1 and Table 1. The Bay Study survey collects and identifies seven species of shrimp (five native

[1] Information on the CDFG Bay Study is available at http://www.dfg.ca.gov/delta/projects.asp?ProjectID=BAYSTUDY

[2] The Bay Study samples more than four dozen stations but the 35 sampling stations used to calculate the indicators are the original sampling sites for which data are available for the entire 1980-2008 period.

native species) (Table 2). It should be noted that, although the Bay Study Otter Trawl survey samples the Bay's open water benthic habitats reasonably comprehensively, it does not survey historic or restored tidal marsh or tidal flat habitats where these 12 species, as well as other crustacean species, may also be found. Therefore, results of the Bay Study and of these indicators should not be interpreted to mean that these are the only species of crustaceans found in the Bay or that these species are found in only these regions of the estuary.

III. Methods and Calculations

Three indicators were developed to assess conditions and trends in the shrimp community in the San Francisco Estuary. For each year, native shrimp abundance in the estuary was measured as:

$$\#\text{ native shrimp}/10{,}000\ m^2 = [(\#\text{ of native shrimp})/(\#\text{ of trawls x av. trawl area, } m^2)] \times (10{,}000)$$

Native shrimp abundance was also measured using this equation for each sub-region of the estuary (i.e., South, Central, San Pablo and Suisun Bay/western Delta).

A second indicator compared the abundance and distribution of native estuarine shrimp that prefer low salinity waters (i.e., Bay shrimp, *C. franciscorum*) with that of native shrimp that prefer saltier waters (all other native shrimp species) and with the two non-native shrimp species (both of which prefer brackish waters). Abundance was calculated as above. Distribution was calculated by comparing the relative abundance of the shrimp populations in each of the four sub-regions of the estuary using the following equation:

$$\text{Distribution} = \text{SD of: } \frac{(\#\text{shrimp}/10{,}000m^2_{(\text{South Bay})})}{(\#\text{shrimp}/10{,}000\ m^2_{(\text{SF estuary})})}, \frac{(\#\text{shrimp}/10{,}000m^2_{(\text{Central Bay})})}{(\#\text{shrimp}/10{,}000\ m^2_{(\text{SF estuary})})}, \frac{(_{(\text{other sub-regions})})}{}$$

A large standard deviation (SD) indicated that the shrimp population was concentrated in one or two sub-regions of the estuary while a small SD indicated that the population was more evenly among the four sub-regions.

A third indicator assessed the species composition of the shrimp community in the four sub-regions by measuring the percentage of the total shrimp community was comprised of native shrimp.

$$\%\text{ native shrimp} = [\#\text{ native shrimp}/(\#\text{ native shrimp} + \#\text{ non-native shrimp})] \times 100$$

Three indicators were used to assess conditions and trends in the crab community. For each year, native crab abundance in the estuary was measured as:

$$\#\text{ native crabs}/10{,}000\ m^2 = [(\#\text{ of crabs})/(\#\text{ of trawls x av. trawl area, } m^2)] \times (10{,}000)$$

The second indicator measured and compared the abundance of Dungeness crabs (*Cancer magister*) and of Rock crabs (*C. antennarius*, *C. gracilis*, and *C. productus*). Abundance for each was calculated as above.

The final indicator assessed species composition of the crab community by measuring the percentage of the total crab community was comprised of native crabs.

