Pseudodiaptomus forbesi and *P. marinus* (Copepoda: Calanoida), the Latest Copepod Immigrants to California's Sacramento-San Joaquin Estuary

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Abstract

Ongoing zooplankton studies in the Sacramento-San Joaquin Estuary have resulted in several new records for Asian copepods. The identification of *Pseudodiaptomus forbesi* increases the number of West Pacific species discovered in California to four. Distribution of the species is limited to the upper reaches of the estuary, and varies with temperature and salinity. Reported from China and Japan, this species appears to be restricted to the freshwater estuaries of the Yellow and East China Seas. Another imported species, *P. marinus* replaces *P. forbesi* in the more brackish to saline waters in the lower estuary.

The introduction of aquatic organisms into new habitats by means of ballast water discharged from ocean-crossing ships has become increasingly common (Carlton 1985). The Sacramento-San Joaquin Estuary of California has an extensive trans-Pacific commerce and in recent years has experienced the invasion of three Asian copepods (Orsi et al. 1983; Ferrari & Orsi 1984). It has major ports at San Franisco and Oakland that border on San Francisco Bay and also at Stockton and Sacramento on the San Joaquin and Sacramento rivers that empty into San Francisco Bay. Minor ports and landings are scattered along the shores of San Pablo and Suisun bays that connect San Francisco Bay with its tributary rivers. Hence, it has habitats that are vulnerable to the introduction of marine, fresh water and brackish water orgamisms. This paper reports on the recent introduction of the calanoid copepods, *Pseudodiaptomus forbesi* (Poppe & Richard 1890) and *P. marinus* (Sato 1913).

Pseudodiaptoms forbesi appears to be endemic to fresh and brackish water habitats of the Yangtze River, China (Poppe & Richard 1890). The original range of *P. marinus* was the boreal, marine waters of Japan (Walter 1986), but it has been introduced to Hawaii (Jones 1966), Mauritius (Grindley & Grice 1968), and two small bays north of San Diego, California (Fleminger & Kramer 1988).

The California Department of Fish and Game (CDFG) has an extensive and long-term plankton sampling program that runs from March to November of each year throughout the Suisun Bay and Delta areas of the estuary, and during high fresh water outflows of spring, into San Pablo Bay. Oblique bottom to surface tows are taken with a Clarke-Bumpus net with 154 μm mesh at a number of fixed stations (Orsi & Mecum 1986). Surface electrical conductivity (converted to salinity) and temperature are also measured.

Pseudodiaptomus forbesi (Poppe & Richard 1890) (Fig. 1A-L)

Schmackeria forbesi Poppe & Richard 1890, p. 396, pl. 10, figs. 1-14. —Shen & Tai 1962, p. 116. —Shen 1979, p. 67, fig. 26a-h.

Pseudodiaptomus forbesi. —Burckhardt 1913, p. 379, pl. 11e, figs. 1, 6, pl. 11f. fig. 5, pl. 11g. figs. 5, 9, pl. 12h, figs. 5, 6, 9. —Kikuchi 1928, p. 69, pl. 19, figs. 19-20; 1936, 282, tbl. 1. —Marsh 1933, p. 44, pl. 21, figs. 4, 5, 7. —Mashiko 1951, p. 151, fig. 6e-h; 1955, p. 140.—Mashiko & Inoue 1952, p. 184, fig. 8f-k. —Borutzky 1960, p. 22, fig. 4(5).

Material. —Specimens were deposited at the U. S. National Museum, Smithsonian Institution. Collected from United States, California, Sacramento-San Joaquin River Estuary, Suisun Bay, 38°00′ N 122°00′ W, oblique tow from near bottom to surface, coll. by Orsi, J. J., USNM 239296, 07 SEP 1989, 50F, 50M. Sacramento River, USNM 239237, 10 JUN 1988, 50F, 50M. China, Pearl River, coll. by Chen, Q. C., USNM 216282, 12 FEB 1982, 10F, 11M.

Abbreviations used in the text to describe morphological features are: A1=first antenna, P1-5=swimming legs 1-5, Pdg1-Pdg5=pedigers 1-5, Pr=prosome, Ur=urosome, Ur1-5=urosome 1-5, CR=caudal rami, B1-B2=basipods, Re=exopod, Ri=endopod, Se=outer spine, Sp=spermatophore.

