Current Report

Introduction

This report presents zooplankton annual and monthly abundances and distribution trends from 1974 through 2022 for the most common copepods (calanoid and cyclopoid), cladocerans, rotifers, and mysids of the upper estuary.

Trends

The overall abundance of zooplankton in the estuary has decreased significantly over the course of the Zooplankton Study (Figure 2). Cyclopoid copepods are the only group that has increased in abundance over the study period, driven by the invasion and spread of *Limnoithona tetraspina*. The overall decrease in zooplankton abundance can be attributed to invasive species colonizing the estuary, most notably the Asian clam *Potamocorbula amurensis* in the mid-1980s (Kimmerer, Gartside, and Orsi 1994; Carlton et al. 1990). Abundances of both phytoplankton and zooplankton in the upper estuary have been impacted by the proliferation of *P. amurensis*, as it is a highly efficient filter feeder and consumes both phytoplankton and copepod nauplii. In addition to decreased abundance of most zooplankton groups, community compositions have changed dramatically during the study period, driven by a combination of the introduction and spread of non-native species and changes in the abiotic and biotic environments.

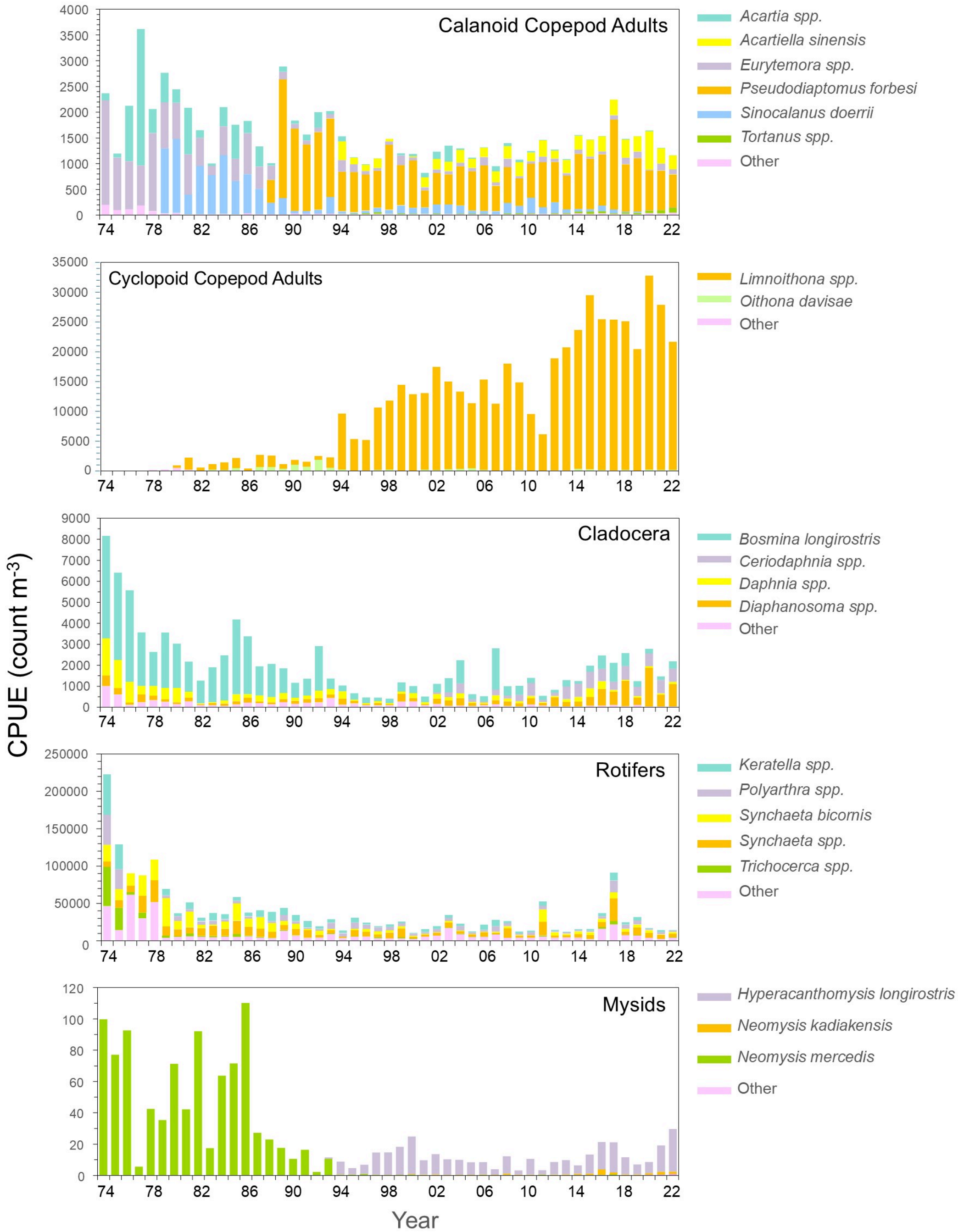

Figure 2. Annual (Mar-Nov) mean CPUE from 1974 through 2022. Panels from top to bottom: adult calanoid copepods from the CB net, adult cyclopoid copepods from the pump, Cladocera from the CB net, rotifers from the pump, mysids from the mysid net.