% native crabs = [# native crabs/(# native crabs + # non-native crabs)] x 100

VI. Indicator Evaluation and Reference Conditions

The San Francisco Estuary Partnership's Comprehensive Conservation and Management Plan (CCMP) calls for "recovery" and "reversing declines" of estuarine fish and wildlife but does not provide quantitative targets or goals. The length of the available data records allows for use of historical data to establish "reference conditions." However, there is also good evidence that characteristics of the shrimp and crab communities in the Bay, in particular abundance, are influenced by environmental and ecological conditions in the nearby Pacific Ocean, outside of the estuary and not directly linked to local estuarine or marsh habitat, freshwater inflow or pollution conditions (e.g., Cloern et al., 2007; 2010). Therefore, evaluation of indicators based on indicator levels measured in the estuary in the past may not reflect changes in the estuary's health but rather unrelated changes in ocean conditions and must be interpreted cautiously. With this caveat, the reference condition for the abundance indicators was established as the average abundance for the first ten years of the Bay Study, 1980-1989. Abundance levels that were greater than the 1980-1989 average were considered to reflect "good" conditions.

There is an extensive scientific literature on the relationship between the presence and abundance of non-native species and ecosystem conditions. In general, ecosystems with high percentages of non-natives (e.g., >50%) are considered to be seriously degraded while high percentages of native species (e.g., >85-95%) are indicative of less impacted ecosystems. San Francisco Estuary is known to be heavily invaded with non-native species (Cohen and Carlton, 1998), with some non-native species present in the Bay for more than 100 years and new species being introduced every year. Therefore, the reference condition was established at 85% native species.[3] Percentages that were greater than this value were considered to reflect "good" conditions.

The distribution indicator for shrimp was analyzed and interpreted but not compared to a quantitative reference condition.

For all the indicators, differences among sub-regions and different time periods, and trends with time were evaluated using analysis of variance and simple linear regression.

V. Results

Results of the estuary-wide native shrimp and crab abundance indicators are shown in Figures 2-8.

Abundance of native shrimp and crabs in the San Francisco Estuary has increased.

[3] This is the same reference level used in the species composition indicators for the estuary's fish community.

Since the 1980s, abundance of both shrimp and crabs in the San Francisco Bay has increased significantly (regression, $p<0.001$, both tests) (Figure 2). From the 1980s to the most recent decade, shrimp abundance doubled, from 3,645 shrimp/10,000m^2 to 7,745 shrimp/10,000m^2. Crab abundance increased by more than 400%, from just 9.6 crabs/10,000m^2 to 44.7 crabs/10,000m^2. For both groups, the increase occurred in the late 1990s and coincided with a shift in the Pacific Decadal Oscillation (PDO) from its "warm regime" (mid-1970s to the later 1990s) to its "cool regime" (NFSC, 2010), as well as an unusually wet sequence of years and high freshwater outflow conditions (see Freshwater Inflow Index). The short duration decline in crab abundance in the mid-2000s also coincided with a short duration reversal in the PDO to a warm regime

Abundance and trends in abundance of native shrimp differ among the four sub-regions of the estuary.

When the Bay Study survey began, native shrimp were significantly more abundant in Suisun and San Pablo Bays than in Central and South Bays (Kruskal-Wallis One Way Analysis of Variance for 1980-1989; Suisun>Central and South, San Pablo>South; $p<0.05$, all listed comparisons) (Figure 3). During the past three decades, shrimp abundance has significantly increased in all sub-regions of the estuary except Suisun Bay (regression, $p<0.05$, all tests). The magnitudes of the population increases differed substantially: shrimp abundance increased more than ten-fold in Central Bay, doubled in South Bay but only increased by 45% in San Pablo Bay. Now, in the most recent decade, native shrimp are significantly more abundant in Central Bay than most other sub-regions of the estuary (Kruskal-Wallis One Way Analysis of Variance for 1999-2008; Central>South and Suisun; $p<0.05$, all listed comparisons).

Increased shrimp abundance is attributable to increased abundance of "coastal" shrimp species.

