

**Copepods of the San Francisco Estuary: potential effects of
environmental toxicants**

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Introduction

Copepods are aquatic crustaceans that play an essential role in pelagic food chains and aquatic ecosystems (Bouley *et al.*, 2006). They are abundant and are distributed in saltwater and freshwater bodies worldwide (Lee, 1999). Copepods are the largest source of protein and the largest biomass in the oceans; most economically important fishes depend on them as their major food source. There are over 21,000 documented species, 2,600 genera, 250 families, and 10 orders of copepods (Walter and Boxshall, 2008).

The San Francisco Estuary (SFE) hosts several copepod populations. Two orders of copepods are most common in the SFE: Cyclopoida and Calanoida. Members of the Cyclopoida are benthic dwellers that consume diatoms and other algae found on the substrate. Most of the copepod populations in the SFE belong to the order Calanoida. Their unique morphological properties of this genus, including long and feathered antennae and a joint between the 5th and 6th segment of their body, allow them to propel through the water column with relative ease.

Biology and Ecology of copepods

Upon reaching adulthood, female copepods typically become impregnated. Following copulation, a spermatophore containing sperm and other secretions attaches to a female's genital area. These secretions can be stored allowing the female to produce several broods of eggs even if copulation occurs only once. After a few hours or days, an egg sac develops on a female's abdomen. Many species of copepods can produce diapause eggs, which will delay hatching until environmental conditions are favorable (Ambler *et al.*, 1985). Egg production and survival are affected by temperature, diet, light-penetration, and dissolved oxygen levels (Ambler *et al.*, 1985; Dahl *et al.*, 2009). For example, egg production by *Eurytemora affinis*, which produce diapause eggs, has been found to be affected by food concentration and quality, as well as temperature. Development time has been shown to be more affected by temperature when food sources were scarce (Ban, 1994).

Larvae, called nauplii, transition through six naupliar stages of growth. The nauplii molt between each stage until the sixth, when a more significant metamorphosis occurs. In this stage, the size, segmentation, and appendage structure of the nauplii changes and it becomes a copepodite. After a few further molts, the copepod becomes an adult. This entire process typically takes 12 to 15 days, depending upon environmental conditions and availability of food (Forget-Leray *et al.*, 2005; Hairston *et al.*, 1998).

Copepods consume phytoplankton (including diatoms), ciliates, and detrital carbon. The abundance and quality of food sources is important for the health of copepod populations (Ambler *et al.*, 1985). The timing of maximum copepod population densities often correlates with the timing of phytoplankton blooms. Phytoplankton biomass is lowest during the spring and summer, and copepod food supplies are reduced in these months. However, nanoplankton blooms are common in the spring and summer, providing an alternate food source (Ambler *et al.*, 1985).

Populations of the calanoid copepods *E. affinis* and *Pseudodiaptomus forbesi* have been significantly reduced in recent decades (Bennett, 2005; Souza, 2009). These copepod species are a key food source for numerous fish in the SFE, including larval striped bass, juvenile longfin smelt, and delta smelt. It has been postulated that the decline of *E. affinis* and *P. forbesi* have

contributed to the decline of these fish species (commonly referred to as the Pelagic Organism Decline or POD). However, other factors have been implicated in POD; these include reduced water flow, fish entrainment, and competition from invasive species, toxic algae, contaminants, water quality, and the overall reduction of food supply.

Toxic algal blooms may have contributed to the decline of *E. affinis* and *P. forbesi*. Toxic blooms of *Microcystis* have increased in frequency in the SFE, and toxins produced by *Microcystis* may affect copepod populations. Diatoms may also affect copepod populations. Some species of diatoms produce chemicals that decrease egg production and hatching success, cause malformations in nauplii, and lower copepod survival rates (Dahl *et al.*, 2009; Jonasdottir *et al.*, 1998).

Distribution of Copepods in Northern California

The SFE can be divided into five regions: South Bay, Central Bay, San Pablo Bay, the Carquinez Strait, and Suisun Bay. The bays all have deep (10 – 15 m) channels running through their centers, where the light can penetrate to ~10% of the water depth. In the shallower reaches of the bays, the photic zone is much larger, between 50 to 100% of the water depth (Cole *et al.*, 1984). In the South Bay, waters are well-mixed with little freshwater input, low circulation, and a minimal salinity gradient. The South Bay is typically less turbid than the northern reaches of the SFE, but can become so during the rainy season (Hooff *et al.*, 2004; Ambler *et al.*, 1985). The seaward boundary is found in the Central Bay, where saltwater inputs are greatest. In the North Bay, waters are characterized by high suspended sediment and more freshwater inputs (Ambler *et al.*, 1985).