Calanoid copepods

Calanoid copepod abundance declined only slightly over the study period, but their community composition changed dramatically (Figure 2). When the study began in the early 1970s, the calanoid copepod community was dominated by *Eurytemora affinis* (an introduced species) and *Acartia spp.* Even though *E. affinis* is not a native species, it once comprised the primary prey of the endangered Delta Smelt. However, as its abundance declined, fish increasingly preyed on more recently introduced calanoids like *Pseudodiaptomus forbesi* (Moyle et al. 1992; Slater and

Baxter 2014). One of the first recorded calanoid copepod introductions was *Sinocalanus doerrii*, a freshwater species native to China that invaded the estuary in 1978 and remained the most dominant calanoid species for a decade (Orsi et al. 1983). The calanoid *P. forbesi* was first detected by this study in October 1987 (Orsi and Walter 1991), shortly after the *Potamocorbula amurensis* invasion in the mid-1980s (Kimmerer, Gartside, and Orsi 1994; Carlton 1990). Combined effects of these introductions may have influenced subsequent declines in abundances of *E. affinis* and S. doerrii. *P. forbesi* quickly became the numerically dominant calanoid in the upper estuary and remains the most abundant to this day. The predatory calanoid copepod *Acartiella sinensis* was introduced in 1993 and quickly became the second most abundant calanoid in the upper estuary, dominating the low-salinity zone in the Suisun Marsh and Confluence regions (Orsi and Ohtsuka 1999). This invasion appears to have narrowed the range of *P. forbesi* towards freshwater areas of the estuary, potentially in relation to *A. sinensis* predation on *P. forbesi* nauplii (Kayfetz and Kimmerer 2017).

Aside from the 25-year high in calanoid copepod abundance in 2017, total abundance was similar from 1995 to 2022 (Figure 2). Although abundance declined in 2021 and again in 2022, these levels remained in the range of the previous two decades.

In general, calanoid copepod abundance was highest in the estuary during the summer and fall months (May to November) and lowest during winter months (Figure 3). Distribution of calanoids throughout the estuary in 2022 was similar to recent years, with *P. forbesi* most abundant in summer and fall months (May to October) in the South Delta and Central Delta and abundant in the North Delta in May and November, though numbers in this region were lower from June to October in the presence of increasing numbers of the predatory *Acartiella sinensis* (Figure 3). Abundance of *A. sinensis* was highest from June to December in the Confluence region, with a fall (September to October) peak in Suisun Marsh. In both of these regions, *A. sinensis* co-occurred with high densities of one of its primary prey items *Limnoithona tetraspina* (Figure 4). *P. forbesi* was most abundant in the Central and South Delta regions and was the most common calanoid species in these regions from May to November. In the North Delta region *P. forbesi* was more abundant in May but declined starting in June, simultaneous with increasing abundance of *A. sinensis*. *P. forbesi* abundance was low in Suisun Marsh in 2021 and remained low in 2022. This shift in distribution upstream out of Suisun Marsh could be related to ongoing drought conditions that persisted throughout 2022.

There is a marked difference in the calanoid community in the lower reaches of the estuary. *Acartia spp.* was the only native calanoid commonly found in 2022. These copepods prefer brackish water and were present year-round in San Pablo Bay, though monthly abundances were highly variable (Figure 3). In Suisun and Grizzly Bays, *Acartia spp.* abundances were low from January to March and essentially absent from April to October but increased in November and comprised about half of the calanoid copepods found in December. This was also the only region where *Tortanus spp.* was abundant. *Eurytemora affinis* was the most common calanoid in the North, Central, and South Delta regions in the spring of 2022, similar to seasonal distribution patterns during the last two decades (Figure 3).