The increase in shrimp abundance in the San Francisco Bay was driven by substantial increases in the abundance of shrimp species that prefer saltier water (referred to as "coastal" species in Figure 4, middle panel) and which are distributed in the downstream regions of the estuary (see also Figure 3). Population increases in "coastal" shrimp occurred throughout the three decades of the Bay Study survey but tended to coincide with periods of dry hydrological conditions, when freshwater inflows to the estuary were low (i.e., late 1980s to early 19902; early 2000s, and 2007-2008). In contrast, during those periods, abundance of Bay shrimp, which prefer low salinity water, tended to decline (Figure 4, top panel). The distributions of these two types of shrimp also responded to hydrological conditions. In "wet" years, the distribution of Bay shrimp broadened as the shrimp were able to occupy more downstream regions of the estuary (i.e., the distribution metric decreased). During dry periods, Bay shrimp distribution became more concentrated in the upstream region of the estuary (i.e., the distribution metric increased). Coastal shrimp species exhibited the opposite pattern, with broader distributions during dry periods than during wet periods. Non-native shrimp abundance and distribution have fluctuated throughout the past three decades, with no significant trends or no clear patterns relative to either hydrological or ocean conditions (Figure 4, bottom panel). However, the distribution of non-native shrimp in the estuary has broadened (regression, $p<0.05$) as the more abundant Oriental shrimp, which was concentrated in Suisun and San Pablo Bays during 1980s and 1990s, has become established in South Bay.

Variations in the crab abundance largely reflect changes in ocean conditions.
Both Dungeness crab and the other rock crab species exhibited significant increases in abundance in the late 1990s (Figure 5), coincident with a regime shift in the Pacific Decadal Oscillation, from a "warm regime" (~1975-1997) to a "cool regime" (~1998-2002) (Figure 6). For both groups, abundance declined sharply during the short-duration shift back to a "warm regime" in the mid-2000s and then rebounded with the return of "cool regime" conditions in 2008.

The San Francisco Estuary's shrimp and crab communities are dominated by native species.
Native species dominate the San Francisco Estuary's shrimp (Figure 7) and crab communities (Figure 8). The two non-native shrimp species (one, a recent arrival first reported in the 2001) prefer brackish, low salinity waters but even in Suisun Bay, the most upstream region of the estuary, they comprise an average of only 5% of the shrimp population. In all other regions of the estuary, the shrimp community is >98% native. As a percentage of the shrimp community, the prevalence of non-native shrimp species in the estuary has not changed in the past three decades. Only one non-native crab has been reported collected by the Bay Study, the Chinese mitten crab. This species first appeared in the mid-1990s and by 1999 it comprised more than 25% of the crab community. After this, its numbers dropped and, since the mid-2000s, mitten crabs have not been collected by Bay Study surveys.

VI. Summary and Conclusions

Collectively, the abundance, distribution and species composition indicators provide a reasonably comprehensive picture of the shrimp and crab communities in the open water benthic habitats of San Francisco Bay. The results illustrate the influences of environmental conditions both within and outside of the estuary on the shrimp and crab communities in the Bay. With the notable exception of the estuary-dependent Bay shrimp, shrimp and crab abundance appears to be largely driven by ocean conditions, which influence reproduction, recruitment and larval survival for most of these coastal spawning species. In contrast, freshwater inflow to the estuary appears to influence the distribution of shrimp species within the estuary. In dry years, marine-type shrimp species extend their range upstream in the estuary while the abundance of the estuarine Bay shrimp declines and its distribution becomes more restricted. Based on the recent substantial increases in shrimp and crab abundance, as well as the relatively stable Bay shrimp populations, overall ecological conditions in the estuary appear to be "good" for shrimp and crab.

VII. Peer Review

The Shrimp and Crab indicators build upon the methods and indicators developed by The Bay Institute for the 2003 and 2005 Ecological Scorecard San Francisco Bay Index and for the San Francisco Estuary Partnership Indicators Consortium. The Bay Institute's Ecological Scorecard was developed with input and review by an expert panel that included Bruce Herbold (US EPA), James Karr (University of Washington, Seattle), Matt Kondolf (University of California, Berkeley), Peter Moyle (University of California, Davis), Fred Nichols (US Geological Survey, ret.), and Phillip Williams (Phillip B. Williams and Associates).