Sex	No.	Length (mm)	$\bar{x}$	Pr $\bar{x}$	Ur $\bar{x}$	Pr:Ur
Female	40	1.10−1.18	1.16	0.76	0.42	1.8 : 1
Male	40	0.97−1.04	1.00	0.64	0.36	1.8 : 1

Both sexes with mouthparts and P1-4 same as in Nishida (1985) and Walter (1986). Head fused with Pdg1, rostrum with 2 long slender filaments. Pdg5 with rounded corners.

Female: Pdg2-4 with very fine spinules along proximal margin extending incompletely dorsad. Pdg4-5 fused; Pdg5 with 2 small posterodorsal spines (sometimes bifid), rounded lateral protrusion, and ventrolateral spinules (Fig. 1A-B). A1 with 21 segments (Fig. 1C), segment 3 with posterior spinule row. Urosome with 4 segments. Ur1 with proximolateral fine spinules extending dorsad, larger dorsal spinules at midlength decrease in size laterad. Ur1-3 with distal scales. CR symmetrical, 3x longer than wide, with 5 terminal plumose setae (Fig. 1D), lateral seta shortest and spiniform, 3 setae after medial divided into 3 sections. Ur segments and CR with proportions 30:19:20:11:20=100. Egg sacs paired.

Female P5 posterior view (Fig. 1E): B1 with 2 distally directed proximal and 1 medially directed spinule rows. B2 with 1 large dorsal spinule, 3 rows of fine medial

