## Title

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# Food for Thought: Connecting Zooplankton Science to Management in the San Francisco Estuary

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## KEY WORDS

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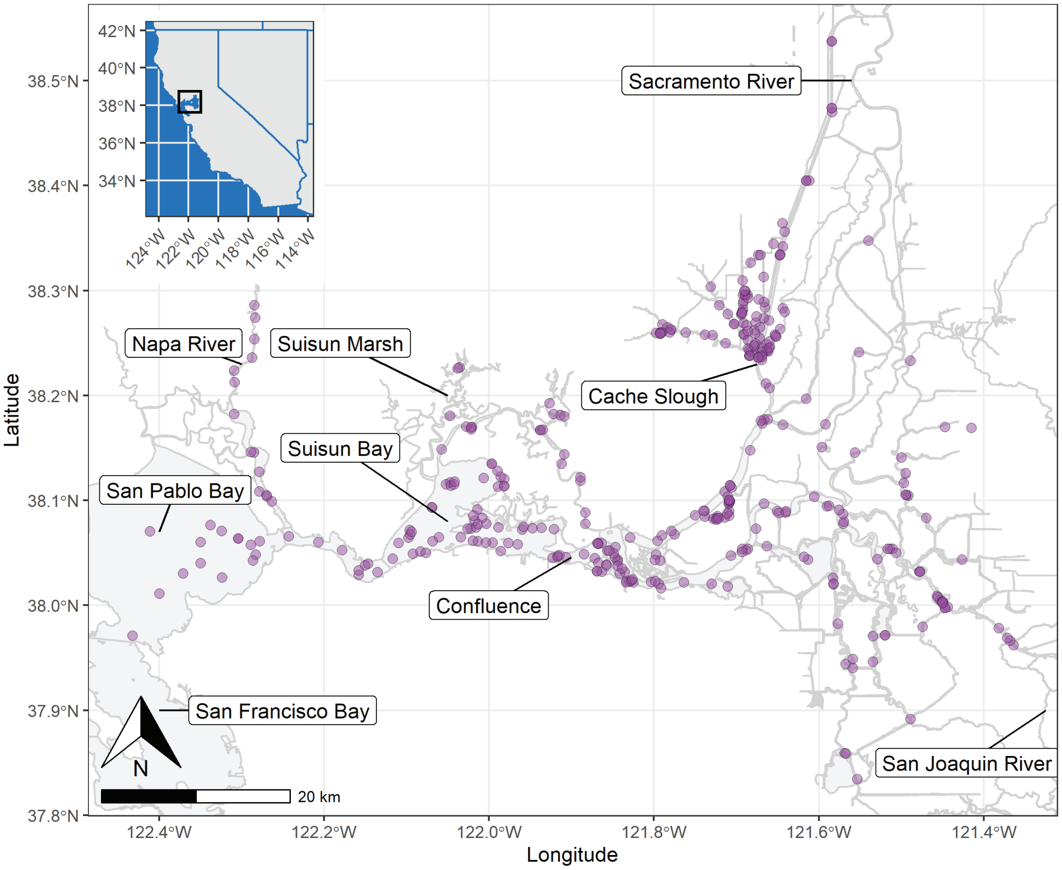
Pelagic fish in the San Francisco Estuary (estuary) are harder to catch in recent decades. Over the past thirty years, Delta Smelt catch in the Fall Midwater Trawl (FMWT) has declined by 99%, Longfin Smelt catch has declined by over 95%, and even the notoriously hardy Striped Bass have declined by over 75% (California Department of Fish and Wildlife [CDFW] FMWT data, unpublished, see "Notes"). To manage the system and reverse these declines, we need a better understanding of the "bottom-up" processes that exert control on these populations—we need to study fish food. In other words, in addition to studying fish directly, we need to increase our understanding of what pelagic fish eat: zooplankton (Brown et al. 2016).