VIII. References

Cloern, J.E., A.D. Jassby, J.K. Thompson, K. Hieb. 2007. A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay. *Proceedings of the National Academy of Sciences of the United States of America* 104(47):18561-18656

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Kimmerer, W. J. 2002. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. Estuaries 25:1275-1290.

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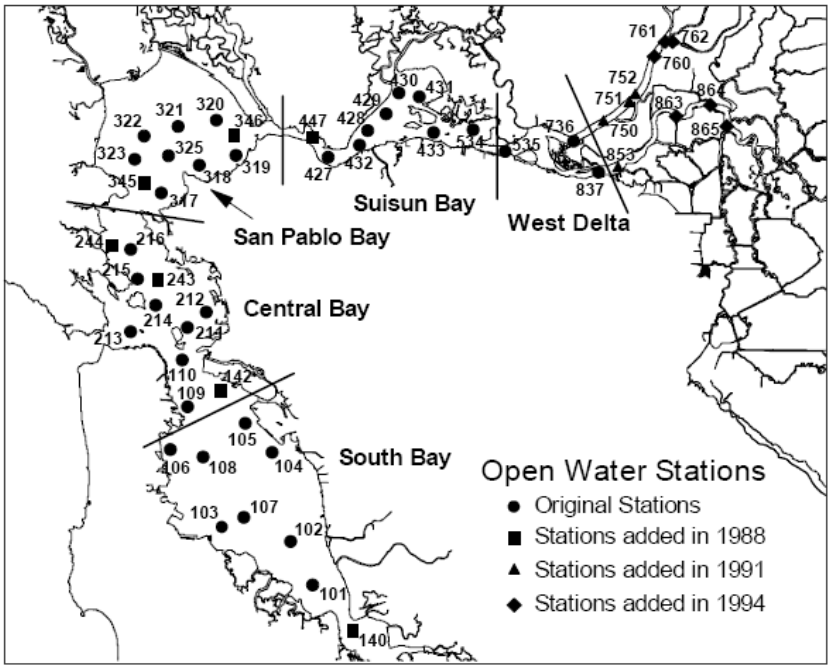


Figure 1. Locations of the sampling stations for the CDFG Bay Study Otter Trawl survey in different sub-regions of the San Francisco Bay. For the Crab and Shrimp indicators 2007 Fish Index, only data from the "original stations" (sampled continuously for 1980-2006 period) were used to calculated indicators for four sub-regions: South Bay, Central Bay, San Pablo Bay, and Suisun Bay (which for this study includes the West Delta sub-region).

Table 1. Sampling stations and total numbers of surveys conducted per year (range for the 1980-2009 period) by the CDFG Bay Study Otter Trawl survey in each of four sub-regions of San Francisco Bay. See Figure 1 for station locations.

Sub-region	Sampling stations	Number of surveys (range for 1980-2005 period)
South Bay	101, 102, 103, 104, 105, 106, 107, and 108	64-96
Central Bay	109, 110, 211, 212, 213, 214, 215, and 216	64-96
San Pablo Bay	317, 318, 319, 320, 321, 322, 323, and 325	64-96
Suisun Bay (includes West Delta sub-region shown in Figure 1)	425, 427, 428, 429, 430, 431, 432, 433, 534, 535, 736, and 837	88-132

Table 2. Shrimp and crab species collected by the CDFG Bay Study Otter Trawl survey, 1980-2009.

