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Recent introduction of the planktonic calanoid copepod *Sinocalanus doerrii* (Centropagidae) from mainland China to the Sacramento-San Joaquin Estuary of California

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Abstract. The planktonic calanoid copepod, *Sinocalanus doerrii*, a native of the rivers of mainland China was found in 1978 in California's Sacramento-San Joaquin Estuary during routine plankton sampling. Previous plankton surveys in 1963 and from 1972 to the present indicate that the introduction occurred a relatively short time before specimens were first caught. The most probable mode of introduction is ballast water from Japanese freighters previously docking in China. *S. doerrii* became abundant in the Sacramento and San Joaquin Rivers in 1979 and may be regarded as well established. Its impact on the native plankton is as yet unknown.

Introduction

In the past 133 years between 75 and 100 species of marine invertebrates have been introduced into San Francisco Bay and its upstream reaches (Carlton, 1979a, 1979b). However, only one of these was a copepod, *Mytilicola orientalis*, which is a shellfish parasite. No introductions of planktonic species have been reported. This paper describes the first introduction of a pelagic copepod, *Sinocalanus doerrii*, to the Sacramento and San Joaquin Rivers, which discharge into San Francisco Bay. The species is endemic to the rivers of mainland China.

Methods

S. doerrii was taken in the routine plankton sampling programs of the California Department of Fish and Game (DGF), the U.S. Geological Survey (USGS), and Ecological Analysts, a private consulting firm. The DFG used a No. 10 (154 μm mesh) Clarke-Bumpus net mounted on a steel frame towed obliquely in several steps from bottom to surface for 10 min. The USGS pumped water from surface, midwater and bottom depths through a 64 μm mesh with a Jabsco 5 cm pump. Ecological Analysts employed a pair of conical nets, 2.5 m long, mouth diameter 0.5 m, cod end 9 cm, 505 μm mesh, with General Oceanics digital meters to measure water volumes filtered. Tows were 5 min on the bottom, followed by a 5 min stepwise oblique tow to the surface. The DFG sampled

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throughout Suisun Bay and the Delta, with excursions into San Pablo Bay during high winter-spring river flows. The USGS sampled from the western Delta throughout San Francisco Bay. Ecological Analysts sampled intensively in the Pittsburg area of Suisun Bay with occasional surveys up the Sacramento and San Joaquin Rivers. Stations were usually sampled twice a month during spring through fall and once a month in winter. Various environmental measurements were made at each station: the DFG took surface electrical conductivity (EC), temperature, chlorophyll *a* (1 m depth), and Secchi disc measurements; USGS measured vertical distribution of salinity, temperature, chlorophyll *a*, and light extinction coefficients; Ecological Analysts measured surface and bottom temperature and electrical conductivity. The DFG began its study in January 1972, USGS in February 1978, and Ecological Analysts in May 1978.

Results

Taxonomy

The genus *Sinocalanus* was proposed by Burckhardt (1913) for 3 species of calanoid copepods of the family Centropagidae, 2 of which had previously been assigned to the genus *Limnocalanus* Sars, 1863, and a new species, *S. mystrophorus*, now considered a junior synonym of *S. doerrii* (Brehm, 1909). Five species of *Sinocalanus* are currently recognized, 4 from estuaries and coastal rivers of China and one, *S. tenellus* (Kikuchi, 1928), from Japan, Korea, the Kurile Islands, Sakhalin Island, and the mouth of the Suifun River (near Vladivostok).

Sinocalanus was initially misidentified as *Limnocalanus* by personnel of the three organizations. This is not surprising, since keys to North American fresh- and brackish-water copepods, such as those of M.S. Wilson (1959) and Pennak (1978), did not include *Sinocalanus*, specimens of which key out in these works to *Limnocalanus*. The more extensive key to calanoid genera of C.B. Wilson (1932) is faulty in the couplet separating *Limnocalanus* and *Sinocalanus* and does not lead unequivocally to the latter. To forestall future misidentifications, we list below in tabular form the characteristics that separate the 2 genera.

Sinocalanus	*Limnocalanus*
Pediger 5 with spine on each posterior corner	Pediger 5 unarmed
Caudal rami without surface spinules	Caudal rami with surface spinules
Antenna 2 exopod longer than endopod	Endopod longer than exopod
Antenna 2 distal endopod segment not longer than wide	Distal segment much longer than wide
Antenna 2 exopod 2nd segment not distally bilobed	2nd exopod segment distally bilobed
Maxilliped 2nd basipod segment with modified short setae	2nd basipod with normal setae
♀ leg 5: 2nd exopod segment without outer spine; 1st endopod segment without inner seta	♀ leg 5: 2nd exopod segment with outer spine; 1st endopod segment with inner seta
♂ right leg 5: 1st basipod segment without medial process; 2nd basipod segment with medial process (except in *S. solstitialis*)	♂ right leg 5: 1st basipod segment with medial process; 2nd basipod without medial process

The species of *Sinocalanus* can be distinguished by the medial process on the 2nd basipod of the ♂ right leg 5. This process is thumblike in *S. doerrii*, membranous in *S. laevidactylus*, pointed in *S. sinensis*, absent in *S. solstitialis*, and bifurcate in *S. tenellus*. A key to the species of *Sinocalanus*, with diagnoses and illustration of each species, is given by Shen and Song (1979).

The San Francisco Bay specimens are *Sinocalanus doerrii* (Brehm, 1909). Brehm's description is brief, and only the ♂ right antenna 1 and right leg 5 are illustrated. However, *S. doerrii* was described at great length and fully illustrated by Burckhardt (1913) as *S. mystrophorus*. To redescribe the species here would be repetitious and unnecessary, but to document that the species in the Bay is *S. doerrii* and to aid in its identification, we provide illustrations of our specimens (Figures 1 and 2) which have been deposited in the U.S. National Museum.