Zooplankton are small, pelagic animals, including crustaceans, rotifers, and larval fish. These small animals are collected using fine mesh nets and are usually preserved when collected for later identification in a laboratory. In the estuary, zooplankton have been monitored regularly since 1972, and research conducted by the Interagency Ecological Program (IEP) has concluded that zooplankton have been in decline since the 1970s (Kimmerer and Orsi 1996; Orsi and Mecum 1996), that fish are often food-limited (Sommer et al. 2007; Hammock et al. 2015), and that many invasive species have significantly altered the food web (Bouley and Kimmerer 2006; Winder and Jassby 2011). Zooplankton are also food limited because of loss of phytoplankton due to grazing by invasive clams (Kimmerer et al. 2014), changes to residence time by upstream dam releases (Jassby 2005), and potentially through loss of upstream subsides by freshwater exports (Jassby and Powell 1994; Jassby et al. 2002;  Hammock et al. 2019). In 2019, the IEP and associated groups, including the CDFW Fish Restoration Program, collected an estimated 3,148 zooplankton samples from the San Francisco Estuary (Figure 1). Researchers at UC Davis, San Francisco State University, and others contributed

**Figure 1** Zooplankton sampling locations from the Delta Science Program's integrated zooplankton data set. Sample timing varies from every 2 weeks to twice per year, and some stations have been sampled since 1972, whereas others have only been sampled since 2016. *Data source: https://deltascience.shinyapps.io/ZoopSynth/*



hundreds more. Collectively, these samples were processed by traditional microscopy, image recognition software, and high-throughput sequencing to translate data about jars of animals into synthesized information that can improve management of the estuary's ecosystem.

Recent advances in online reference material, flow cytometry, image processing, genetics, autonomous samplers, quantitative modeling, and machine learning are making it easier to study zooplankton than ever before (Gislason and Silva 2009; Álvarez et al. 2011; Stanislawczyk et al. 2018; Ohman et al. 2019; Zamora–Terol et al. 2020). However, there is a disconnect between the information gathered from zooplankton data and management decisions. This is part of a broader issue about how science informs management, and how managers use field data; disconnects between scientists and managers are common throughout estuary resource management (Sommer 2020).

Zooplankton data can be complicated and difficult to understand, making it less likely that the information will be acted on. Solving this problem means educating zooplankton ecologists about the water management landscape and educating managers about zooplankton. In the fall of 2020, the Delta Science Program and IEP convened a symposium to share the latest data and information on zooplankton sampling methodology and ecology[1]. Researchers from across the country met not only to discuss the latest behavioral studies, habitat relationships, and sampling techniques, but also to discuss better integration of zooplankton data into water resource management. One major take-away of the workshop was the importance of increasing the quality of communication between zooplankton researchers and managers.

One way to illustrate the relatively low degree of outreach by zooplankton researchers is to examine patterns in publications in the primary journal for the estuary, *San Francisco Estuary Watershed Science* (*SFEWS*). *SFEWS* is arguably the most management relevant scientific journal for the region because it is open access, has the single largest repository of articles about the system, targets a broad audience (e.g., managers, scientists, and educators), and has a relatively large readership (Luoma and Muscatine 2019). Based on a review of *SFEWS* publications (2003 through early 2021) that include 271 essays and research articles, we identified just two articles (Kimmerer and Slaughter 2016; Kimmerer et al. 2018) in which zooplankton were the featured topic, representing less than 1% of the total articles published in that period. For comparison, we noted at least 13 articles which featured contaminants, a driver considered to be relatively underappreciated and understudied for the management of the estuary (Fong et al. 2016).