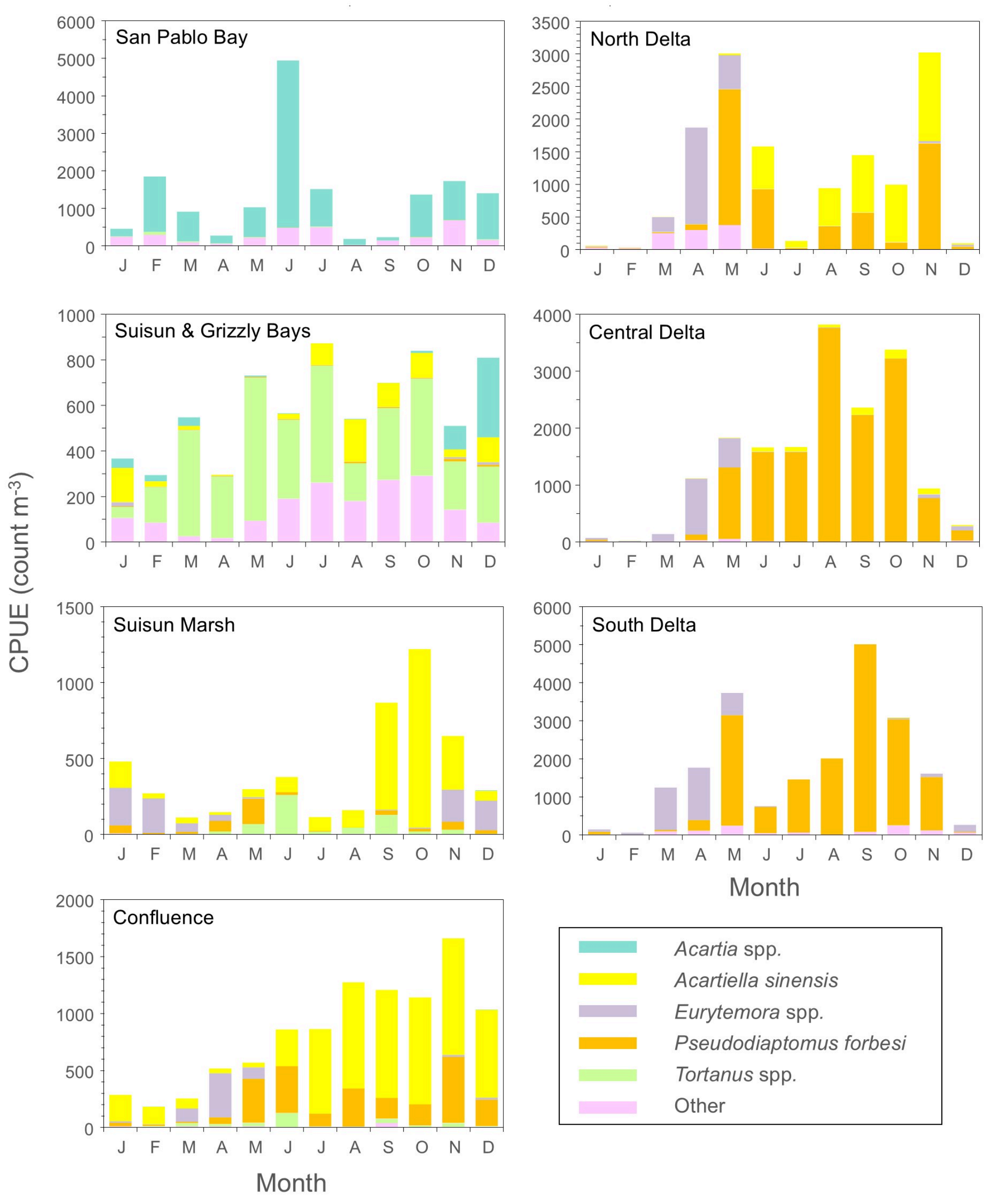

Figure 3. Monthly mean CPUE for 2022 by region for adult calanoid copepods collected with the CB net. Note the variable scales on the y-axes.

Cyclopoid copepods

In contrast with the general decline of most zooplankton groups during the study period, cyclopoid copepods increased dramatically, particularly during the last decade (2012 to 2022) (Figure 2). Abundances of *Oithona spp.* and *Acanthocyclops copepods* were low when the study began, and the increase in cyclopoid abundance resulted from the introduction of *Limnoithona sinensis* in the early 1980s and subsequent identification of the invasive *Limnoithona tetraspina* in 1993 (Ferrari and Orsi 1984; Orsi and Ohtsuka 1999). These two species were reported together as *Limnoithona spp.* from 1980 through 2006. Limnoithona were identified to species starting in 2007, leading to the discovery that *L. tetraspina* is by far the dominant species. In 2022, *L. tetraspina* comprised 99.9% of all Limnoithona collected. For the sake of consistency, abundances are combined and reported here as *Limnoithona spp.* In 2022, *Limnothona spp.* had the highest abundance of any copepod group monitored in this study (Figure 2).

Cyclopoid copepod abundance has increased dramatically since the early 1990s, and the small *L. tetraspina* has become the most common zooplankton species in the upper estuary (Figure 2). The increase in *L. tetraspina* abundance was possibly related to decreased predation due to the decline of Northern Anchovy in the upper SFE (Kimmerer 2006). In addition, the small size, high growth rate, and motionless behavior of *L. tetraspina* may decrease its vulnerability to predation in a region where most fish are visual predators (Bouley and Kimmerer 2006; Greene et al. 2011, Kimmerer 2006). The introduction of *L. tetraspina* is linked to a change in the distribution of *P. forbesi* out of the low-salinity zone of the estuary, as higher densities of *L. tetraspina* may sustain larger populations of the predatory *A. sinensis*, which also preys on *P. forbesi* nauplii (Kayfetz and Kimmerer 2017).