S. doerrii was originally described from a pond at Lung-wa Pagoda, Shanghai (Brehm, 1909). Burckhardt (1913) recorded it (as *S. mystrophorus*) from 3 localities near Shanghai. It occurs throughout the middle and lower reaches of the Yangtse River and its neighboring waters. Mashiko (1951a, 1951b, 1954) found it in the river and in 4 ponds in the suburbs of Hankow, and further up the river in Lake Tungting-hu, ~ 1000 km from the mouth of the Yangtse. To the north it occurs in the Yellow (Huang) River at Tung Ping Lake (Shantung Province), Bai-Yang-Dien (Hopeh Province), and Wu-La-Su-Hai (Inner Mongolia) (Shen and Tai, 1962). To the south, it has been reported from the Pearl (Chu) River Delta (Shen and Tai, 1964). Both Shen and Tai (1962) and Mashiko (1951a, 1951b) state that *S. doerrii* is a freshwater species.

Appearance and spread in the Sacramento-San Joaquin Estuary

The first specimens of *S. doerrii* were taken from the Sacramento River near Pittsburg on 31 May 1978 by Ecological Analysts (Figure 3). They took additional specimens in July, but the DFG did not catch any until October, although it sampled near Pittsburgh every month of that year beginning in January. The USGS first caught the species on its December 1978 cruise. Specimens were sent to the second author, who made the identification of *S. doerrii*.

Since DFG sampling was the most extensive, its data will document the spread of the species. *S. doerrii* first appeared in DFG material in Grizzly Bay in early October 1978 with a density of 29 adults m^{-3}, at 3.4‰ S, and in Suisun Slough, 100 adults m^{-3} at 4.2‰ S. By November, it was found at scattered locations throughout Suisun Bay, a little past Collinsville in the Sacramento River, and in the San Joaquin River near its junction with the Sacramento at salinities from 0.5 to 10.2‰. Maximum density of 373 m^{-3} was reached above Collinsville at

December 1978 through March 1979 sampling was incomplete in the Sacramento and San Joaquin Rivers but enough stations were occupied to show that *S. doerrii* moved upstream during these months (Figures 4 and 5). By late March 1979, *S. doerrii* was common throughout both rivers to about Decker Island in the Sacramento River and the mouth of Old River in the San Joaquin. It was not taken at Stockton until April I survey (4 April 1979) and did not reach Hood on the Sacramento River until the July I survey (29 June 1979). The high runoff of January 1980 carried *S. doerrii* into San Pablo Bay (Figure 6), but it was never taken in USGS San Francisco Bay samples.

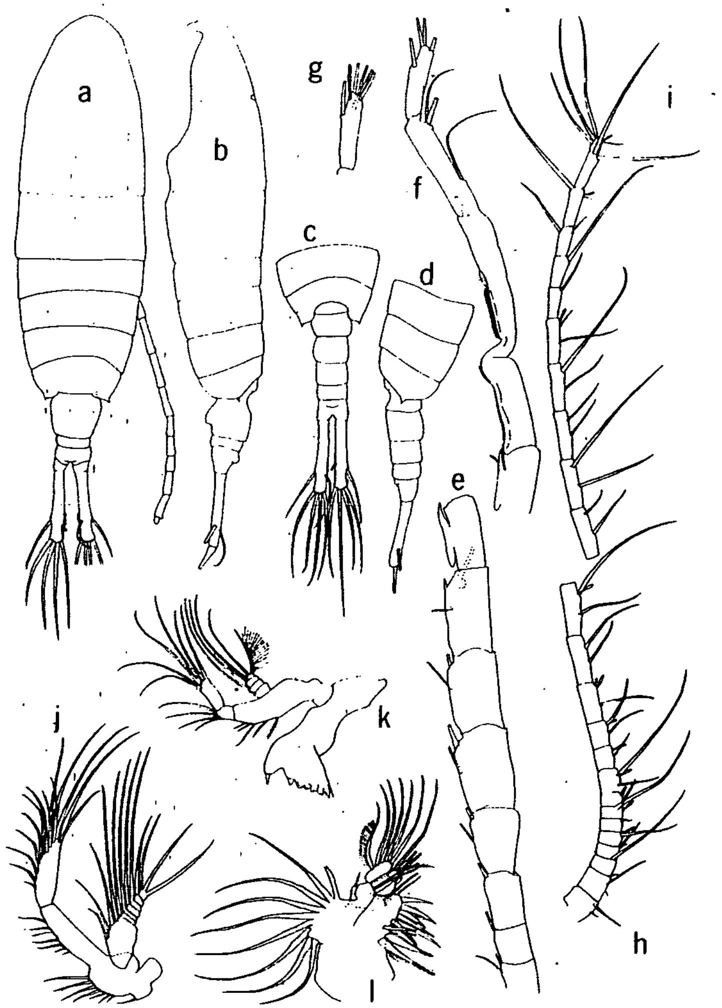

Fig. 1. *Sinocalanus doerrii*: a, Female, dorsal; b, Female, lateral; c, Male posterior pedigers and urosome, dorsal; d, Same, lateral; e, Male right antenna 1, segments 10–17; f, Same, segments 17–24; g, Female antenna 1, segment 24; h, Female antenna 1, segments 1–14; i, Same, segments 15–24; j, Antenna 2; k, Mandible; l, Maxilla 1.

Distribution and abundance in the Sacramento-San Joaquin Estuary

During the years 1978–1981, *S. doerrii* was taken from eastern San Pablo Bay through Carquinez Strait, Suisun Bay, the Suisun Marsh sloughs, and the Delta to at least Mossdale on the San Joaquin River, Hood on the Sacramento River, and New Hope on the Mokelumne River. We have not found it in the Sacramento River at the City of Sacramento. In that river its abundance declined moving upstream from the deep channel above Rio Vista into the shallow channel between Grand and Brannan Islands, and continued to decline farther upstream to Hood (Figure 8).

The downstream extent of *S. doerrii* may be regulated by both salinity and by the entrapment zone. This is a region of long water residence times, high turbidity and high concentrations of suspended material, phytoplankton and zoolankton occurring between ~1.2 and 5.6‰ surface salinity (Arthur and Ball, 1979). Its location depends on river flow. During 1978–1980, the zone was in Carquinez Strait during high winter-spring flows and from eastern Suisan Bay to the western tip of the Delta, during low summer-fall flows.