Zooplankton have not been ignored by estuary scientists and have been included as a factor in many *SFEWS* articles featuring fish or ecosystem processes (Slater and Baxter 2014; Brown et al. 2016; Frantzich et al. 2018). Still, the low number of feature articles about zooplankton themselves suggests that this topic will be less visible to resource managers. As a result, many new efforts towards habitat improvement in the estuary have been stymied by lack of understanding about zooplankton. For example, a recent structured decision-making effort to prioritize Delta Smelt recovery management actions began when consultants asked zooplankton researchers: “How much zooplankton is produced per acre of tidal wetlands in the estuary?” Zooplankton researchers did not know how to answer because: (1) zooplankton are undersampled in tidal wetlands; (2) the question was posed without a specific time of year, taxa of interest, or region of the estuary—all of which impact production rates; and (3) researchers were hesitant to put a number on a metric of high uncertainty. Neither the researchers nor the managers knew how to ask and answer questions about zooplankton in a way that the other group could use to aid the decision-making process.

Because zooplankton biology is complex, zooplankton ecologists need to become effective communicators and advocates for their data. This means becoming familiar with management-relevant research questions and management-relevant applications for existing data sets. One helpful way to approach this issue is to provide specific examples of management actions that could be informed by zooplankton data and which metrics are most relevant to management actions (Figure 2).

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[1] A livestreamed video of the symposium is available at this link: *https://youtube.com/playlist?list=PLqTHCliW1HhoSZmAYfGtnNoFH3GSw_k5O*.

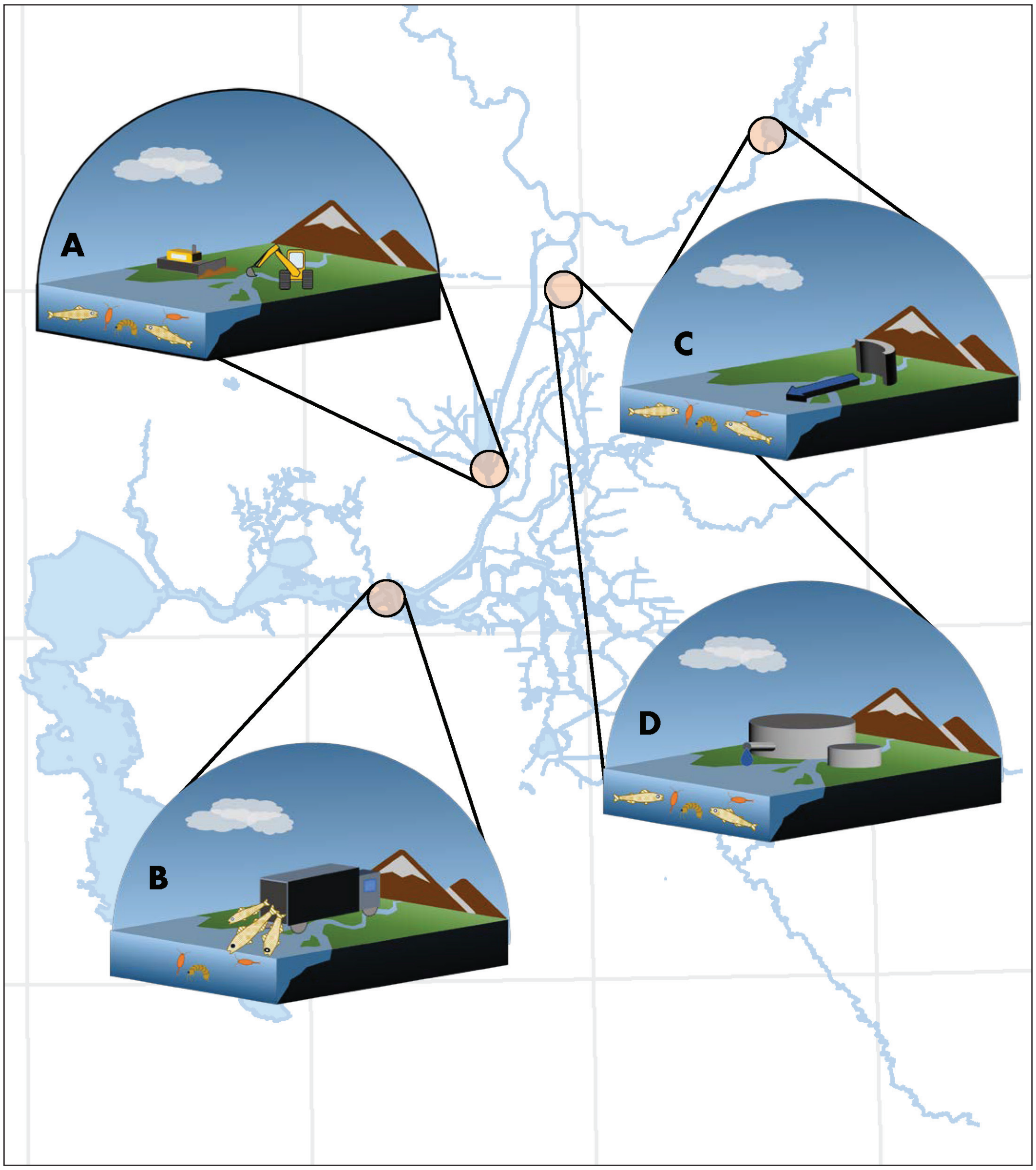
- **Wetland restoration**—Over 8,000 acres of tidal restoration are planned or recently completed in the upper estuary, under the premise that wetland restoration will increase food supply for at-risk fishes (Herbold et al. 2014; Sherman et al. 2017). Monitoring the effectiveness of these restoration projects hinges on measuring that food supply, much of which is in the form of zooplankton and aquatic macroinvertebrates. Useful metrics here include increases in biomass of the zooplankton before and after restoration, ability of fish to access zooplankton in the wetland, and percent of wetland carbon in zooplankton diets and biomass. (Figure 2A)

