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Introduction of the Asian copepods *Acartiella sinensis*, *Tortanus dextrilobatus* (Copepoda : Calanoida), and *Limnoithona tetraspina* (Copepoda : Cyclopoida) to the San Francisco Estuary, California, USA

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Abstract: Three new Asian copepods were found in the San Francisco Estuary, California, in 1993: *Acartiella sinensis*, *Tortanus dextrilobatus*, and *Limnoithona tetraspina*. The most likely mode of their introduction is ballast water. These introductions raise the total number of copepod species introduced to the estuary to 8. All are from Asia. No native species are known to have been eliminated by the exotic copepods but the abundance of *Eurytemora affinis* and *Diaptomus* spp. has decreased.

Key words: ballast, Copepoda, East Asia, San Francisco Estuary, introduction

Introduction

Ballast water is well-recognized means of transporting aquatic animals around the globe (Carlton 1985). The San Francisco Estuary has proved very vulnerable to invasion by means of ballast water and other vectors: 212 species of fish, invertebrates, vascular plants, and protists have been confirmed as introduced and another 123 species are cryptogenic (Cohen & Carlton 1995). The zooplankton in the low-salinity (1–6 psu) zone of the estuary has been invaded by 5 copepod species: *Sinocalanus doerrii* Brehm (Orsi et al. 1983), *Oithona davisae* Ferrari & Orsi (Ferrari & Orsi 1984), *Limnoithona sinensis* (Burckhardt) (Ferrari & Orsi 1984), *Pseudodiaptomus forbesi*, (Poppe & Richard) and *P. marinus* Sato (Orsi & Walter 1991). This paper reports the introduction of 3 additional species: *Acartiella sinensis* Shen & Lee, *Limnoithona tetraspina* Zhang & Li, and *Tortanus dextrilobatus* Chen & Zhang.

Materials and Methods

The California Department of Fish and Game has maintained a long-term zooplankton monitoring program in Suisun Bay and the delta region of the San Francisco Estuary since 1972 (Fig. 1). The number of stations sampled has varied over the years but the gear has always been a 154-μm mesh Clarke–Bumpus net, 12.7 cm in diameter, and a small pump. See Orsi & Mecum (1986) for a description of sampling.

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Results

Acartiella sinensis was first taken on 7 October 1993 at Stns 54 to 60 in Suisun Bay and at Stn S42 in Suisun Slough (Fig. 1). The salinity at these stations ranged from 2.8 to 4.6 psu. The maximum abundance of *A. sinensis* since 1993 occurred in 2.5–8.6 psu, but the species ranged from freshwater to >20 psu. Its maximum abundance was approximately $10^3 m^{-3}$. It was usually not found before July and its peak abundance occurred in October. Length ranges for males were 1.17 to 1.34 mm, for females 1.27–1.64 mm. This agrees with lengths of 1.23 mm for males and 1.38 mm for females reported from Chaikiang (Chiekong) River, China (Shen & Lee 1963).

Tortanus dextrilobatus was first taken on 11 August 1993 at Stn 44 in Suisun Bay, at 3.6 psu (Fig. 1). Its salinity range was 1.2 to >13 psu. Its maximum abundance of 10^2 to $10^3 m^{-3}$ occurred at the highest salinities, suggesting that it may have been even more abundant downstream from the sampling area. The peak abundance was usually in October but this was influenced by the timing of salinitiy intrusion into Suisun Bay. Male length ranges were 1.85–1.99 mm,

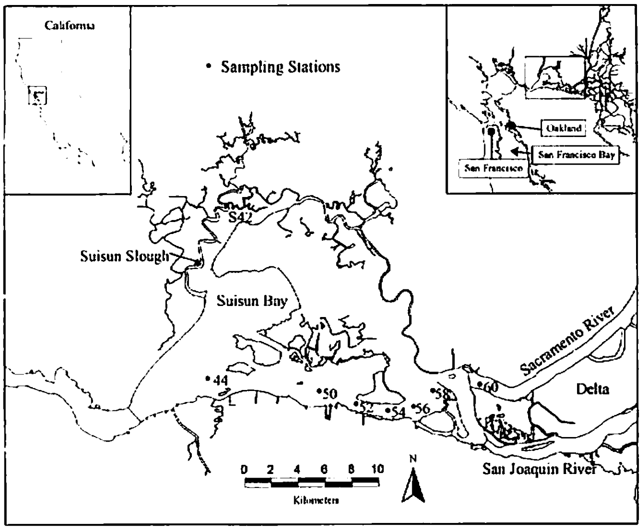

Fig. 1. Map of the San Francisco Estuary showing locations of stations where copepods were first caught.