Monthly abundances of *Limnothona spp.* were low in winter and spring and peaked in summer and fall (Figure 4). As in prior years, cyclopoids were most abundant in the low salinity regions of the estuary in 2022, including Suisun Marsh, Suisun and Grizzly Bays, and the Confluence regions (Figure 4). Abundances of *Limnothona spp.* were high in the North Delta region in September to October, and abundances and monthly patterns were similar to those of *P. forbesi* in the South Delta and Central Delta regions. *Limnothona spp.* were virtually absent from San Pablo Bay, where the introduced *Oithona davisae* was the most abundant cyclopoid in summer and fall (Figure 4).

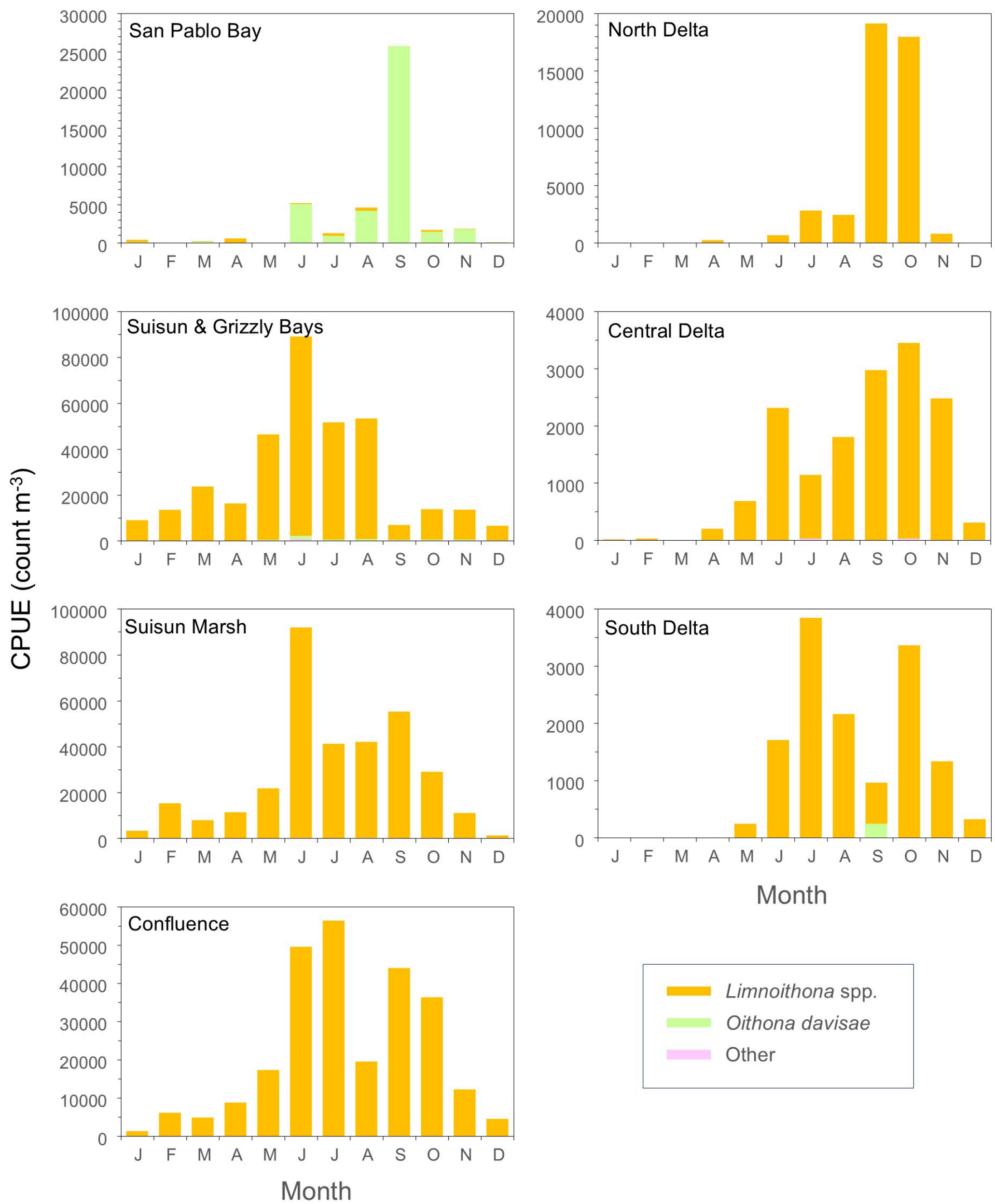

Figure 4. Monthly mean CPUE for 2022 by region for cyclopoid copepods collected with the pump. Note the variable scales on the y-axes.