- **Floodplain restoration**—Early observations that floodplain habitats are rich in invertebrate food resources, including zooplankton, were a key rationale for recent floodplain restoration projects. For example, several projects within the Yolo Bypass floodplain are being designed to increase fish access to these resources either by allowing juveniles to rear on the floodplain or by flushing phytoplankton and zooplankton biomass from the floodplain to surrounding channels (Frantzich et al. 2018; Sommer et al. 2020). Important metrics include biomass of zooplankton on floodplains in comparison to surrounding rivers, timing of peak biomass in relation to length of inundation, and relative importance of zooplankton versus insects in fish diets. (Figure 2A)

- **Release of hatchery fish**—Salmonids have been raised in hatcheries to supplement wild populations for decades, and supplementation of Delta Smelt populations with cultured fish is pursuant to the 2019 US Fish and Wildlife Service Biological Opinion (USFWS 2019). However, fish released into a habitat without sufficient food resources may not be successful. Zooplankton data may be key for determining optimal release timing and locations to ensure adequate food supply (Beauchamp et al. 2004). Also, if fish are raised on processed fish food, they may need a "training period" during which they are fed zooplankton before release (Brown et al. 2003). Useful metrics here include distribution of zooplankton eaten by fish at potential release sites, seasonality of peak zooplankton abundance in relation to release timing, and taxa found in the wild that may be used for hatchery feed. (Figure 2B)

- **Managed flow actions**—Flow is considered a controlling variable that has a dominant effect on the environment of the estuary (Kimmerer 2002). Many management actions can include managing freshwater outflow to mimic a more natural hydrologic regime and improve overall ecosystem health (Sommer 2020). If these measures are effective, we would expect the aquatic community to have the same characteristics during a managed flow period as a natural high-flow period. Useful metrics here include zooplankton community composition, timing of peak biomass, and comparisons between natural flow regimes and managed flow actions. (Figure 2C)

**Figure 2** Management actions throughout the San Francisco Estuary can be improved by use of zooplankton data: (**A**) wetland and floodplain restoration, (**B**) release of fish from hatcheries or captive-rearing programs, (**C**) flow management, (**D**) water treatment