The SFE has been deemed the most invaded estuary in the world (Hooff *et al.*, 2004; Avent *et al.*, 2000). Numerous species of invasive copepods are now established in the SFE. In the SFE, copepods are primarily organized by salinity gradients and their tolerance to these gradients. However, temperature, river discharge, coastal hydrography, and phytoplankton cycles affect their distribution as well. River discharge and coastal hydrography control the amount of freshwater that enters the San Francisco Bay and temperature will affect egg hatching and copepod mortality.

The cyclopoid copepod *Oithona davisae* was introduced in 1963 and by 1980 it was one of the most prevalent species in the SFE (Fuller, 2005). Today, it still dominates the zooplankton community in these regions, alongside *Limnoithona tetraspina*. It is primarily located in shallow lagoons in the South Bay, San Pablo Bay, and the Carquinez Strait. *O. davisae* is not found where significant freshwater sources are present (Ambler *et al.*, 1985; Avent *et al.*, 2000).

Sinocalanus doerri was introduced from mainland China, and is found in the deep river channels of the Sacramento and San Joaquin Rivers. However, *S. doerri* has been found in the SFE at salinities between 6.2 - 14.8%¹. Though the timing and location of introduced copepods into this region cannot be specifically identified, *S. doerri* was first documented in May of 1978. It first appeared in Grizzly Bay and Suisun Bay in early October 1978. It then moved upstream from December through March 1979, and was common in both the Sacramento and San Joaquin Rivers by April 1979. In 1980, high runoff carried it into San Pablo Bay. The downstream extent

¹As a reference, fresh water is $\leq 0.05\%$ salinity (0.5 ppt), brackish water is about 1.7% salinity (17 ppt), and ocean water is 3.5% salinity (35 ppt); see <http://www.onr.navy.mil/Focus/ocean/water/salinity1.htm> and http://www.windows.ucar.edu/tour/link=/earth/Water/dissolved_salts.html&edu=high.

of *S. doerri* may be regulated by salinity. Members of this genus do not produce diapause eggs and their eggs are not carried in an egg sac, but rather they are distributed directly into the water. This characteristic could make the genus a good candidate for introductions, as eggs released to the water are independent of the fate of the parent. The greatest populations of *S. doerri* appear to fluctuate between Suisun Bay and the Delta, contingent upon river flow. Prior to the arrival of this species, copepods were not abundant in the Delta (Ambler *et al.*, 1985). The lack of competition by other copepods species may have contributed to their success. *S. doerri* are a notable food source for juvenile striped bass and they provide an alternate food source to *E. affinis* for these fish. Having another major food source may increase the opportunity for juvenile striped bass to survive farther downstream where *E. affinis* is not present. Due to the differences in salinity preference, *S. doerri* and *E. affinis* are unlikely to compete against one another (Orsi *et al.*, 1983).

P. forbesi was introduced in the 1987. Recently their populations, which reach maximum density in the late summer and early fall, have been declining. This may be a result of predation, environmental pollutants, or other factors (Ger *et al.*, 2009; Norbriga, 2002; Souza, 2009). As other food sources for larval and juvenile delta smelt have diminished, they have consumed more *P. forbesi*. As a result, *P. forbesi* populations have been reduced, allowing populations of the cyclopoid *L. tetraspina* to increase. *L. tetraspina* is not a good food source for delta smelt (Bennett, 2005). *L. tetraspina* was introduced to the SFE in 1993. Originally from the Yangtze River in China, it is now widely distributed across the Eastern Pacific region. It has become the most abundant copepod in the low salinity zone within a year of its introduction and is still the dominant species in this zone. Due to its relatively small size, *L. tetraspina* is not an important food source for visually-selective fish in the SFE (Bouley, *et al.*, 2006).