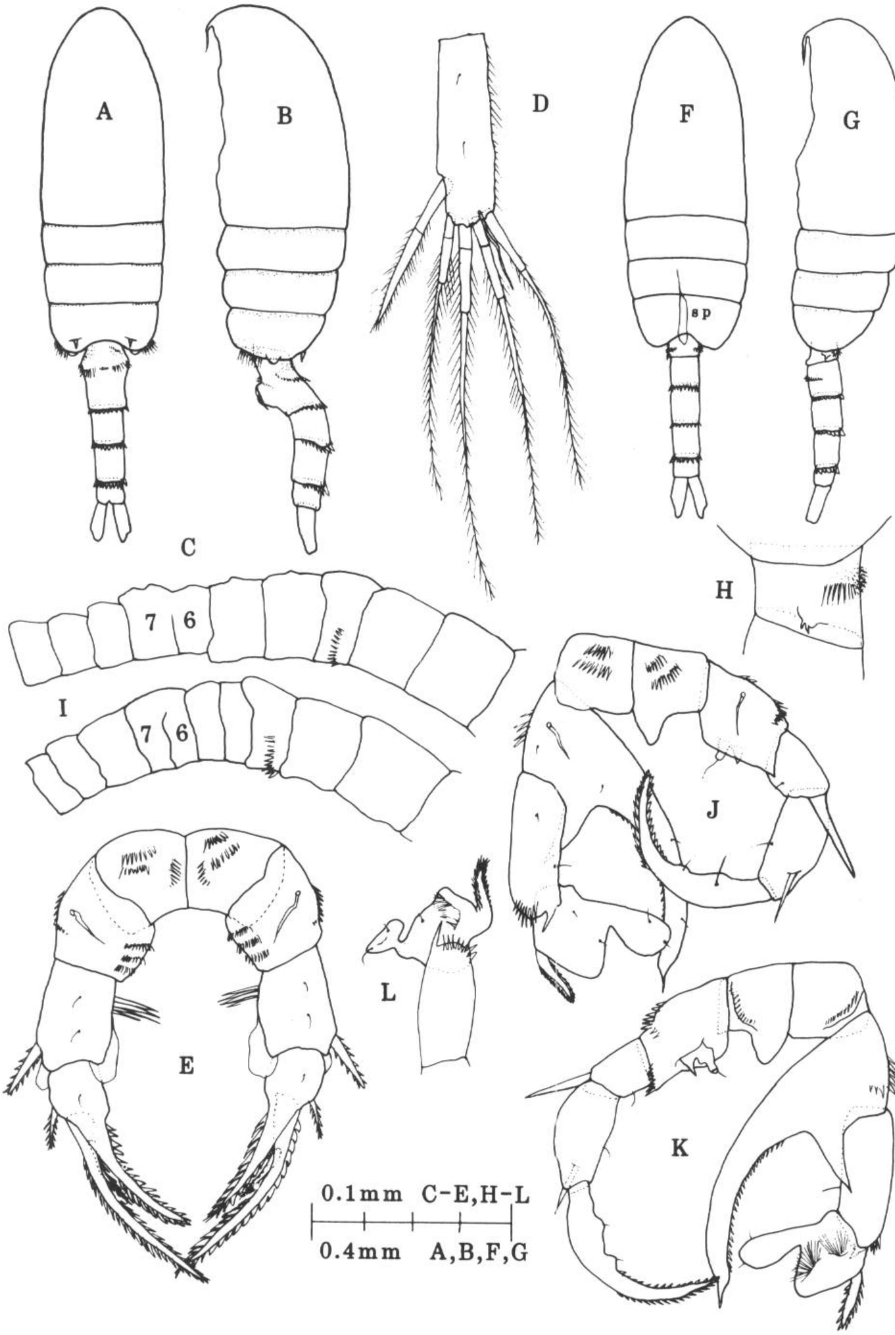

Fig. 1. *Pseudodiaptomus forbesi,* Poppe & Richard, 1890. Female A-E; A. Habitus, dorsal; B. Habitus, lateral; C. A1 first 10 segments; D. Caudal ramus; E. P5, posterior view; Male F-L; F. Habitus, dorsal; G. Habitus, lateral; H. Ur1 left lateral; I. A1 first 10 segments; J. P5, posterior view; K. P5 anterior view; L. P5, lateral view.

spinules and row of lateral spinules. Re1 with 2 small dorsal spinules, 3-5 large strong medial spinules, distomedial corner with large variably shaped lobate hyaline membrane, smaller distolateral hyaline membrane and distolateral Se strongly serrate. Re2 with surface seta, lateral Se serrate, and distomedial spiniform process strongly serrate. Re3 longer than Re2 process with serrate proximomedial process less than 1/2 the length of Re2 process.

Male: Pdg5 lacking dorsal spines. Spermatophore small and slender. Ur1 with lateral spinules extending dorsad, left lateral spiniform process occasionally bifid (Fig. 1F-H). Left A1 with 21 and right A1 with 19 segments, segment 3 with spinule row (Fig. 1I). Ur2 with 1 ventral spinule row. Ur2-4 distal scales complete. CR symmetrical, 3x longer than wide, setae as in female. Ur segments and CR with proportions 11:17:21:19:11:21=100.

Male P5 posterior view (Fig. 1J): Right leg, B1 with 2 proximal rows of spinules, medial margin produced into large triangular process. B2 with large surface surface spinule, distolateral spinule row. Re1 and Re2, with small medial seta, the former with naked Se 3/4 length of Re2, the latter with naked Se 1/2 length of Re2. Re3 elongate with 2 medial knobs and setae, distal margins serrate. Left leg, B1 same as in right though without knob. B2 with 4 small and 1 large surface setae, medial margin produced into very large, laterally directed, acutely pointed bifid process; lateral margin serrate between points, lateral point more than 1/2 length of Re1, medial point extends beyond Re2. Re1 with 2 surface setae, distolateral spinule row and laterally directed distomedial spiniform process. Re2 with 4 surface setae, serrate lateral Se, and distolateral edge deeply cut into "V" shape (approx. 45° cut) producing a rounded digitiform apical process. Anterior view (Fig. 1K): Both B1 with subapical spinule row along suture. Both B2 with distolateral spinules, right B2 with distomedial spinules, and small bifid Ri at midlength, proximal process irregular shape with apical seta, distal point shorter and acutely pointed. Left Re2 with surface hair row. Lateral view of left Re1-2 (Fig. 1L).