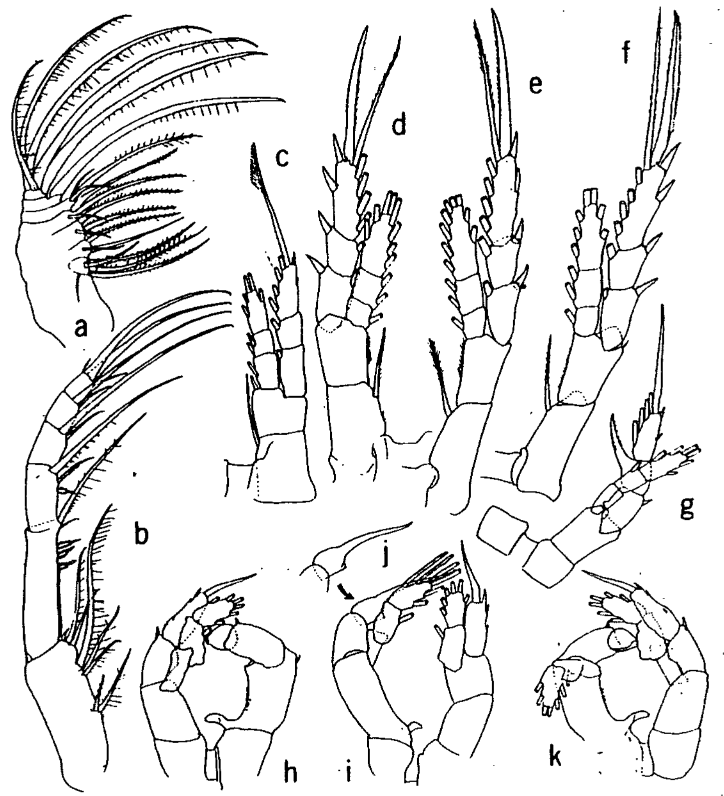

Fig. 2. *Sinocalanus doerrii*: a, Maxilla 2; b, Maxilliped; c, Leg 1; d, Leg 2; e, Leg 3; f, Leg 4; g, Female leg 5; h, Male leg 5, anterior; i, Same, posterior; j, Distal segment of male right leg 5, posterior; k, Male leg 5, posterior, from different specimen.

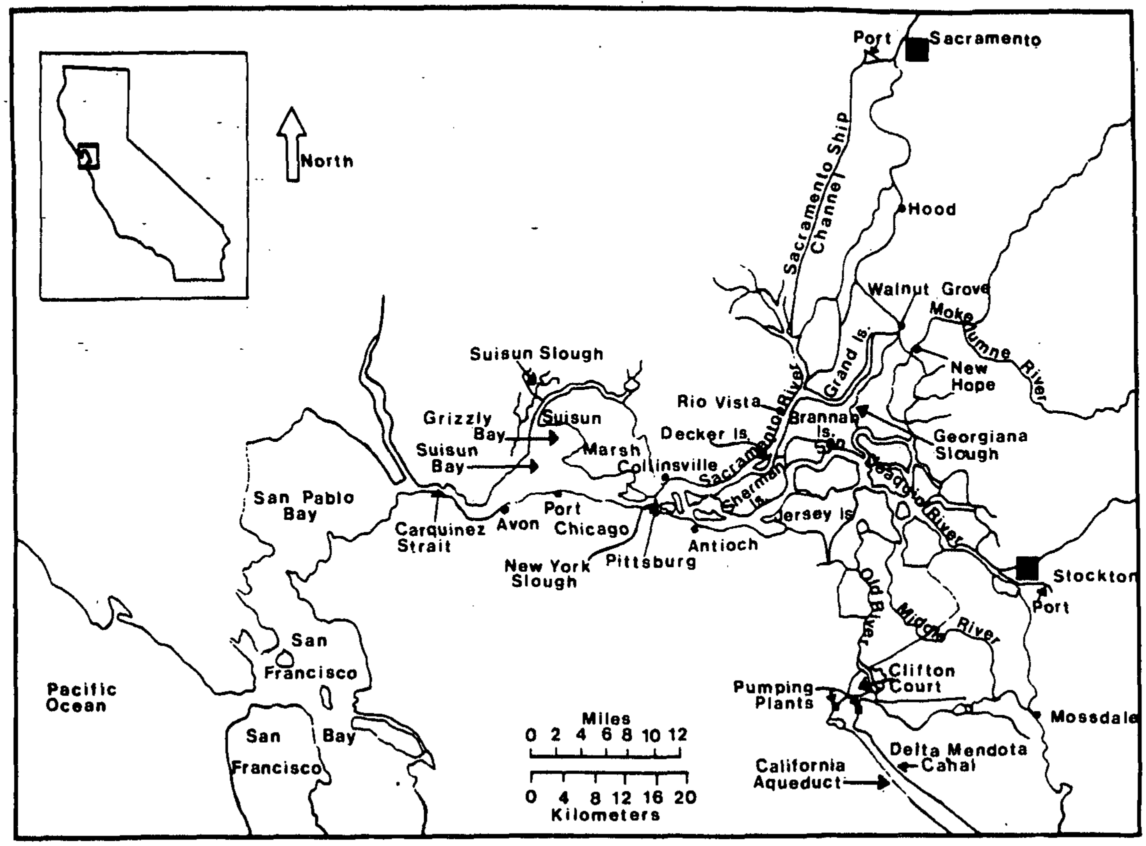

Fig. 3 Map of the Sacramento-San Joaquin Estuary.