Cladocerans

Cladocerans in the upper estuary primarily comprise species in the genera *Bosmina*, *Daphnia*, *Ceriodaphnia*, and *Diaphanosoma*. These populations have declined substantially during the study period (Figure 2). Cladocerans are largely herbivorous and feed primarily on phytoplankton so likely were impacted by the invasion of *P. amurensis* (Baxter et al. 2008; Kratina and Winder 2015). Cladocerans comprise a significant portion of the diets of Delta Smelt, juvenile Chinook Salmon, and young-of-the-year Striped Bass throughout the upper estuary (Heubach et al. 1963;

Slater and Baxter 2014; Goertler et al. 2018). The increased numbers of invasive copepods such as *P. forbesi* and the decline in native cladocerans has shifted the nutritional content of the planktonic prey available to fish (Kratina and Winder 2015).

In the early years of the study, the cladoceran community was dominated by *Bosmina longirostris* and *Daphnia spp.* (Figure 2). Over the last decade, cladoceran abundances increased from the low levels in the late 1990s and the community shifted to higher proportions of *Ceriodaphnia spp.*. and *Diaphanosoma spp.*, though *B. longirostris* and *Daphnia spp.*. are still present (Figure 2).

In high outflow years cladocerans may be found further downstream, but with low outflow in 2022, abundances were highest in the South and Central Delta regions (Figure 5). All groups except *Diaphanosoma spp.* were found in the North Delta region from January to March and in December, and in the Confluence region in January (Figure 5). There were trace concentrations of cladocerans in Suisun and Grizzly Bays and Suisun Marsh. Only the “Other Cladocera” group occurred in San Pablo Bay, with CPUE ranging from 100 to 150 in February and March and trace concentrations in other months.