Remarks. This species was originally reported from and appears to be endemic to the Yangtze River region of China. It is a stenohaline species found in low salinity waters of less than 8‰, though it may occasionally be found in higher salinity waters, for short periods, of time. Studies by Kikuchi (1928 & 1936) indicated that *P. forbesi* was found in Sibayama Lake, Hokuriku District, Japan. Unfortunately, he indentified the species based on only the female and its urosome and CR setae. Later, Mashiko (1951) and Mashiko & Inoue (1952) sampled the same areas and found only *P. inopinus,* noting that most females have the typical thick CR setae. However, some individuals were reported to have thin CR setae as in *P. forbesi.* From personal examination of both species (by T. C. W), we are convinced that Kikuchi misidentified *P. inopinus,* as *P. forbesi,* since the species appears to have variably shaped CR setae, possibly due to changes in environmental conditions or differences among subspecies.

The arrival of *P. forbesi* to California is the first confirmed report of this species outside of Chinese waters. Its transport to this region is discussed below.

Pseudodiaptomus marinus Sato 1913
This species was collected from the Sacramento-San Joaquin River Estuary, Suisun Bay and has been deposited as USNM 239291. It was originally described by Sato (1913) from Hokkaido, Japan. It is known throughout Japan, with subsequent reports indicating a possibly wider distribution. Recently, it was reported in the California, San Diego region by Fleminger & Kramer (1988) and Walter (1989). See the above references for a complete review of the species and its distribution.

Distribution in the Sacramento-San Joaquin Estuary

Pseudodiaptomus forbesi first appeared in CDFG samples in late October 1987 at three stations in the San Joaquin River between Stockton and the mouth of the Mokelumne River (Fig. 2). This was in fresh water and in a channel 10 m deep. It was also taken at the same time in Old River near the intake for the State and Federal pumping plants that export water to the San Joaquin Valley and southern California. This was also fresh water and in a 5 m deep channel. During November, *P. forbesi* disappeared from these locations and was collected farther down the San Joaquin River below the mouth of the Mokelumne River and in the Sacramento River at Decker Island, all fresh water locations.

In 1988, *P. forbesi* was first observed in early April at the pumping plant intake in Old River. It was rare during May, but in June it appeared in the San Joaquin River at Stockton and spread downstream from there (Fig. 3). The CDFG was unable to sample during July and when sampling resumed in August, *P. forbesi* had spread throughout the Delta and down into Suisun Bay. It remained abundant and

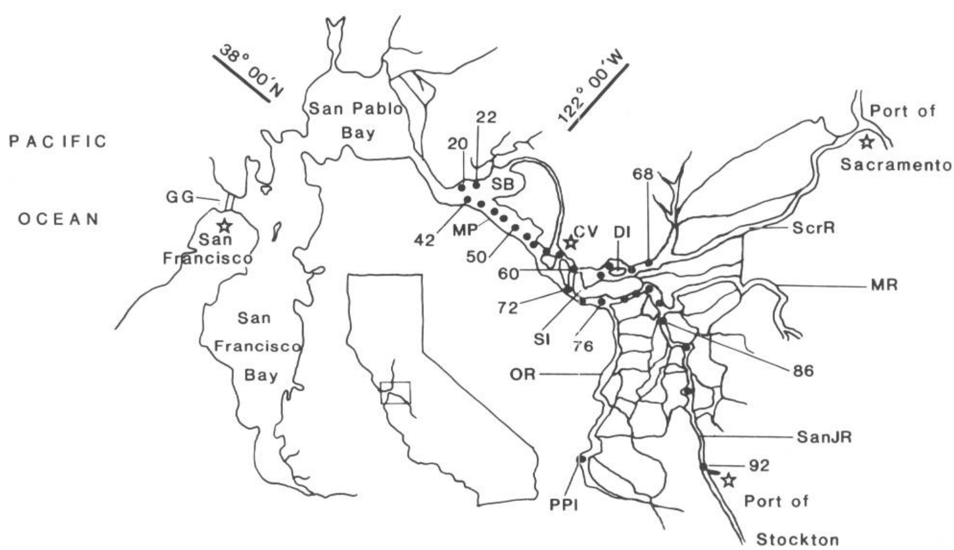

Fig. 2. Map of the Sacramento-San Joaquin Estuary. Black dots are sampling locations. CV—Collinsville, DI—Decker Island, GG—Golden Gate, PPI—pumping plant intake, MP—Middle Point, MR—Mokelumne River, OR—Old River, —SI Sherman Island, SanJR—San Joaquin River, ScrR—Sacramento River, SB Suisun Bay.