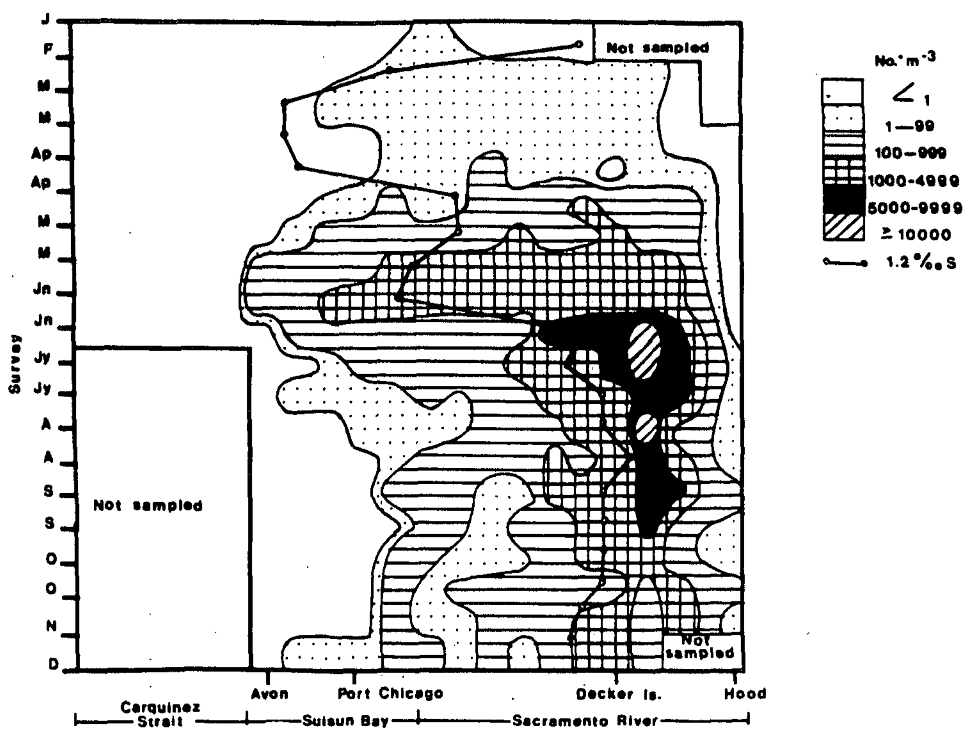

Fig. 4. Abundance (number $^{-3}$) of *S. doerrii* from Carquinez Strait through Suisun Bay to Hood on the Sacramento River on each 1979 sampling survey. Location of upstream end of entrapment zone (1.2‰ S) shown by solid line and circles.

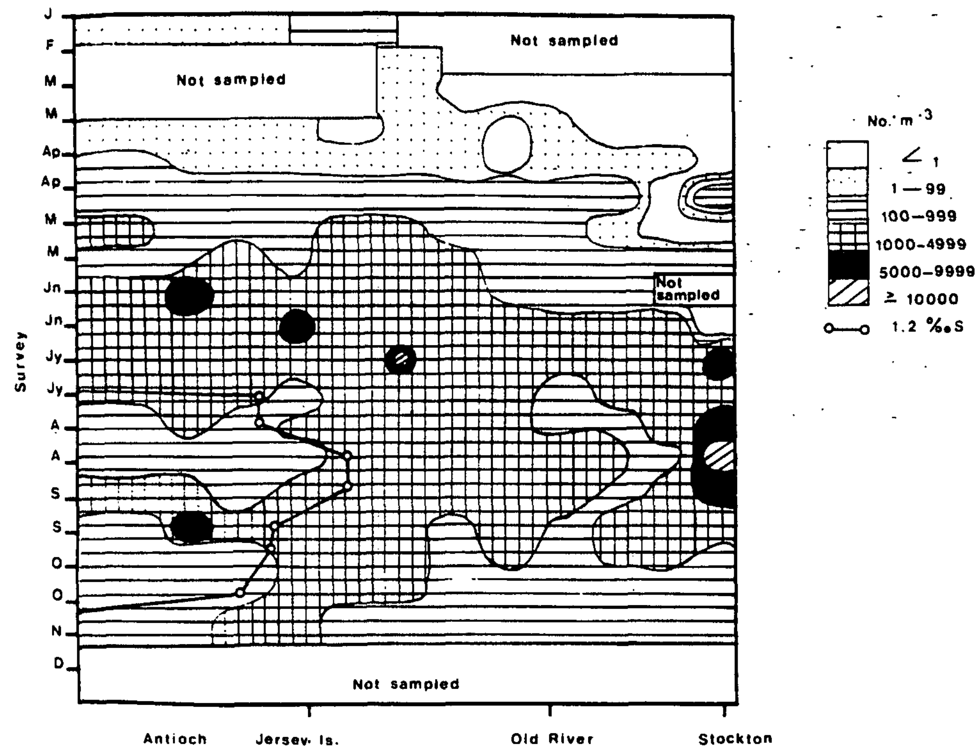

Fig. 5. Abundance (number m^{-3}) of *S. doerrii* in the San Joaquin River on each 1979 sampling survey. Location of upstream end of entrapment zone (1.2°/₀₀ S) shown by solid line and circles.

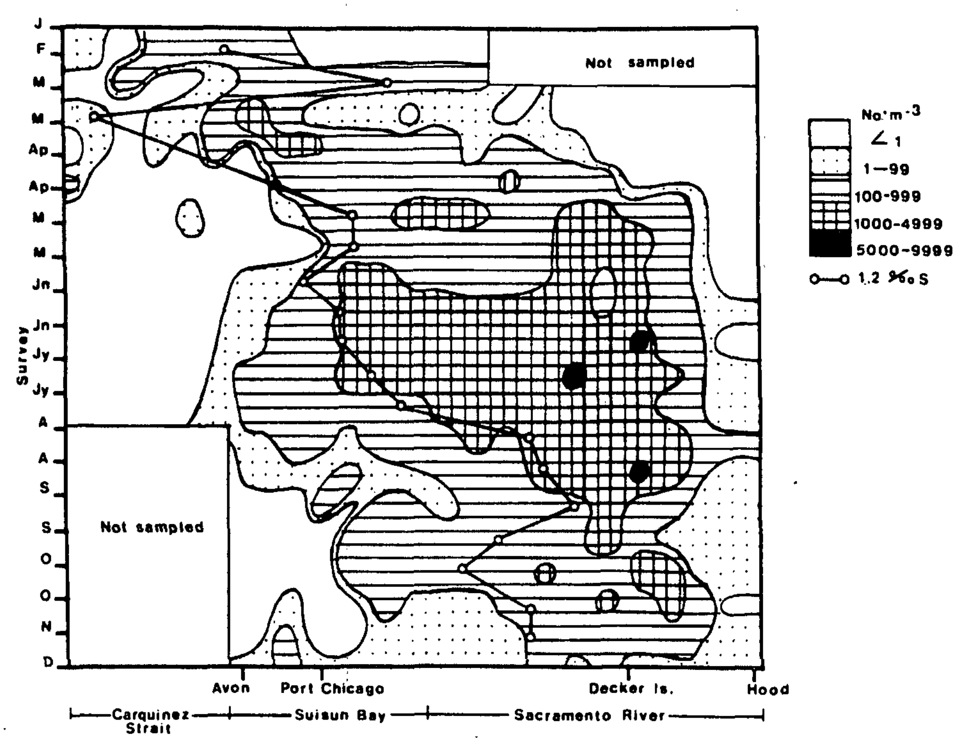

Fig. 6. Abundance (number m^{-3}) of *S. doerrii* from Carquinez Strait through Suisun Bay to Hood on the Sacramento River on each 1980 sampling survey. Location of upstream end of entrapment zone (1.2°/₀₀ S) shown by solid line and circles.