- **Water treatment**—Recent upgrades to the Sacramento Regional Wastewater Treatment Plant are expected to reduce nutrient concentrations and alter nutrient ratios in the Delta, impacting primary and secondary productivity (Cloern et al. 2020). This may alter phytoplankton community composition and abundance, which may alter zooplankton community composition and abundance (Kraus et al. 2017). The degree to which this action will cascade up the food chain will depend on how zooplankton respond to the change in food source. Useful metrics include changes to zooplankton community composition and biomass before and after the upgrade, zooplankton diet, and presence of species sensitive to wastewater contaminants before and after the upgrade. (Figure 2D)

While zooplankton ecologists must become effective in translating their research to apply to management actions, managers need also to improve their zooplankton literacy. It is not necessary to know everything about zooplankton, but some understanding of their role in the food web will help identify situations in which zooplankton data may be informative and allow the development of management-relevant questions. Towards that goal, we suggest a few facts about zooplankton from the recent symposium that resource managers should be aware of (Figure 3).

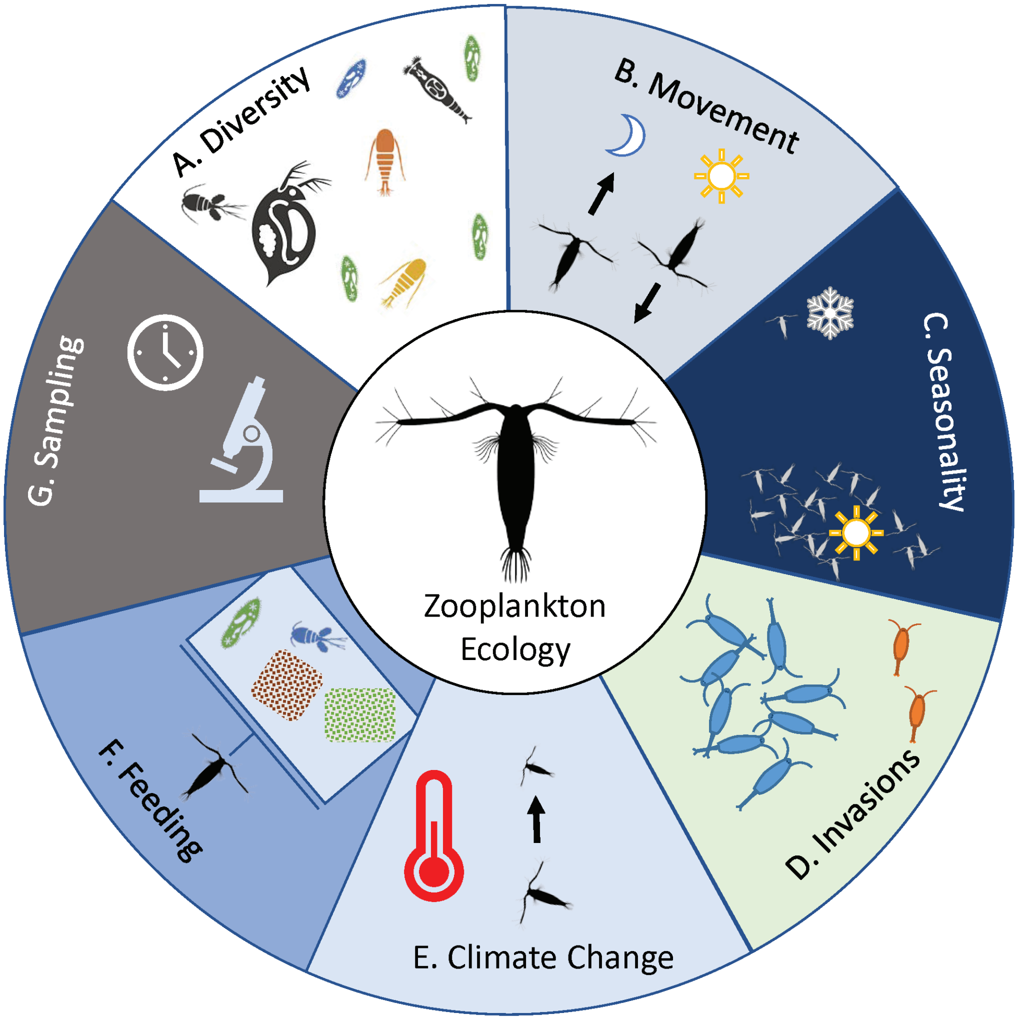
- **Zooplankton are diverse** and the specific species that are present matter. While fish in the estuary comprise two taxonomic classes (a difference equivalent to that between birds and mammals), zooplankton comprise multiple phyla (differences equivalent to those among vertebrates, worms, insects, and all other types of animal life). The fish community usually has between 40 and 110 species, depending on salinity (Stompe et al. 2020). Zooplankton includes hundreds of species (Kayfetz et al. 2020). Not all zooplankton make good fish food, and different zooplankton taxa may respond to different environmental conditions. While some generalizations apply, a single metric of zooplankton abundance may not provide the information needed to assess management actions. (Figure 3A)