Common name	Scientific name	Native v Non-native
Shrimp		
Bay shrimp	*Crangon franciscorum*	Native
Blacktail bay shrimp	*C. nigricauda*	Native
Blackspotted bay shrimp	*C. nigromaculata*	Native
Stimpson coastal shrimp	*Heptacarpus stimpsoni*	Native
Smooth bay shrimp	*Lissocrangon stylirostric*	Native
Siberian prawn	*Exopalaemon modestus*	Non-native
Oriental shrimp	*Palaemon macrodactylus*	Non-native
Crabs		
Dungeness crab	*Cancer magister*	Native
Pacific rock crab	*C. antennarius*	Native
Graceful rock crab	*C. gracilis*	Native
Red rock crab	*C. productus*	Native
Chinese mitten crab	*Eriocheir sinensis*	Non-native

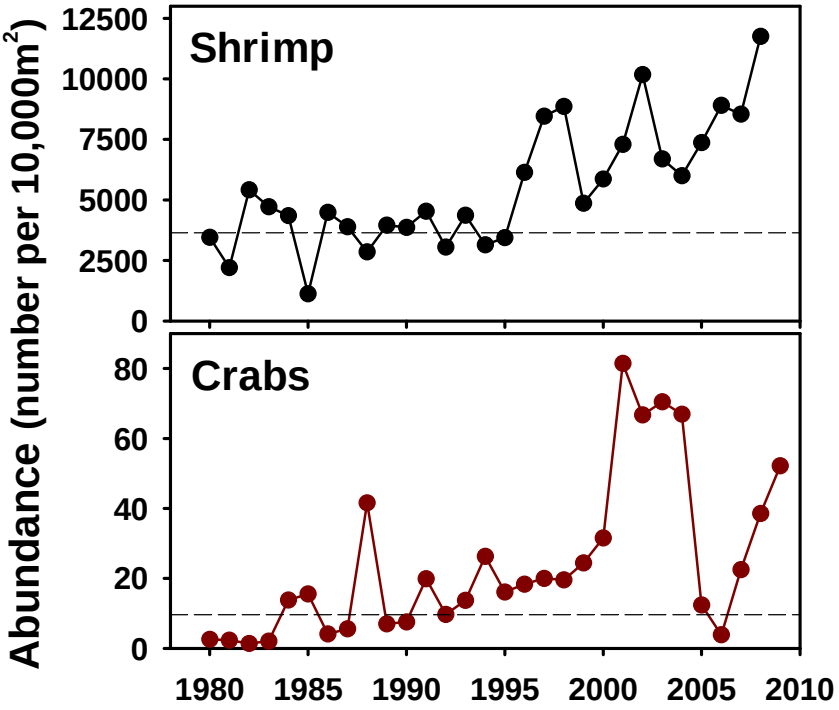


Figure 2. Changes in the Native Shrimp Abundance (top panel) and Native Crab Abundance indicators. Horizontal dashed line shows the reference condition (1980-1989 average).

Figure 3. Changes in the native shrimp abundance in each of the four sub-regions of the San Francisco Estuary, from 1980-2008. Horizontal dashed line shows the reference condition (1980-1989 average).