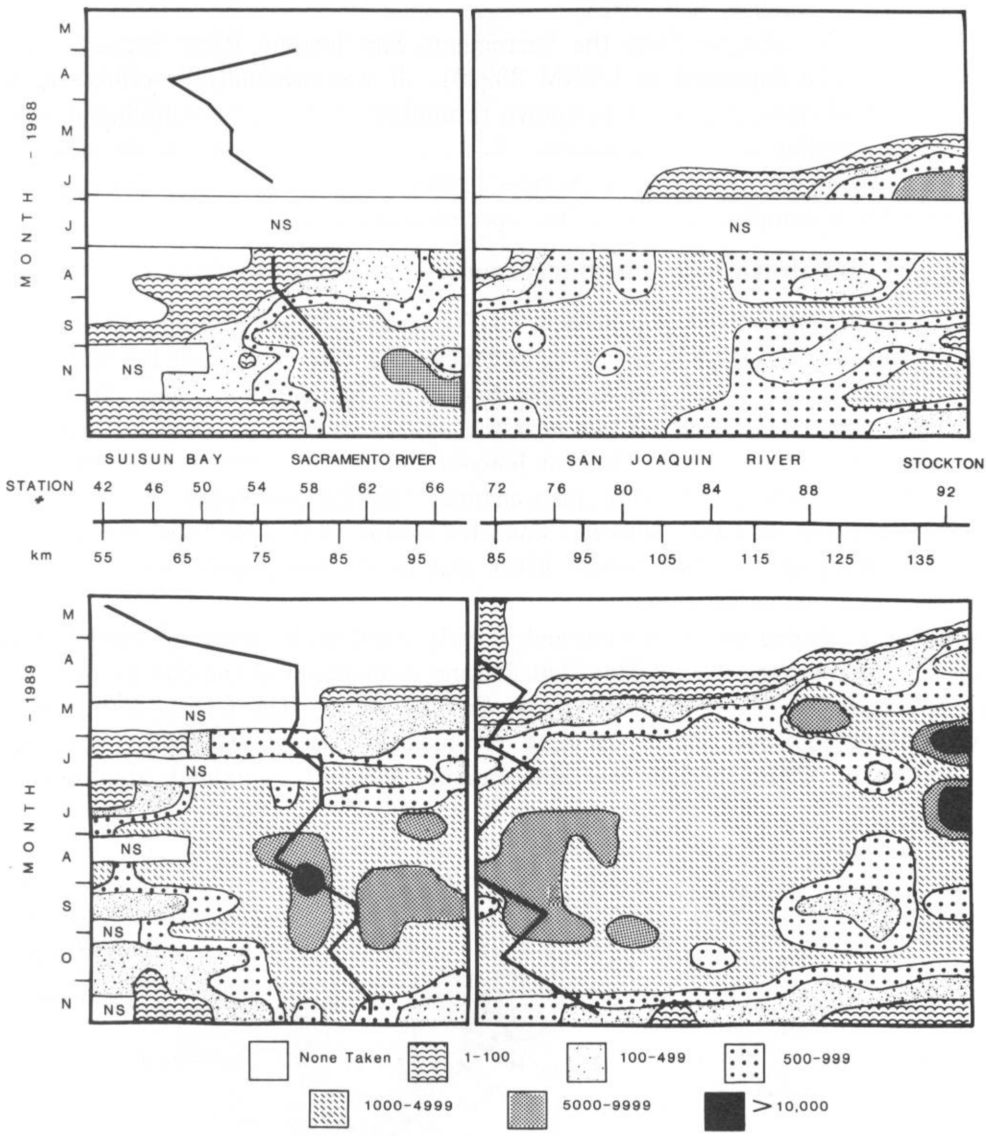

Fig. 3. Monthly abundance and distribution for *Pseudodiaptomus forbesi* based on number of copepods m^{-3} during 1988 and 1989. Area covered is from western Suisun Bay up the Sacramento River to Rio Vista (Sta. 68) and in the San Joaquin River to Stockton (Sta. 92). The black line is the 1.2‰ isohaline showing the approximate location of the entrapment zone. NS=no sample collected. Distance is in kilometers from the Golden Gate Bridge.

widespread the rest of the year throughout the Bay and Delta. Salinity ranged from fresh water to a high of 16.1‰ at the surface and 16.4‰ at the bottom in Suisun Bay. The maximum abundance of 5651 adults m^{-3} was recorded in the Sacramento River at Decker Island at 0.6‰ surface salinity.