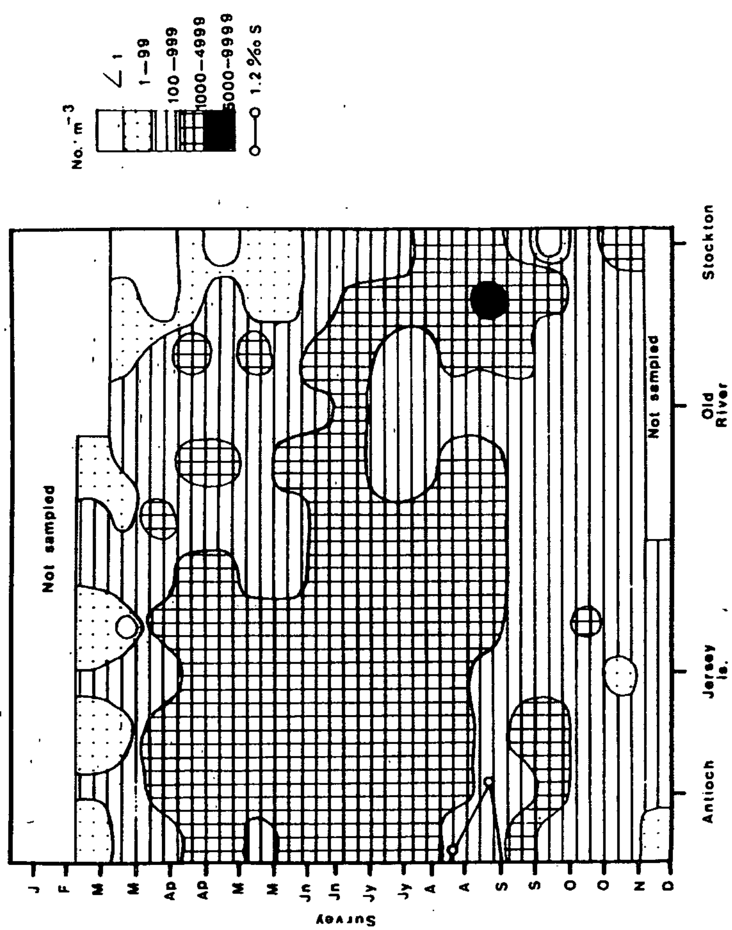

Fig. 7. Abundance (number m^{-3}) of *S. doerrii* in the San Joaquin River on each 1980 sampling survey. Location of upstream end of entrapment zone (1.2‰ S) shown by solid line and circles.

The highest salinity at which *S. doerrii* has been taken is 14.8‰ S, but ~6.2‰ S is a more common limit. Densities ≥ 5000 m^{-3} were almost always located upstream from the entrapment zone (Figures 4–7). Maximum density was usually reached in fresh water (<0.5‰ S) at varying locations along the deep tidal channels of the Sacramento and San Joaquin Rivers. Oceanic salinity intrusion into Suisun Bay during the summers of 1979 and 1980 markedly reduced density there (Figures 4 and 6).

In the San Joaquin River, density was often much lower at the mouths of Old and Middle Rivers (Figures 5 and 7) than farther downstream or upstream. The water export pumping plants in the South Delta pull water out of the Sacramento at Walnut Grove and draw it across the Delta via the Mokelumne River and Georgiana Slough. This dilutes the San Joaquin at the mouths of Old and Middle Rivers with Sacramento water containing low densities of *S. doerrii*, and explains its reduced abundance in this area.

Density of *S. doerrii* was generally higher in the Sacramento River below Rio Vista than in the San Joaquin in both 1979 and 1980. The difference was greatest during the summer when density was highest and least during spring and fall (Figures 9 and 10). Dilution of the San Joaquin by Sacramento water from Walnut Grove would be partly responsible for the lower San Joaquin abundance.

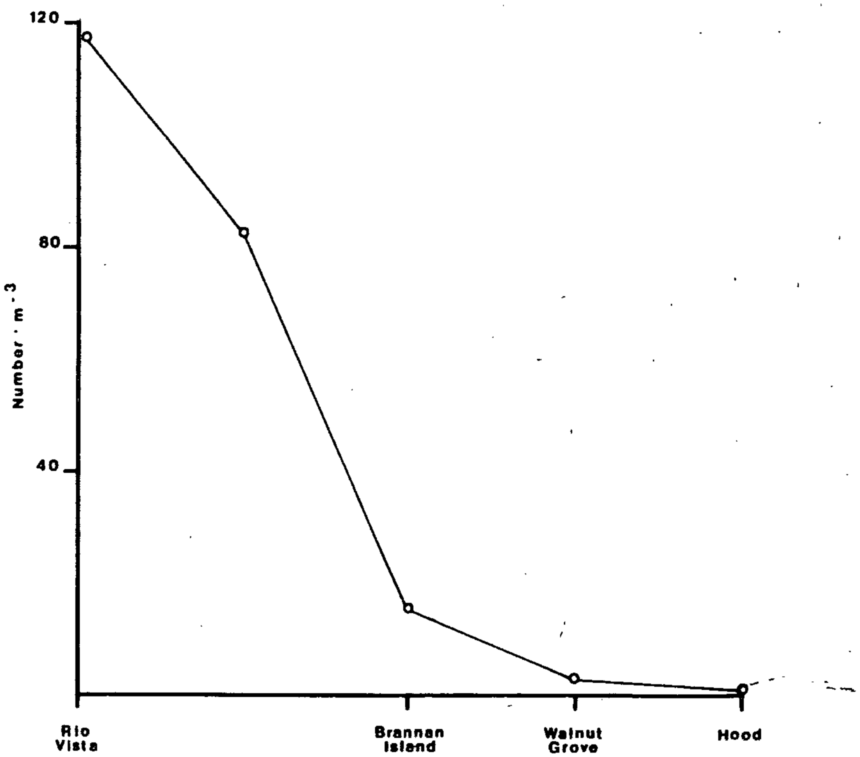

Fig. 8. Abundance (number m^{-3}) of *S. doerrii* in the Sacramento River from Rio Vista to Hood during August, 1981.