- **Zooplankton are not passive particles**—Zooplankton cannot actively swim against a strong current, but they can move up and down in the water column to "surf" with the tides, avoid predation, and maintain their position in the estuary (Kimmerer et al. 1998). These movements can even impact how carbon is cycled through the ecosystem (Steinberg and Landry 2017). Hence, increased freshwater flow will not simply flush zooplankton into San Francisco Bay. (Figure 3B)

- **Timing is important**—Zooplankton have seasonal life history patterns. Many fish (such as Striped Bass) eat zooplankton only during the early part of their life. Some zooplankton taxa may be an order of magnitude more abundant during the summer than the winter (Hennessy 2018). Higher zooplankton concentrations can increase fish feeding success, growth rates, and survivorship (Sommer et al. 2001; Baskerville–Bridges et al. 2004). Therefore, management actions that target increases in zooplankton should be timed when fish can best take advantage of these resources. (Figure 3C)

- **Our zooplankton come from all over the world**—Some non-native zooplankton can have sweeping impacts on zooplankton communities (Strecker and Arnott 2008), leading to both bottom-up and top-down effects on the ecosystem. However, not all invaders are created equal. The non-native copepod, *Pseudodiaptomus forbesi*, now composes 30% to 50% of summertime Delta Smelt diets (Slater and Baxter 2014; Slater et al. 2019). In contrast, another non-native invasive copepod, *Limnoithona tetraspina*, is much smaller than *P. forbesi* (and therefore not as nutritious), and it is selected against by fish (Bouley and Kimmerer 2006; Slater and Baxter 2014; Sullivan et al. 2016). Monitoring programs should watch carefully for new zooplankton species and be ready to evaluate their new role in the ecosystem. (Figure 3D)

**Figure 3** Some aspects of zooplankton science and ecology are important to understanding management implications of zooplankton data: (**A**) zooplankton community composition impacts their role in the environment, (**B**) zooplankton move to avoid predators and maintain their location, (**C**) zooplankton have seasonal cycles of growth and reproduction, (**D**) non-native species are common in the estuary, and new species may change the community, (**E**) climate change may shift the community towards smaller species, (**F**) zooplankton may eat detritus and other zooplankton, as well as many different types of phytoplankton, (**G**) zooplankton data are time-consuming to collect and require specialized skill sets



- **Climate change impacts zooplankton**—As the estuary warms, the zooplankton community may shift towards species with smaller body size, higher thermal tolerance, or different timing of peak abundance. Individual species may also adapt to the changing environment (Dam 2013). These changes could impact fish by creating a mismatch between the timing of peak food availability and critical fish development stages. Therefore, management actions that work under current conditions may not have the same impacts on zooplankton in the future. (Figure 3E)

- **Zooplankton eat many different things.** While most often thought of as primary consumers of phytoplankton, larger, predatory copepods prey on smaller zooplankters and may even control their population (Kayfetz and Kimmerer 2017). Therefore, some zooplankton may compete with fish for food resources. Other zooplankton may eat plant detritus more often than we think, particularly near tidal wetlands (Harfmann et al. 2019). Some zooplankton even eat cyanobacteria traditionally thought of as "poor food" (Kimmerer et al.