In 1989, the population developed earlier than in 1988, starting in April at

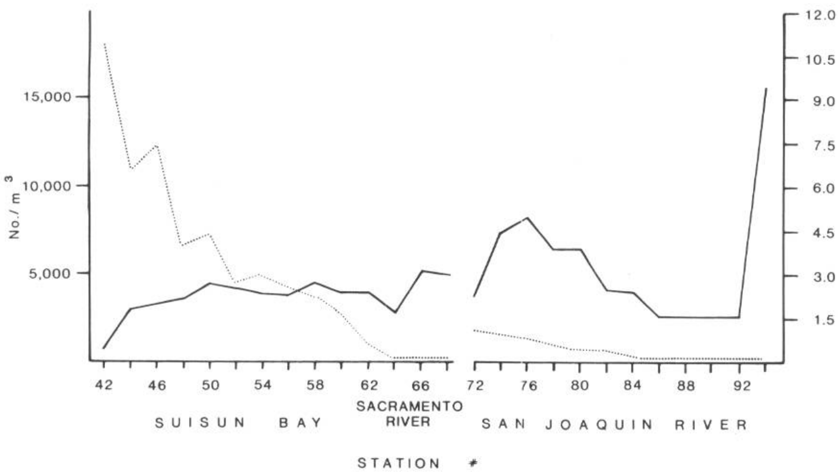

Fig. 4. Abundance of *Pseudodiaptomus forbesi* (solid line) in relation to salinity (dotted line) throughout Suisun Bay and the Sacramento and San Joaquin Rivers on the second July 1989 survey.

Stockton and spreading downstream from there (Fig. 3). By June it was present throughout Suisun Bay and the Sacramento and San Joaquin rivers. Abundance was generally >1000 m^{-3} over the entire sampling area from July to October except in western Suisun Bay where salinity was highest and in the San Joaquin River at the mouth of the Mokelumne River. Peak abundance of 22,408 m^{-3} was recorded at Stockton during early June in fresh water.

Abundance at all channel stations from western Suisun Bay (Sta. 42) to Rio Vista (station 68), and Stockton (Sta. 92) was examined on the second July survey (Fig. 4). At this time, abundance was fairly constant at 3000 to 6000 m^{-3} throughout central and eastern Suisun Bay and up the Sacramento River as far as Rio Vista in spite of the large salinity range from freshwater to 7.3‰ surface salinity.

Populations declined sharply at the westernmost Suisun Bay station where salinity reached 10.8‰. Abundance was higher in the lower San Joaquin River than in either the Sacramento River or in Suisun at comparable salinities. The San Joaquin population had two modes, one at Sherman Island and a larger one at Stockton. The lower abundance between these modes may be caused by the entrance of large volumes of Sacramento River water into the San Joaquin via Mokelumne River. This water is introduced as a result of pumping Sacramento River water across the Delta to the export pumps on Old River (Orsi & Mecum 1986). This Sacramento River water originates upstream from the Delta where *P. forbesi* may not extend. The very high abundance at Stockton is also typical of native zooplankton and may be caused by higher temperatures and/or long water residence times in this section of the river (Orsi & Mecum 1986).

Abundance of *P. forbesi* was unrelated to the entrapment or null zone, a region of long water residence times, high turbidity, high concentrations of suspended sediments, phytoplankton and some species of zooplankton, which occurs between surface salinities of 1.2 and 5.6‰. Salinity is typically stratified in this zone with a net seaward flow of surface water and a net upstream displacement of the bottom water. However, because of low fresh water outflow during the summer and autumn of 1988 and 1989, salinity stratification and the surface and bottom currents were poorly developed, and hence, may have ineffective at concentrating the copepods.

The lower spring abundance of *P. forbesi* during 1988 as compared to 1989 was probably the result of its recent introduction in the fall of 1987 and the time required for the population to build up. The absence of specimens during March suggests that the population may develop from resting eggs.