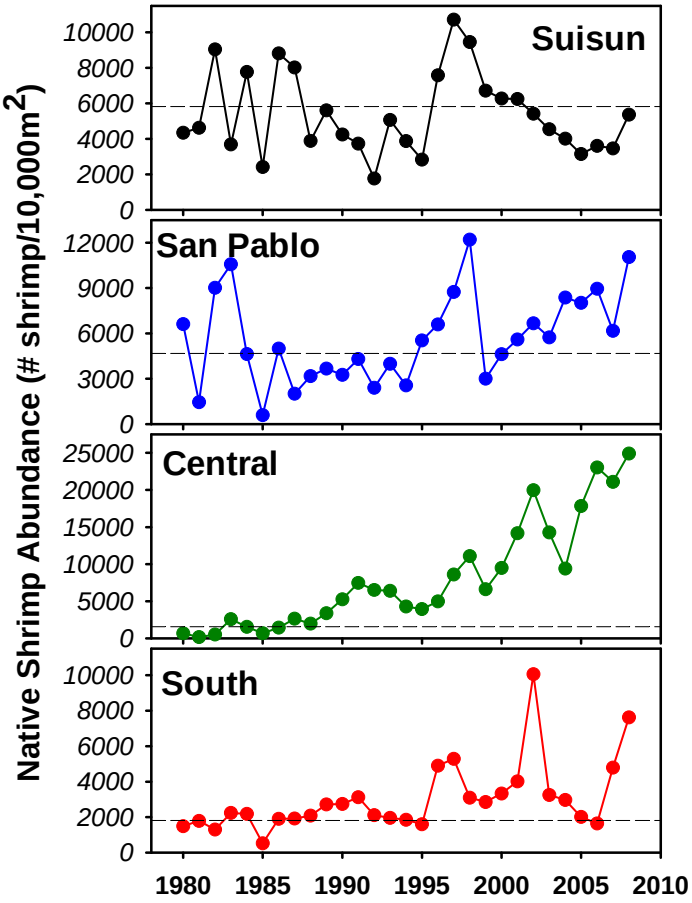
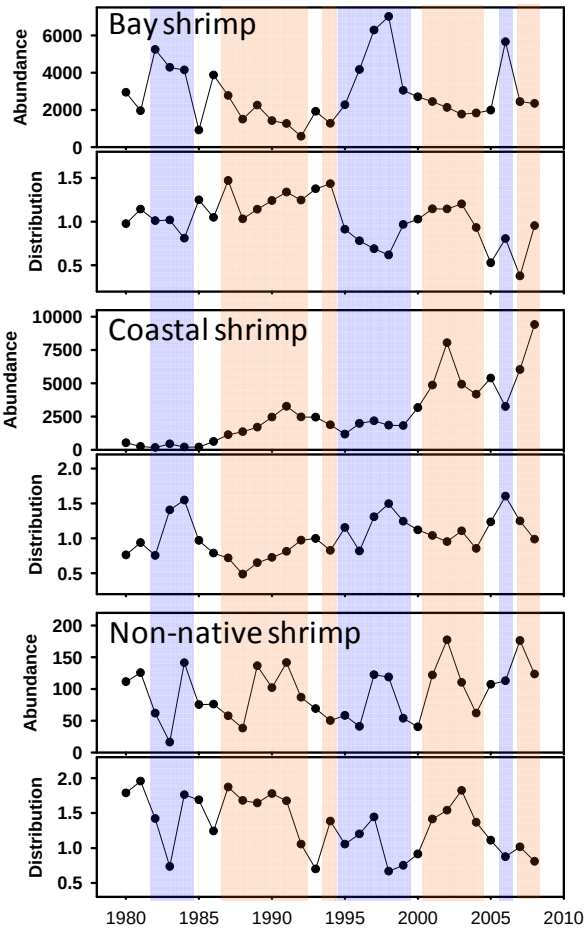


Figure 4. Abundance and distribution of Bay shrimp (top panels), which prefer low salinity waters, “coastal” shrimp (middle panels), which prefer saltier waters, and non-native shrimp (bottom panels). For distribution, low numbers (<1.0) indicate relatively broad and even distribution among the four sub-regions of the estuary, while larger numbers (>1.0) indicate narrower and more uneven distribution within the estuary. The pink bars indicate dry hydrological conditions (i.e., “dry” or “critically dry” freshwater outflow conditions) and the blue bars indicate “wet” hydrological conditions with high freshwater outflows..