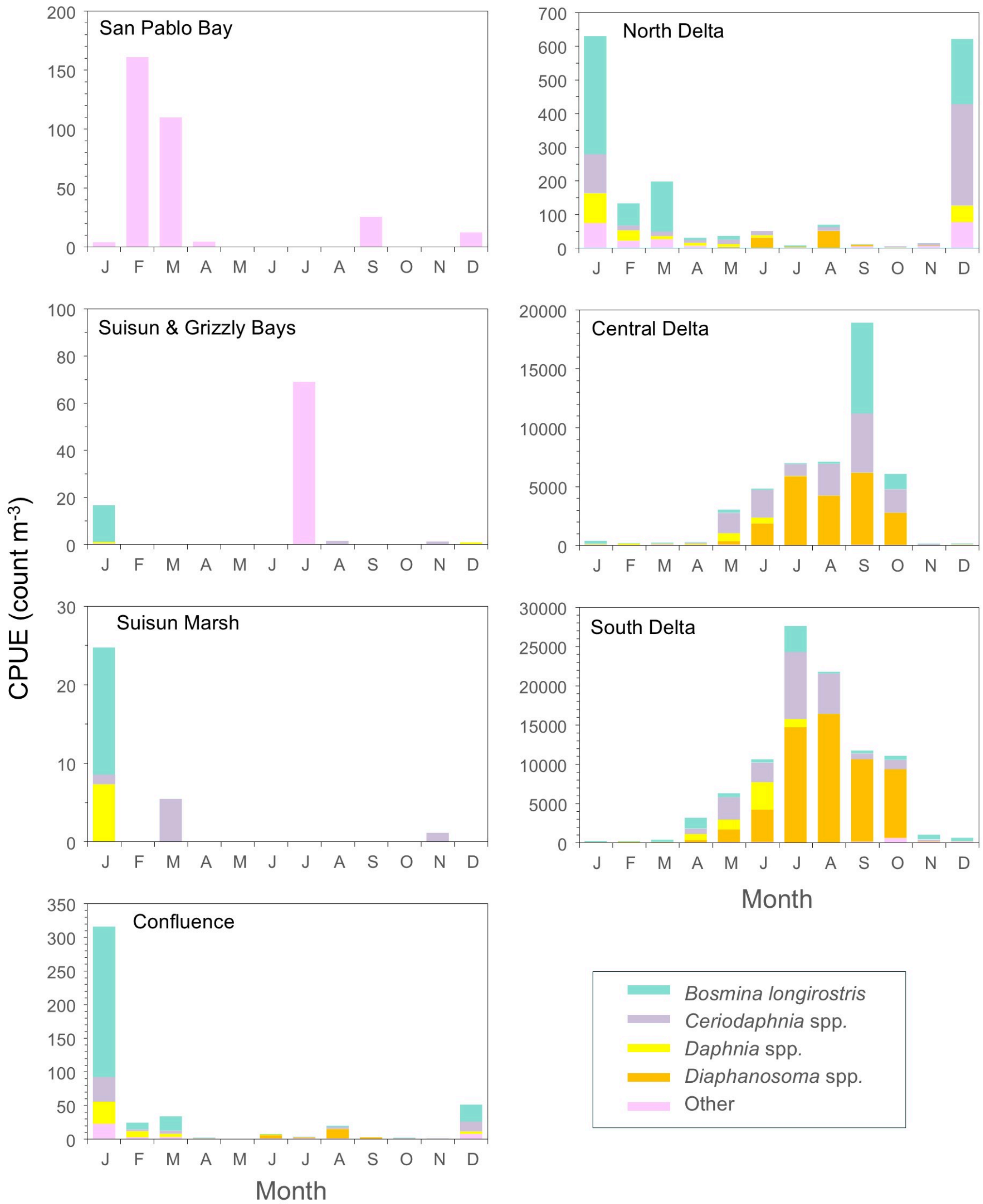

Figure 5. Monthly mean CPUE for 2022 by region for cladocerans collected with the CB net. Note the variable scales on the y-axes.

Rotifers

Although rotifers are the most abundant type of zooplankton in the estuary, their abundance decreased dramatically since the start of the study (Figure 2). Interestingly, the decline in rotifer abundance began in the late 1970s, preceding the invasion by *P. amurensis* (Cloern and Jassby 2012). The rotifer community comprises species from the genera *Polyarthra*, *Synchaeta*, *Keratella*, and *Trichocerca*, as well as the “other” rotifer category, which includes the genus *Asplanchna*.

Rotifer abundance and species composition in 2022 were similar to the past few years. *Synchaeta spp.* were the most abundant, with smaller numbers of *Synchaeta bicornis* and *Keratella spp.* (Figure 6). Keratella and Polyarthra tended to be most abundant in freshwater and low-salinity regions, their preferred habitats (Winder and Jassby 2011), while *Synchaeta spp.* were most abundant in the higher-salinity areas of San Pablo Bay and Suisun and Grizzly Bays. A spatial and temporal split was discernible between Synchaeta and the other rotifer groups, with highest densities of *Synchaeta spp.* in Suisun March, Suisun and Grizzly Bays, and San Pablo Bay during winter and spring months. There was a noticeable increase in *S. bicornis* abundance in June in the Confluence, Suisun Marsh, and Suisun and Grizzly Bay regions, though *Synchaeta spp.* was also present. The “other” rotifers group was most abundant in the South and Central Delta during summer, and moderately abundant in the North Delta in the winter (January and December) (Figure 6).