Pseudodiaptomus marinus, was first observed almost a year before *P. forbesi.* It was collected in western Suisun Bay at stations 20 and 22, in water 8.5 m deep, during October and November 1986 at surface salinities of 6.1 to 7.8‰ and bottom salinities of 8.6 to 9.5‰. The CDFG did not sample again until March 1987 and it was not until late June 1987 that additional specimens were caught, again at station 22. *Pseudodiaptomus marinus* continued to appear in CDFG catches on every biweekly survey of 1987, always in western and central Suisun Bay at surface salinities from 6.3 to 14.8‰ and bottom salinities of 7.7 to 16.6‰. Its maximum abundance was 390 m^{-3} at the maximum salinity recorded, 14.8‰.

In 1988, *P. marinus* first appeared in early April, once again in western Suisun Bay. It was caught consistently throughout the year and ranged upstream as far as Collinsville on the Sacramento River. The salinity range was 2.5 to 17.9‰ surface, 4.0 to 18.9‰ bottom. Maximum abundance reached 838 m^{-3} at a surface salinity of 17.1‰.

During 1989, it was somewhat less abundant with a maximum of 296 m^{-3} at a surface salinity of 14‰ and it extended only as far upstream as Middle Point in Suisun Bay. The sampling area in these years, all of them low outflow years except 1986, was obviously at the upstream limit of the range of *P. marinus.*

Discussion

Dumping of ballast water from ocean-crossing ships has been the mechanism judged most likely to have caused the introductions of *Sinocalanus doerrii* and *Limnoithona sinensis* (Orsi et al. 1983; Ferrari & Orsi 1984) and is the most likely mode of introduction of *P. forbesi.* However, shipments of organisms for shellfish aquaculture is believed responsible for the appearance of *P. marinus* in Mission Bay and Agua Hedionda Lagoon near San Diego as there are no ports in these embayments (Fleminger & Kramer 1988). *Pseudodiaptomus marinus* has recently been noted in Tomales Bay (W. Kimmerer, pers. commun.), 43 km north of San Francisco Bay, where oysters are extensively cultured. The possible means of introduction to San Francisco Bay are thus: 1) direct introduction by ship ballast from the Orient, 2) indirect introduction by coastal currents from either San Diego or Tomales Bay (assuming the Tomales Bay specimens arrived first in oyster shipments).

It is difficult to ascertain the impact of *P. forbesi* on the introduced and native calanoids in Suisun Bay and the Delta. Both *Eurytemora affinis* and *Sinocalanus doerrii* were reduced in abundance during 1988 and 1989 but this is also the time frame when an Asian clam, *Potamocorbula amurensis,* became established in the estuary (Carlton et al. 1990). In laboratory experiments the clam fed extensively on the nauplii of *E. affinis* and on phytoplankton (W. Kimmerer, pers. commun.), and thus could have been at least partly responsible for the decline of this copepod.

Pseudodiaptomus forbesi was the most abundant calanoid in Suisun Bay and Delta during 1989 and the fall of 1988. These were both dry years when river outflow was low. High fresh water outflow might reduce the abundance of the clam and allow the three copepods to interact in unpredictable ways. Or, if ballast dumping is not stopped, additional organisms, benthic and planktonic, might be introduced and continue to alter this vulnerable ecosystem.

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Literature Cited

Borutzky, E. V., 1960. Key to the identification of the free-living fresh water copepods of the USSR and neighboring countries according to fragments in the intestines of fish. Ichthyol. Comm.; Inst. Animal Morph. of A. N. Severtsova., 218pp.

Burckhardt, G., 1913. Wissenschaftliche Ergebnisse einer Reise um der Erde von M. Pernod und C. Schröter. III. Zooplancton aus ost-und süd-asiatischen Binnengewässern. *Zool. Jahr., Abt. Okol. Geogr. Tiere.,* 34:341-472, pls. 9-17.

Carlton, J. T., 1985. Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. *Oceanogr. mar. Biol. Ann. Rev.,* 23:313-371.

Carlton, J. T., J. K. Thompson, L. E. Schemel, & F. H. Nichols, 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian Clam *Potamocorbula amurensis.* I. Introduction and dispersal. *Mar. Ecol. Prog. Ser.,* 66:81-94.