2018) or fail to thrive on diatoms considered "good food" (Jungbluth et al. 2020). Protists and bacteria are frequently ignored but are also an important part of the food web (Rollwagen–Bollens et al. 2011). This means that zooplankton feeding (and therefore fish feeding) may not follow simple linear responses to management actions designed to increase phytoplankton. (Figure 3F)

- **Zooplankton sample processing is time consuming and labor-intensive**, which needs to be factored into monitoring for management actions. One fish trawl generally takes between 15 and 30 minutes to collect and process. One zooplankton sample takes approximately 15 minutes to collect and between one and 8 hours to process through traditional microscopy. Occasionally, samples can take up to 16 hours to process due to high amounts of debris or organic matter. High processing times mean that zooplankton data often are not available until a year after collection, further complicating the ability to determine the effects of management actions. Genetic analysis and photo-recognition software could greatly reduce processing time (Gislason and Silva 2009; Bucklin et al. 2016), but still take more time than water quality or fish data. (Figure 3G)

In the San Francisco Estuary, we are fortunate to have a long history of zooplankton monitoring, providing both scientists and resource managers with a wealth of information to work with (Kayfetz et al. 2020). Recent efforts to integrate some of the data from different monitoring programs and visualize the results (Bashevkin et al. 2020) will increase our ability to use zooplankton data to make decisions, but only if scientists and mangers can collaborate to make zooplankton meaningful.

To maximize the use of these data for management, we propose several recommendations for both managers and scientists:

- **Managers and scientists should work together** to develop clear goals and objectives for management actions. Is there a threshold of zooplankton biomass or abundance to achieve? Or is the goal simply higher biomass of certain taxa? This will make it easier to design a study that provides management-relevant results.

- **Scientists should understand management goals** and keep the end goal in mind. If the end goal is fish food, study taxa that are most common in fish diets. If the primary interest is contaminant effects, focus on sensitive species.

- **Invest in new technology.** Many new zooplankton sampling and analysis methods, such as autonomous samplers, metabarcoding, and photo-recognition, produce data that is different in taxonomic resolution or quantitative accuracy (or both) when compared to traditional microscopy (Gislason and Silva 2009; Bucklin et al. 2016; Ohman et al. 2019). However, these tools may provide faster and more useful data for some applications, and often reduce costs. Integrating new sampling techniques with recent quantitative advances in zooplankton modeling may allow data to be used in a more predictive way.

- **Communicate openly.** To maximize the value of zooplankton data, it is important to maximize its accessibility to scientists and managers. Scientists should share data in publicly available places in easy-to-read formats as recommended by Kayfetz et al. (2020). Similarly, managers should share lessons learned from management actions widely, and use them for adaptive management. Both scientists and managers should be encouraged to ask questions of each other to ensure both understand the best uses for zooplankton data. This sharing of information can occur during project-specific technical meetings, at scientific conferences and symposia, through distribution of memos and fact sheets, peer-reviewed scientific papers, or even through blog posts. Using multiple communication avenues will be more helpful than relying on a single platform.

Keeping these recommendations in mind will allow the broader resource management community to effectively manage the entire ecosystem, including zooplankton, and perhaps gain a greater appreciation for these critters for their own sake—not just as fish food. Returning to our Delta Smelt structured decision model example, a more productive conversation could have started this way: “We want to compare the relative benefit of wetland restoration and flow actions. Can we quantify the contribution of tidal wetlands to Delta Smelt food resources?” Defining the reason behind the question (Delta Smelt food resources) allows the zooplankton scientist to home in on the type of data that will be most useful. Even though tidal wetlands are understudied, the zooplankton scientists could provide a summary of available data to see whether any generalities can be made. The two groups (managers and scientists) can have a dialog about which metrics can best be used to compare wetlands and flow actions: Biomass of zooplankton per acre or productivity of phytoplankton per acre? We hope that this type of discussion can lead to better incorporation of zooplankton research results into water resource management decisions.

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