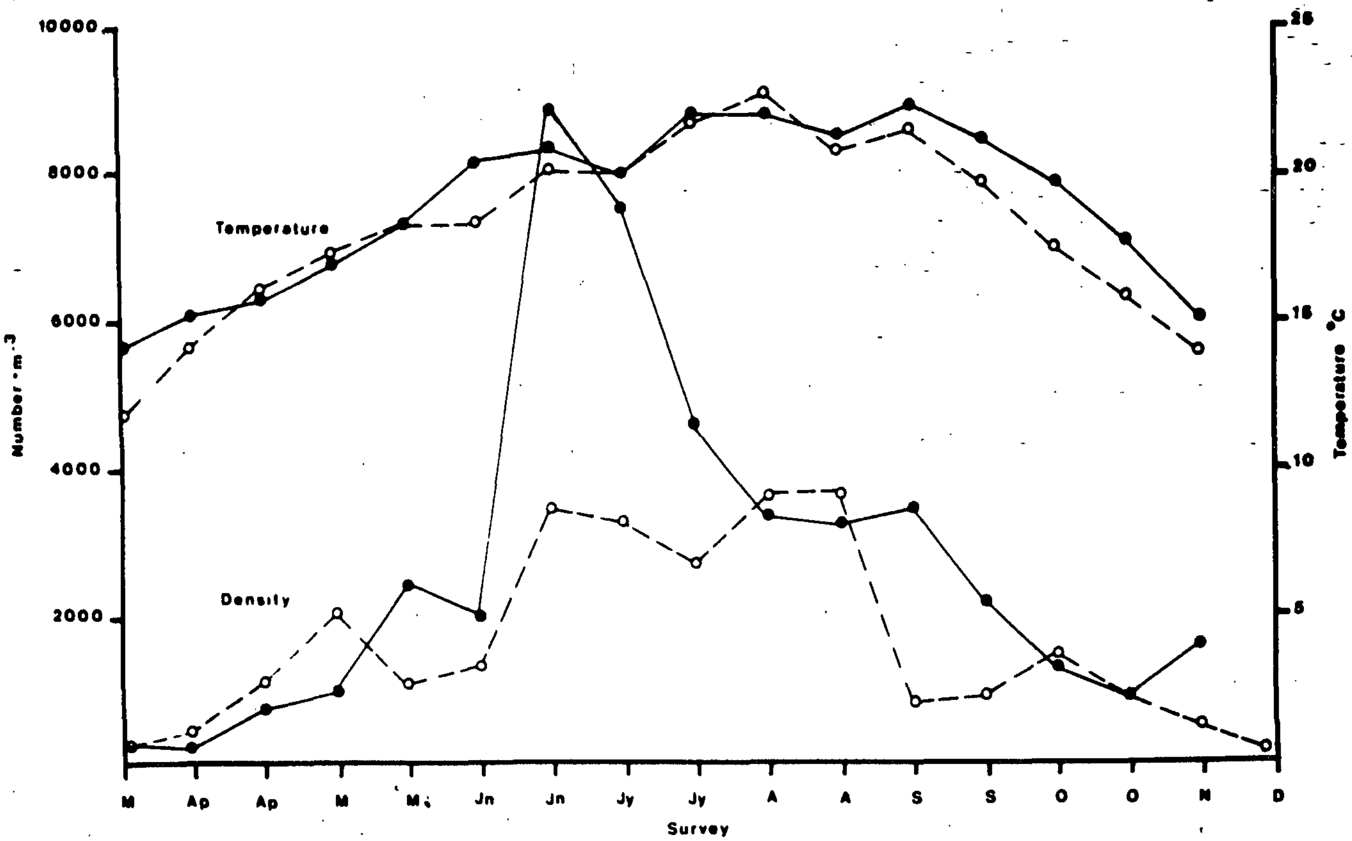

Fig. 9. Mean abundance (number m^{-3}) of *S. doerrii* and mean temperature in the Sacramento River on each 1979 (———) and 1980 (— — — —) sampling survey.