female lengths 2.02–2.20 mm. This is larger than the 1.53–1.79 mm for males and 1.74–1.79 mm for females from the Somjin River, Korea (Ohtsuka et al. 1992) but is close to the larger sizes of 2.00–2.05 mm for males and 2.00–2.25 mm for females from China (Chen & Zhang 1965).

Limnoithona tetraspina was first taken on 9 September 1993 at Stns 50, 52, and 60 in Suisun Bay at 1.0–3.8 psu. The maximum abundance was $>5\times10^4\,m^{-3}$ and occurred between 1.0–3.2 psu in July and August. Female length ranged from 0.44 to 0.54 mm, compared to 0.48 to 0.53 mm reported by Zhang & Li (1976). *Limnoithona tetraspina* was much more abundant in all seasons, particularly summer, than its congener *L. sinensis* was.

All 3 copepods first appeared in 1993 over 3 consecutive months. They were probably introduced earlier that year because it should not take more than 1 year for them to become abundant enough to detect. Their abundances typically rise from zero or near-zero in winter.

Discussion

East Asian pelagic copepods have been introduced not only to California but also to Hawaii (Jones 1966), Australia (Williams et al. 1988), Chile (Hirakawa 1986, 1988), and Washington State (Cordell et al. 1992). The San Francisco Estuary has been more heavily invaded by copepods than any other locality on the American west coast. Invasions have been postulated to occur in the estuary when it is perturbed by flood or drought. However, the sheer volume of ballast water arriving can also be a factor as shipping at the Port of Oakland increased greatly in the years prior to the 1992–1993 appearance of several species, including 2 species of mysid shrimp (Modlin & Orsi 1997) and 1 crab (Cohen & Carlton 1995).

As Carlton (1987) suggested, the Pacific coast of North America is a distinct "receiver area", whereas East Asia is a major "donor area". The reasons why some regions are donor areas and others are receivers must be examined in the light of evolution and ecology (Carlton 1987). According to Ohtsuka et al. (1995), ~80% of the East Asian brackish water calanoids can be classified as "East Asian initial endemic element", and may have originated from the ancient East China Sea that existed from the middle Pliocene to the Pleistocene (Nishimura 1980, 1981). Generally, marine organisms belonging to this element evolved as taxa highly adapted to brackish water. Pelagic copepods of this element predominate in brackish regions of East Asia (Suh et al. 1991; Ohtsuka et al. 1992, 1995). Nishimura (1980) suggested that initial endemic taxa correspond to a phylogenetically young and evolutionarily activated stage, whereas relict endemic taxa are regarded as a phylogenetically old and evolutionarily declined stage. Hence, East Asian initial endemic copepods may be able to adapt readily to new habitats. Potential copepod invaders of the upper San Francisco Estuary now face an *East Asian fauna rather* than a North American one.

The known ranges of the invading species in Asia are as follows: *Acartiella sinensis* has been found from the estuary of the Pearl River to the east coast of the Luichow Peninsula (Lei-chou Pan Tao), and eastwards to the mouth of the Kiulungkiang River, in southern Fukien (Shen & Lee 1963), and from the mouth of the Chanthaburi River, Thailand (Ohtsuka, unpublished data). It is tropical and stenothermal. *Tortanus dextrilobatus* has been recorded from the coastal regions of Kwangtung Province (Chen & Zhang 1965), the Chaikiang River (Shen & Lee 1966) and the Somjin River, Korea (Ohtsuka et al. 1992). Both *Limnoithona* species have been reported from the Yangtze River mouth (Burkhardt 1913; Zhang & Li 1976).