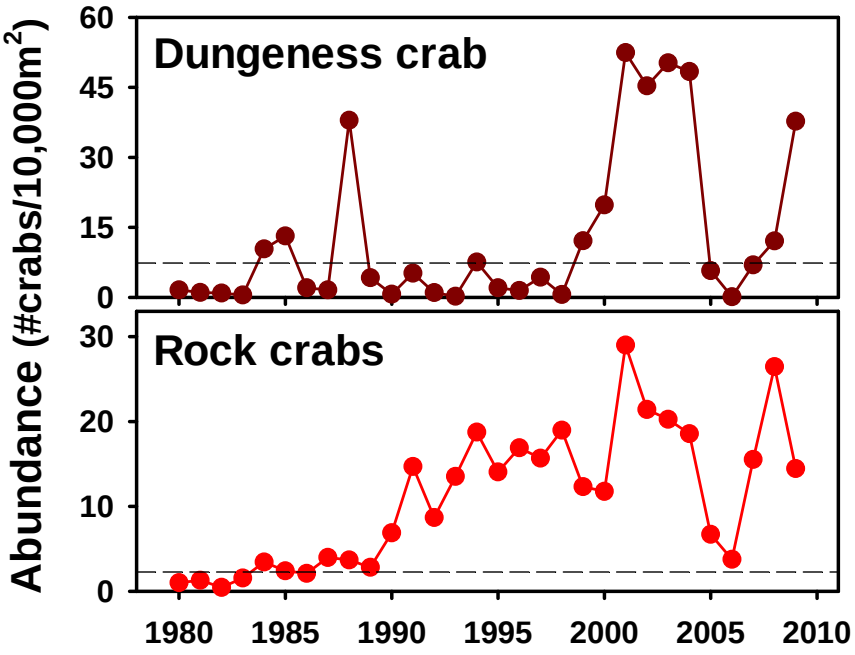


Figure 5. Changes in the Dungeness crab (top panel) and Rock crab (bottom panel) abundance indicators. Horizontal dashed line shows the reference condition (1980-1989 average).

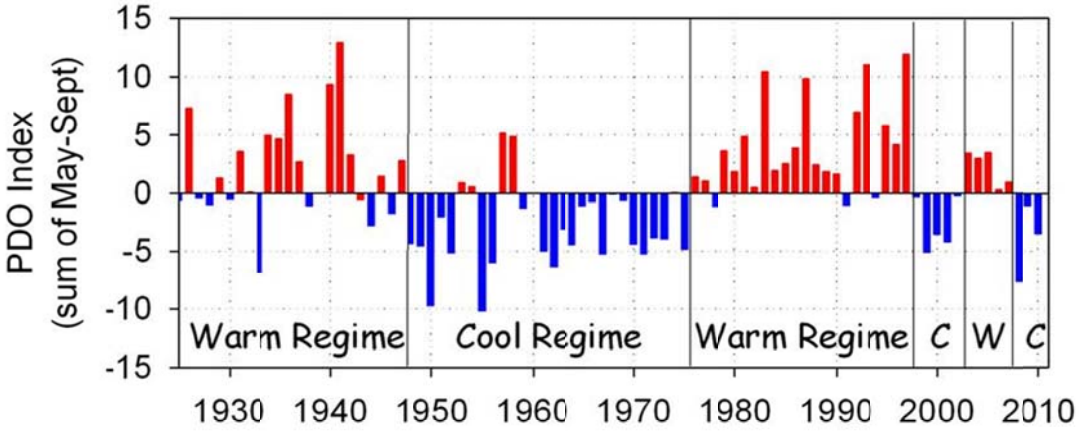
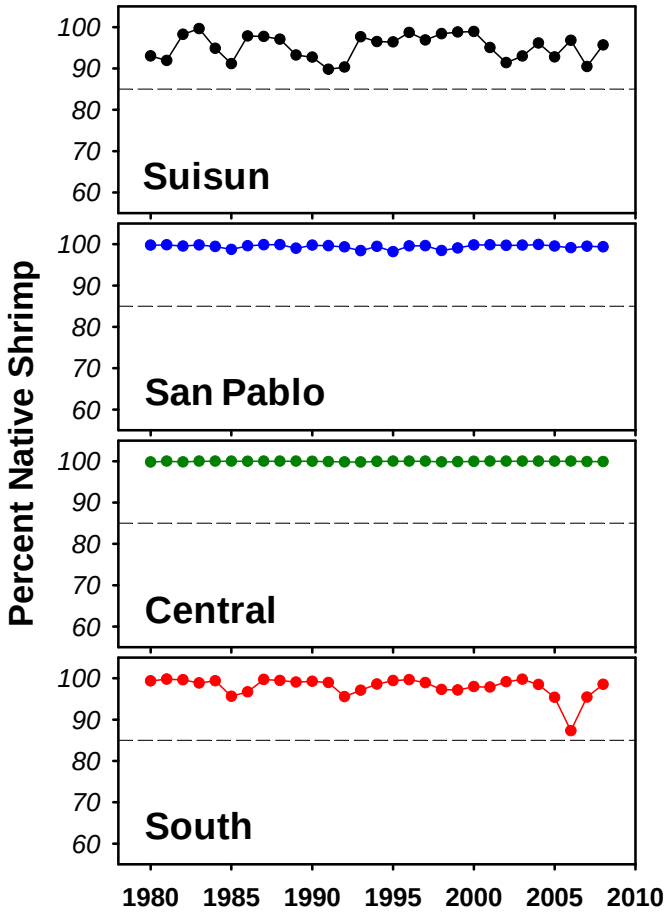