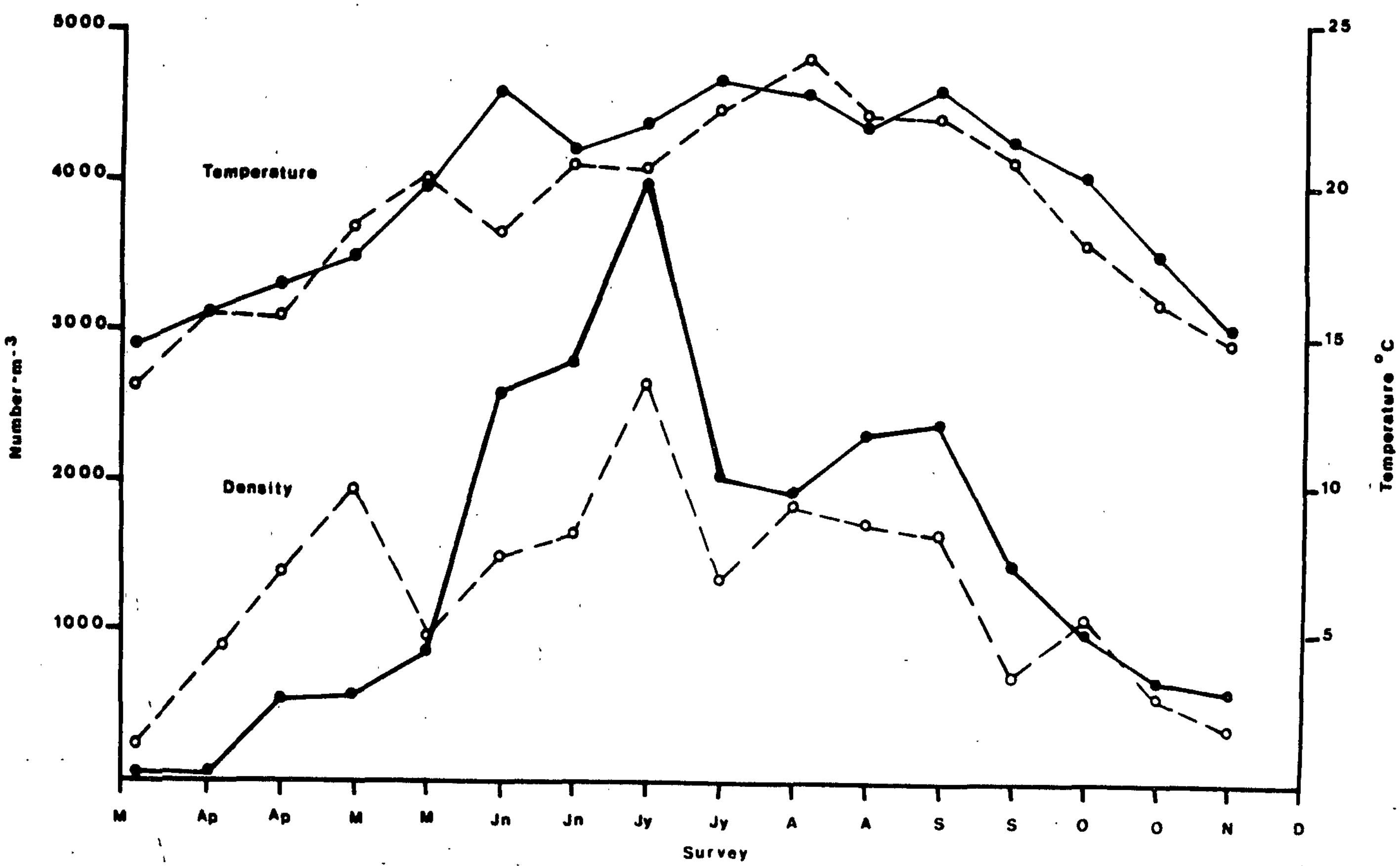

Fig. 10. Mean abundance (number m^{-3}) of *S. doerrii* and mean temperature in the San Joaquin River on each (1979) (———) and 1980 (———) sampling survey.

Table I. Vertical distribution of *S. doerrii* adults and copepodids in 1980 and surface light extinction coefficients (1980 USGS data) in the entrapment zone and up and downstream from it.

	Percent of population at each depth		
	Adults	Copepodids	Mean surface EXCOF
Downstream			
Surface	0	0	5.9
Bottom	100	100	
Entrapment zone			
Surface	39	8	5.2
Midwater	7	53	
Bottom	54	39	
Upstream			
Surface	20	22	5.4
Midwater	36	33	
Bottom	44	45	

On most 1979 surveys, density in both rivers was higher than on most surveys the following year. Peak density in the Sacramento River in 1979 was 8700 m^{-3} on the June II survey, compared to a peak of only 3500 $^{-3}$ in 1980 on the same survey. In 1979, the San Joaquin peak reached 4000 m^{-3} on the July I survey, while the 1980 maximum was only 2650 m^{-3} also on July I (Figures 9 and 10). Density was highest from June to August at temperatures ≥19°C in both years and in both rivers.

Vertical distribution

USGS samples from surface, midwater and bottom in 1980 were used to determine the vertical distribution of *S. doerrii* adults and copepodids. At all salinities adult abundance was always greater near the bottom (Table I). At surface salinities >6°/oo no adults were found on the surface. The largest percentage of adults on the surface, 39%, occurred in the turbid entrapment zone. Copepodids were also absent from the surface at salinities >6°/oo, but only 8% of them were on the surface in the entrapment zone. In that area, 53% of the copepodids were in midwater. Upstream from the entrapment zone, both life stages became progressively more abundant from surface to bottom. The vertical distribution may be regulated by light penetration, which was greatest downstream from the entrapment zone and least in the zone itself.

Discussion

Reports documenting the introduction of planktonic copepods are scarce compared with those of other groups, such as amphipods and isopods, which have more avenues of introduction available. The mechanisms of introduction, summarized by Carlton (1975, 1979a, 1979b) include (1) the introduction by ships of fouling, boring, and ballast-dwelling organisms, (2) the introduction of organisms on and among imported commercial oysters, (3) introduction of organisms associated with algae used to ship American lobsters and other food or bait species from the East Coast. Of the mechanisms, planktonic copepods have available only transport by ships, in water ballast or less likely in fouled seawater systems.

Carlton (1981) has reported the transport of plankton, including copepods, in ballast water from Europe to North America with survival of harpacticoid copepods for >95 days. Carlton (personal communication) has also collected living calanoids in ballast tanks of commercial vessels arriving in U.S. East Coast ports from Europe. Living copepods have also been collected in ballast tanks of a ship sailing from Japan to Australia (Medcof, 1975).

Acartia tonsa Dana is believed to have been introduced to Europe, probably reaching Dutch waters between 1912 and 1916 (Redeke, 1935). Remy (1927) reported it from France in the canal connecting Caen to the coast at Ouistreham and suggested that it might have been transported among fouling organisms on a ship bottom, or that it might have been carried to France in warm currents such as Gulf Stream. Redeke also favored transportation by currents and believed that it had come from North America. Its distribution in Europe has been summarized by Conover (1957), Schwarz (1960), and Brylinski (1981). If *A. tonsa* reached European waters early in the 20th century, we agree that it came from North America, but think transport more likely by ships than by ocean currents.

Redeke (1935) suggested the possibility that *Eurytemora americana* Williams might also have been introduced to Europe from North America, but no supporting evidence has been offered for this proposal.

Jones (1966) reported the possible introduction of *Pseudodiaptomus marinus* Sato from warm neritic waters of Japan to brackish waters of Hawaii. Jones pointed out that the time necessary for transport by ocean currents from Japan to Hawaii would require several generations of *Pseudodiaptomus*. He considered transport in ballast water a 'remote possibility', but did not speculate further on the mode of transport. *P. marinus* has also been introduced into Mauritius (Grindley and Grice, 1968), much farther from Japan than Hawaii. The possibility of transport by ocean currents is even more improbable, and Grindley and Grice considered water ballast the most plausible mechanism. They also thought it possible that *P. marinus* might have adhered to fouling organisms on a ship's hull. Recently Pillai (1980) reported *P. marinus* from the Andaman Sea, but did not comment on the possibility of its having been introduced there. The possible introduction of *P. acutus* from Brazil to Jamaica is discussed by Bowman (1978), but coastal and estuarine plankton in intermediate localities is inadequately known, and the populations may not be disjunct.