E. affinis has made its way into North America, Europe and Asia within the last 70 years (Lee, 1999). *E. affinis* is thought to be the most abundant copepod in the northern hemisphere estuaries today (Gasparini *et al.*, 1999). *E. affinis* have the broadest salinity distribution of all species in the *Eurytemora* genus. These copepods are often found in reservoirs affected by pollution or poor water quality, in brackish zones, or in salinities between 5 – 25 psu², but are also found at salinities as high as 40 psu. Freshwater invasions are thought to arise from saltwater populations because of genetic similarities between freshwater and saltwater populations in geographically similar areas. However, transference of *E. affinis* from saltwater to freshwater can result in a very low survival rate among individuals that produce eggs in saltwater (Lee, 1999; Ambler *et al.*, 1985).

Suisun Bay and Suisun River sites were dominated by *E. affinis* and *S. doerri* until 1989. *E. affinis* was typically not found in the northern reaches of the South Bay although they were occasionally found in the southern reaches where water temperatures range from 10 – 20°C and where salinities are typically between 0.5 – 30‰. However, the greatest populations of *E. affinis* are found at salinities of less than 5‰. Though this species can produce diapause eggs, it is unlikely that it does so in the SFE, as hatching temperatures are above 10°C and typical water temperatures exceed this parameter (Ambler *et al.*, 1985; Bennett, 2005).

Tortanus dextrilobus is a carnivorous copepod that was also introduced to the SFE in 1993. It preys upon *O. davisae* and *Acartia clausi* and *Acartia californiensis*. It is now prevalent in the North Bay and South Bay of the SFE (Hooff *et al.*, 2004).

²psu is approximately equal to ppt (http://www.windows.ucar.edu/tour/link=/earth/Water/dissolved_salts.html).

A. clausi is the dominant copepod species where the salinity exceeds 10%. Members of this species can tolerate a salinity range of 5 – 30‰. *A. clausi* is most abundant when temperatures are less than 20°C, thus peak abundance occurs from January through April. High populations in the South Bay coincide with the spring bloom of phytoplankton. In the 1980s, densities were higher in the South Bay than in the San Pablo Bay (Ambler, *et al.*, 1985). When water temperatures increase in the summer and fall months, *A. californiensis* becomes the dominant copepod species in waters where the salinity exceeds 10%. Populations of *A. clausi* or *A. californiensis* reach maximum density two months after the temperature reaches 15°C, likely a function of the hatching of diapause eggs. Populations decrease rapidly when the temperature falls below this level (Ambler, *et al.*, 1985).

In the Central Bay, *Paracalanus parvus* is prevalent. *P. parvus* is a neritic species, found in the waters lying directly above the sublittoral zone. It is found only near the coastal region, and is not present when coastal upwelling occurs. They are only found when coastal inputs originate from warm southern waters (Ambler *et al.*, 1985).

Toxicity of pesticides to Copepods

Little toxicity data are available for copepod species that reside in the SFE. *E. affinis* and *P. forbesi* have recently been identified as potential indicator organisms for pesticide related toxicity, based on their believed sensitivity and importance in the pelagic food chain in the SFE. Studies are currently underway at UC Davis, where Dr. Swee Teh is developing LC/EC₅₀ data for *E. affinis*. He conducted toxicity tests with *E. affinis* using water samples collected from various sites in the SFE. Preliminary results indicate that this species is sensitive to ammonia, bifenthrin, diuron, hydroxyl polycyclic aromatic hydrocarbons (HPAHs), large polycyclic aromatic hydrocarbons (LPAHs), and lambda-cyhalothrin. In the South Bay, diuron appears to be the primary cause of toxicity. In the North Bay, ammonia, bifenthrin, diuron, HPAH, LPAH, and lambda-cyhalothrin were implicated as the likely cause of toxicity. No toxicity was observed in waters collected from Suisun Bay, and populations exposed to these waters appeared to grow larger, darker, and more fecund (Swee Teh, personal communication).

LC₅₀s for copepods have only been developed for atrazine and cypermethrin (Table 1). More research is needed to determine whether copepod species found in the SFE can serve as indicator species for pesticide-related toxicity.

Table 1. LC50 values for atrazine and cypermethrin.

Chemical	Species	LC₅₀ (ug/L)	Reference
Atrazine	<i>E. affinis</i> nauplii	125	Forget-Leray <i>et al.</i> , 2005
Atrazine	<i>A. clausi</i>	7945	Thursby <i>et al.</i> , 1999
Cypermethrin	<i>A. clausi</i>	1.1	Willis <i>et al.</i> , 2004

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