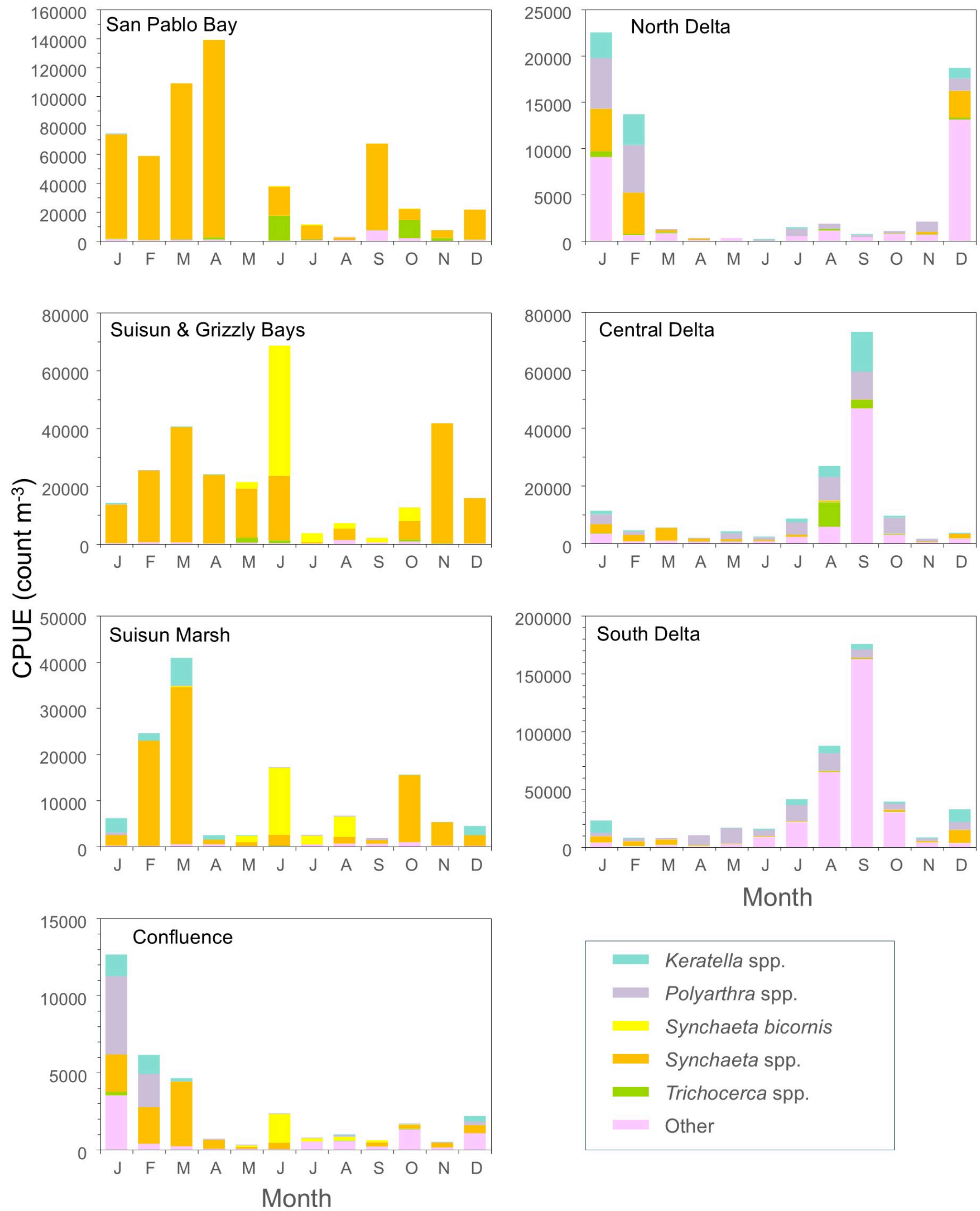

Figure 6. Monthly mean CPUE for 2022 by region for rotifers collected with the pump. Note the variable scales on the y-axes.

Mysids

Mysid abundances were higher overall during the first 12 years of the zooplankton study, with the highest abundance in 1986 (Figure 2). Annual abundances have varied from 2.1 to 29.4 from 1987 to present, with the annual CPUE in 2022 the highest since 1986 (Figure 2). In addition to an overall decline, the community composition shifted dramatically. Prior to 1994, the native *Neomysis mercedis* was the most abundant species but since 1994 the mysid community has been dominated by the non-native *Hyperacanthomysis longirostris* (formerly *Acanthomysis bowmani*) (Figure 2). *N. mercedis* declined significantly during the 1976-1977 drought, likely related to food limitation from a lack of diatoms due to low river discharges (Siegfried et al. 1979; Cloern et al. 1983). *N. mercedis* populations rebounded after the drought and abundances remained high in the Suisun Bay region of the upper estuary until the introduction of *P. amurensis* in the mid-1980s, after which their numbers declined dramatically and remained low.

The introduced mysid *H. longirostris* was first detected by this study in 1993, shortly after the decline of *N. mercedis*. Although *H. longirostris* quickly became the most common mysid in the system, mysid abundances have not returned to their pre-clam (*Potamocorbula amurensis*) invasion levels (Modlin and Orsi 1997, Figure 2). Historically mysids have been critically important in the diets of many fish species in the upper SFE, including Delta Smelt, Longfin Smelt, Striped Bass, and Chinook Salmon (Moyle et al. 1992; Feyrer et al. 2003; CDFG 2009; Goertler et al. 2018). The decline of mysids in the upper estuary led to a significant decrease in their presence in fish diets (Feyrer et al. 2003).

Overall, mysid abundance increased in 2021 and 2022 compared to the low values from 2018 to 2020 (Figure 2). Total abundance in 2022 was similar to 1987 when the population still comprised the native species *N. mercedis*. (Figure 2). *H. longirostris* remained the most common mysid in the estuary, while the abundance of the once dominant native species *N. mercedis* remained low, continuing the overall trend in mysid community composition since 1994.

As in prior years, the mysid community in 2022 was dominated by *H. longirostris*, with the highest concentrations in the low-salinity zone of Suisun Marsh (Figure 7). Mysids were consistently present in moderate abundances in the Confluence region from March to September. Aside from spikes in Suisun Marsh in May and Suisun and Grizzly Bays in June, mysid abundances were low in all regions in other months. San Pablo Bay was the only region where *H. longirostris* was not the dominant mysid species, as it prefers low-salinity estuarine habitats. The mysid community in San Pablo Bay comprises the “other” species (*Acanthomysis aspera*, *Acanthomysis hwanhaiensis*, and *Alienacanthomysis macropsis*) but none were abundant at any time of year in this or any other study region (Figure 7). In 2022, mysids were essentially absent from San Pablo Bay from January to April and in September and October (Figure 7). Note that this study samples only the upper portion of San Pablo Bay, so these findings may not represent mysid community dynamics in other areas of San Pablo Bay.