Factors militating against the transoceanic transport of copepods by ships are: temperature and salinity differences between points of origin and introduction, large mortality enroute, dispersal by currents on arrival so that breeding individuals do not meet, predation and inadequate or inappropriate food upon arrival, small numbers of copepods released when the ballast water is pumped out.

Since *S. doerrii* is a fresh water species, it is not likely to have been introduced by a ship docking in San Francisco Bay. The most probably locations for its introduction are: (1) the Port of Stockton, (2) the Port of Sacramento, and (3) the Pittsburg-Antioch stretch of the San Joaquin River and New York Slough adjacent to Suisun Bay.

The Port of Stockton is located on a dead-end channel branching off the San Joaquin River. Depending on the amount of tidal flushing of this channel, copepods introduced here might be able to stay together, breed, develop a high density, gradually enter the main river, and move downstream to Suisun Bay. A Japanese freighter from Shanghai that docked at Stockton in October 1977 could have introduced *S. doerrii*. Individuals could have moved downstream undetected during the winter as the DFG sampled only two San Joaquin River stations from December 1977 through February 1978. However, our failure to take the species in the San Joaquin River while we were catching it in Suisun Bay during 1978, and its apparent upstream spread in the San Joaquin during the spring of 1979, argues against an introduction at Stockton.

The Port of Sacramento is another apparently ideal place for the introduction of planktonic copepods as it is situated at the end of a long (38 km), isolated ship channel that receives water only through ship locks. However, the upstream spread of *S. doerrii* in the Sacramento River during 1978 indicates that it was probably not introduced here either.

The first catches of *S. doerrii* near Pittsburg are strong evidence for an introduction in the Pittsburgh-Antioch industrial zone which has numerous wharves for large freighters. Japanese flag ships which may have docked in China have been observed at these wharves by our field personnel. Factors unfavorable to an introduction in this area are strong winds and tidal currents which should quickly mix and attenuate a plume of ballast water pumped from a ship. Yet the consequent dispersal may not have been great enough to prevent *S. doerrii* from establishing itself, and this is the most probable site of the introduction.

The time of its introduction cannot be pinpointed but it would be unreasonable to believe it had taken place several years before the discovery and remained undetected in spite of several sampling programs in Suisun Bay and the Delta. The first such program was in 1963 (Painter, 1966). The DFG began its present study in 1972. Other studies were made in 1975 (Caskey, 1976) and in 1976 (Siegfried *et al.*, 1978; Sits and Knight, 1979). The rapid spread of *S. doerrii* a few months afer its first detection in May 1978 also supports the idea of a very recent introduction, perhaps only a few months before it was first caught. We hypothesize that an introduced planktonic species must achieve a critical density necessary for adequate reproduction or the individuals will be dispersed and soon eliminated.

The introduction may have been made either by adults and/or by eggs or recently hatched nauplii. Members of the genus *Sinocalanus* do not have an egg sac; they release their eggs directly into the water (Roff, 1972). This should make the genus a good candidate for introductions as eggs carried in sacs might die with the parent, whereas eggs released to the water are independent of the fate of the parent.

S. doerrii does not appear to be spreading up the Sacramento River very successfully. It is absent or perhaps very rare at the City of Sacramento, becoming progessively less abundant upstream from Rio Vista. Strong currents in this river exceeding 1 m s^{-1} during much of the year and becoming still higher during winter may hamper its upstream spread. This is also true of the Mokelumne River, a shallow, fast-flowing stream. On the other hand, the San Joaquin River has lower flows and lower net velocities, especially during summer, and *S. doerrii* may spread well beyond Mossdale. Since it is abundant in Old River at Clifton Court, it is obviously being pumped out of the Delta into the California Aqueduct and the Delta-Mendota Canal and could be carried to the southern California water project lakes around Los Angeles, Lake Perris, Pyramid Lake, etc.

The *S. doerrii* population appears to oscillate between Suisun Bay and the Delta under the influence of river flow. High winter flows push it as far downstream as San Pablo Bay. Low summer flows permit its upstream movement, while simultaneously allowing salinity intrusion to reduce its abundance in Suisun Bay.

Its concentration on the bottom downstream from the entrapment zone would bring it into the bottom density current which moves upstream to the fresh water end of the salinity gradient. This would serve to keep the species from being swept into salinities beyond its tolerance limits.

S. doerrii has a certain potential for spread along the West Coast *via* shipping. The Columbia River and Puget Sound are likely sites for its introduction. Lower water temperatures in these localities may limit is abundance if it is introduced.

In the Sacramento-San Joaquin Estuary *S. doerrii* may occupy a previously vacant niche, as copepods have never been abundant in its fresh water reaches, except in the San Joaquin River near Stockton and in adjacent sloughs. DFG collections from 1972 to 1979 show that *Diaptomus* spp. densities were typically <100 m^{-3} in the Sacramento River and were only slightly more abundant in the San Joaquin away from Stockton. Cyclopoid densities were usually <1000 m^{-3}. *S. doerrii* is now the most abundant copepod in the Delta and is being consumed in significant quantitites by young-of-the-year striped bass (Lee Miller, DFG, personal communication), which prey mainly on *Eurytemora affinis*, until they grow large enough to feed on the opossum shrimp, *Neomysis mercedis* (Heubach *et al.*, 1963). These fish now have a supplementary food source which is present much farther upstream than *E. affinis* extends. Since the preferred salinity ranges of *E. affinis* and *S. doerrii* differ, competition between the two is likely to be minimal. (Unpublished DFG data shows that *E. affinis* abundance peaks within the entrapment zone and declines progressively moving upstream in fresh water.) Competiton and/or predation between *S. doerrii* and *Cyclops* and *Diaptomus* is a stronger possibility and the interrelationships between these species are worth investigating.

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