Five brackish-water copepods have been found in the Chaikiang River (Shen & Lee 1963) as compared to only 1 in the Sacramento-San Joaquin Estuary (Orsi & Mecum 1986) and that species, *Eurytemora affinis* Poppe, is of cryptic origin. Six freshwater species, 1 cyclopoid, the others calanoids, have been reported from the Chaikiang River. In freshwater areas, the San Francisco Estuary is more than comparable as it has 6 Diaptomidae species, 2 other calanoids, and at least 3 cyclopoids (Orsi & Mecum 1986; Orsi, unpublished data). The low salinity fauna of the San Francisco Estuary is thus depauperate and the low salinity zone is the area most likely to contain unoccupied niches. However, of the invading species, only *P. forbesi*, *A. sinensis*, and *L. tetraspina* can be classified as low salinity species, that is, most abundant at 1–6 psu (Table 1). *Sinocalanus doerrii* and *L. sinensis* are freshwater species, *P. marinus* and *T. dextrilobatus* are brackish water species (Ohtsuka et al. 1995), and *O. davisae* is a coastal species that is abundant in brackish water. Thus, there has been no concentration of invaders in any salinity range.

None of the 8 introduced calanoids has occupied quite the same salinity range as *E. affinis*. The range of the first

Table 1. List of copepods introduced to the San Francisco Estuary.

Name	Year Detected	Salinity Preference	Status
Oithona davisae	1963	Highly brackish	Not abundant
Sinocalanus doerrii	1978	Freshwater	Not abundant
Limnoithona sinensis	1979	Freshwater	No longer caught
Pseudodiaptomus marinus	1986	Highly brackish	Not abundant
Pseudodiaptomus forbesi	1987	Low salinity	Abundant
Acartiella sinensis	1993	Low salinity	Abundant
Tortanus dextrilobatus	1993	Highly brackish	Abundant
Limnoithna tetraspina	1993	Low salinity	Abundant

introduction, *S. doerrii*, overlaps the upstream range of *E. affinis* (approximately 0.5 psu). *Pseudodiaptomus forbesi* occupies much of the same salinity range as *E. affinis* but also extends farther upstream than *E. affinis* did; it is the most oligohaline copepod. *Pseudodiaptomus marinus* is located downstream of the *E. affinis* range and *A. sinensis* does not extend into freshwater. *Eurytemora affinis* abundance declined sharply in 1988 at about the time *P. forbesi* became abundant; however *E. affinis* abundance was probably reduced by predation on its nauplii by the Asian clam, *Potamocorbula amurensis* (Kimmerer et al. 1994), rather than by competiton with *P. forbesi*. The strength of the escape response of nauplii to the shear of the incurrent flow of the Asian clam siphon varies by species (Kimmerer et al. 1994). Although *P. forbesi* nauplii were not tested, its coexistence with the Asian clam suggests that it has an effective escape response.

The invading copepods have been both calanoid and cyclopoid and range from carnivores (*T. dextrilobatus*) (Ohtsuka 1991) to grasping particulate feeders (*L. sinensis*) (Nakamura & Turner 1997) to suspension-feeding omnivores (*P. forbesi*, *P. marinus*, *S. doerrii*, and probably *A. sinensis*) (Tranter & Abraham 1971; Uye & Kasahara 1983; Hada & Uye 1991). Some species carry eggs (*P. forbesi*, *P. marinus*), others broadcast them (*S. doerrii*). They have thus no common features that could explain why they became established in the estuary.

No native species has been eliminated by the exotics but the abundance of *Diaptomus novamexicanus*, *D. siciloides*, and *D. pallidus* has been greatly reduced. More remarkably, the previously introduced *L. sinensis* has been replaced by *L. tetraspina*. This happened between the introduction of *L. tetraspina* in October 1993 and the complete disappearance of *L. sinensis* from our samples in early 1994. It is difficult to believe that *L. tetraspina* was solely responsible for this or even responsible in any way because the salinities in which their abundances are highest differ. These species cooccur at the mouth of the Yangtze River where *L. tetraspina* is reported from brackish water (Zhang & Li 1976) and *L. sinensis* from fresh water (Burkhardt 1913). Because their salinity distributions show little overlap it is unlikely that *L. tetraspina* eliminated *L. sinensis*. However, we cannot identify any change in the estuary in 1992–1993 that could have negatively affected *L. sinensis*.

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