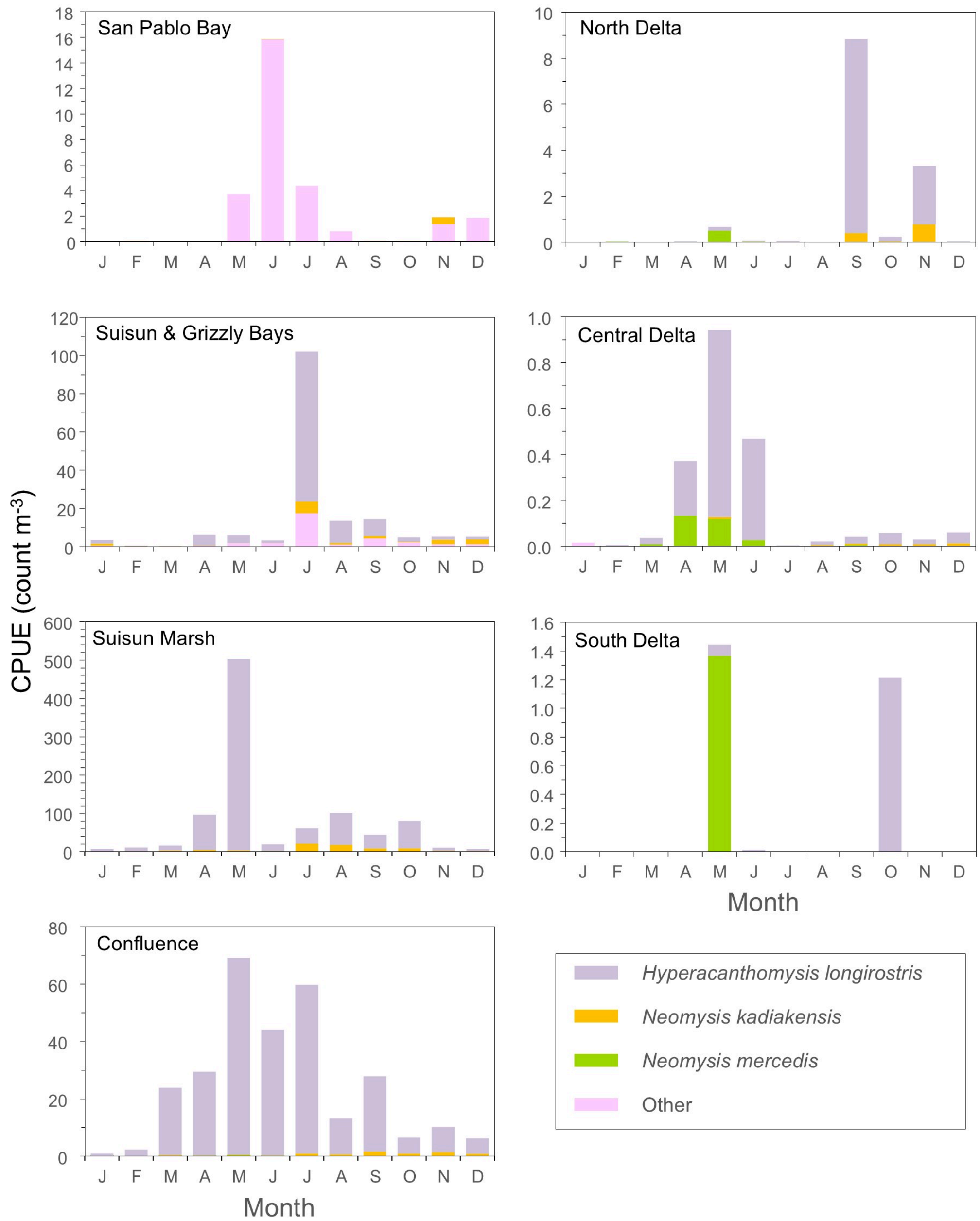

Figure 7. Monthly mean CPUE for 2022 by region for mysids collected with the mysid net. Note the variable scales on the y-axes.

Conclusion

In 2022, the Zooplankton Study recorded the abundances of calanoids, cladocerans, rotifers, and mysids at abundances comparable to recent years and consistent with historic downward trends in the estuary. Abundances for all zooplankton peaked in summer of 2022. The small, introduced *Limnoithona tetraspina* remained the most abundant copepod in the upper estuary. Although mysid abundance in 2022 was the highest since 1986, it was low compared to pre-1987 levels and continued to be dominated by the introduced *Hypercanthomysis longirostris* while the pre-1987 community was dominated by the native *Neomysis mercedis*.

This multi-decade zooplankton study allows researchers and managers to track shifts in zooplankton abundances and community composition across the estuary for over five decades. The Zooplankton Study has documented the introduction and dominance of *Pseudodiaptomus forbesi*, *Limnoithona tetraspina*, and *Hypercanthomysis longirostris*, as well as the community's response to the invasive clam *Potamocorbula amurensis*. Understanding these dynamics and how they have fundamentally changed trophic interactions is critical to assessing food resources for fish and conservation strategies in the San Francisco Estuary.

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