Figure 6. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to 2010. Values are averaged over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 was the most negative since 1956. From: Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, available at: http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/ca-pdo.cfm

Figure 7. Changes in the Percent Native Shrimp indicator in each of four sub-regions of the San Francisco Estuary from 1980-2008. Horizontal dashed line shows the reference condition (85% native).



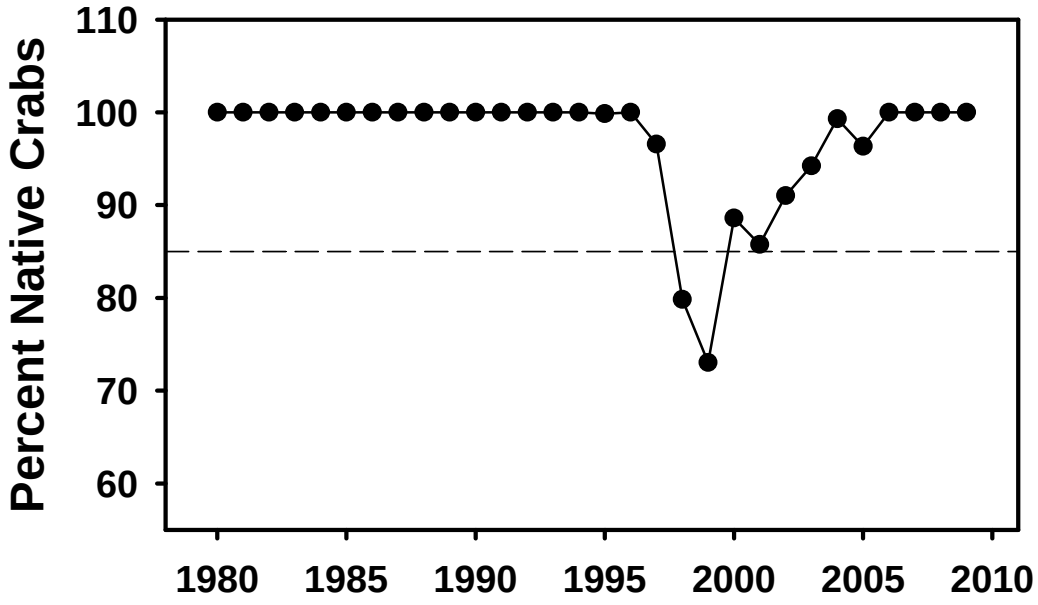


Figure 8. Changes in the Percent Native Crabs indicator in each of four sub-regions of the San Francisco Estuary from 1980-2008. Horizontal dashed line shows the reference condition (85% native).