Ferrari, F. D. & J. Orsi., 1984. *Oithona davisae,* new species, and *Limnoithona sinensis* (Burkhardt, 1912) (Copepoda: Oithonidae) from the Sacramento-San Joaquin estuary, California. *J. crust. Biol.,* 4:106-126.

Fleminger, A. & S. H. Kramer., 1988. Recent introduction of an Asian estuarine copepod, *Pseudodiaptomus marinus* (Copepoda: Calanoida) into southern California embayments. *Mar. Biol.,* 98:535-541.

Grindley, J. R. & G. D. Grice., 1968. A redescription of *Pseudodiaptomus marinus* Sato (Copepoda: Calanoida) and its occurrence at the island of Mauritius. *Crustaceana,* 16:125-134.

Jones, E. C., 1966. A new record of *Pseudodiaptomus marinus* Sato (Copepoda: Calanoida) from the brackish waters of Hawaii. *Crustaceana,* 10:316-317.

Kikuchi, K., 1928. Freshwater Calanoida of middle and southwestern Japan. *Mem. Coll. Sci., Kyoto imp. Univ., Ser. B.* 4:65-79, pls. 18-22.

Kikuchi, K., 1936. Fresh-water and brackish-water calanoid copepods of Japan with notes on their geographical distribution. *Bull. biogeogr. Soc. Japan.,* 6:257-284.

Marsh, C. D., 1933. Synopsis of the calanoid crustaceans exclusive of the Diaptomidae, found in fresh and brackish waters, chiefly of North America. *Proc. U. S. natl. Mus.,* 82:1-58.

Mashiko, K., 1951. Studies of the fresh-water plankton of China (II). *Sci. Rep. Kanazawa Univ.,* 1:137-154.

Mashiko, K., 1955. A study of the brackish-water plankton in Japan, with special reference to the relation between the plankton fauna and the salinity of the water. *Sci. Rep. Kanazawa Univ.,* 4:135-150.

Mashiko, K. & A. Inoue., 1952. Limnological studies of the brackish-water lakes in the Hokuriku District, Japan. *Spec. Publ. Japan Sea region. fish. Res. Lab.* 3rd Anniv. Founding, pp. 175-191.

Nishida, S., 1985. Pelagic copepods from Kabira Bay, Ishigaki Island, southwestern Japan, with the description of a new species of the Genus *Pseudodiaptomus. Publ. Seto mar. biol. Lab.,* 30:125-144.

Orsi, J. J., T. E. Bowman, D. C. Marelli & A. Hutchinson., 1983. Recent introduction of the planktonic calanoid copepod *Sinocalanus doerrii* (Centropagidae) from mainland China to the Sacramento-San Joaquin Estuary of California. *J. Plankton Res.,* 5:357-375.

Orsi, J. J. & W. L. Mecum., 1986. Zooplankton distribution abundance in the Sacramento-San Joaquin Delta in relation to certain environmental factors. *Estuaries,* 9:326-339.

Poppe, S. A. & J. Richard., 1890. Description du *Schmackeria forbesi* n. gen. et sp., Calanide nouveau recueilli par M. Schmacker dans les eaux douces des Environs de Sahnghai. *Mem. Soc. Zool. Fr.,* 3: 396-403.

Sato, C., 1913. Free-swimming Copepoda (1). *Hokkaido fish. Res. Lab. Invest. Rep.,* 1:1-82.

Shen, C. J., 1979. *Fauna Sinica, Crustacea Freshwater Copepoda.* Fauna Edit. Comm., Acad. Sinica, Science Press, Peking, 450pp.

Shen, C. J. & A. Y. Tai, 1962. The Copepoda of the Wu-Li Lake, Wu-sih, Kiangsu Province. I. Calanoida. *Acta Zool. Sinica.* 14:100-118.

Walter, T. C., 1986. New and poorly known Indo-Pacific species of *Pseudodiaptomus* (Copepoda: Calanoida), with a key to the species groups. *J. Plankton Res.,* 8:129-168.

Walter, T. C., 1989. Review of the New World species of *Pseudodiaptomus* (Copepoda: Calanoida), with a key to the species. *Bull. mar. Sci.,* 45:590-628.