Science Foundation Chapter 3
Appendix 3.1 – Case Study
Plankton

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DESCRIPTION OF THE GROUP

This case study considers phytoplankton and zooplankton, emphasizing productivity of foodweb support to upper trophic levels. Phytoplankton or planktonic algae provide most of the energy supply to the pelagic foodweb of the estuary and therefore also to the benthos and some marsh organisms. Much of the phytoplankton production is consumed by microzooplankton and clams. Larger zooplankton consume phytoplankton and microzooplankton.

CRITERIA FOR SELECTION OF THE GROUP

Planktonic production is key to the overall productivity of the estuary and to the food available to fish. In Suisun Bay and the western Delta, the food supply to fish is a severe constraint and has probably contributed to declines in fish and other species. Long-term trends in phytoplankton and zooplankton reveal substantial shifts in abundance and species composition, and further changes can reasonably be anticipated in the future. In the past four decades phytoplankton production has varied considerably in response to various influences including climate in the coastal ocean, introduced bivalves, increasing water clarity, and nutrients. Zooplankton abundance has responded most strongly to alien species introductions.

OTHER INFORMATION ABOUT THE GROUP

Plankton in general either drift passively or swim at low speeds relative to the movement of the water (note: they are not all weak swimmers, but their small size limits their swimming speed). The strong tidal currents throughout much of the estuary mix the plankton between channels and shoals, and vertically except when the channels are stratified by salinity or when some zooplankton undergo vertical migration.

The species composition of plankton changes with salinity from a freshwater assemblage to an oceanic assemblage, with a few species present only at intermediate salinities. Phytoplankton include single cells with sizes from 1 to >100 µm, and chains and aggregates that can be visible to the naked eye. Phytoplankton is a heterogeneous collection across a very wide range of taxonomic groups including some cyanobacteria ("blue-green algae"). Long-term monitoring has shown the dominance of certain species in certain regions, and how that dominance has shifted over time ({Cloern, 2005 #4748; Cloern, 2012 #7097}).

The zooplankton includes microzooplankton (smaller than 0.2 mm) and the larger mesozooplankton (0.2 – 2 mm) and macrozooplankton (>~2mm). Microzooplankton includes single-celled organisms such as ciliates and flagellates, and larval and juvenile stages of copepods. Mesozooplankton includes juvenile and adult copepods, cladocerans, and larvae of various organisms such as clams, crabs, barnacles, and fish.

Phytoplankton Production

Plant production (or productivity) is the rate at which organic matter is produced by photosynthesis within a given area or volume. Phytoplankton production is the largest source of available organic carbon to the open waters of the estuary (Sobczak et al. 2002). Production by other aquatic plants such as attached algae and vascular plants (see Submerged Aquatic Vegetation (SAV) case history) is probably much smaller than that by phytoplankton because of the limited extent of SAV and the high specific growth rates of phytoplankton. Production by benthic microalgae has not been studied much in the estuary, and may also be important in shallow areas (Cornwell et al. 2014).

For the purposes of this discussion, we consider net production, i.e., photosynthesis less respiration. Net production is the product of biomass, the quantity of phytoplankton (usually as organic carbon) per unit estuarine volume or surface area, and specific growth rate, i.e., the daily growth expressed as a fraction of the biomass. These two factors can be considered separately in how they are measured and in what environmental factors affect them.

Several long–term monitoring programs routinely measure chlorophyll concentration, a proxy for biomass. Production has been measured in shorter-term studies, mostly using uptake of radioactively labeled carbon (e.g., Cole and Cloern 1987, Kimmerer et al. 2012). Production is not routinely monitored but can be estimated from biomass together with incident light and water clarity, which are monitored.

Phytoplankton production is influenced by a wide variety of factors, most of which are likely to change in the coming decades. Specific growth rate depends on the following factors:

Light level: Phytoplankton growth rate increases with light level up to its maximum rate, which depends on the other factors below. In this currently turbid estuary, growth rate is typically under severe light limitation in the deep channels except during periods of salinity stratification (Cloern 1984). Phytoplankton growth rate can be high over shoals, and in the surface layer when channels are stratified.

Water depth: In shallow water light may penetrate to the bottom, allowing phytoplankton to grow at all depths. In deep water, the depth-averaged growth rate of phytoplankton can drop below the respiration rate such that net production is negative. The only way this can be supported in the long run is by mixing between regions of high (shoals) and low or negative (channels) production, although periods of stratification in channels can trap phytoplankton in the surface waters and cause positive growth (Cloern 1984, Lucas et al. 1999).

Nutrient concentrations and composition: In many estuaries high nutrient concentrations cause eutrophication, by which excessive growth of phytoplankton produces excessive organic matter, resulting in shading out of SAV, and in some cases depletion of oxygen in bottom waters. In the San Francisco Estuary over the last several decades eutrophication has not been a problem despite high nutrient concentrations, mainly because of high turbidity.

This situation is no cause for complacency for three reasons. First, the waters of the estuary are becoming clearer (Kimmerer 2004) as the pool of available sediment has declined (Schoellhamer 2011). At some point this could allow for phytoplankton growth to accelerate to the point where large blooms occur and eutrophication is possible.

Second, there is some evidence that the form of nitrogenous nutrients may affect the growth rates of some phytoplankton. Specifically, nitrate uptake is inhibited by moderate to high ammonium concentrations ({Dortch, 1990 #6468}), and some diatoms may grow faster when using nitrate as a nutrient source than when using ammonium ({Dugdale, 2007 #5650}). The exact relationship of ambient phytoplankton growth to ammonium concentration is uncertain, and the putative link between ammonium concentration and suppression of diatom blooms is controversial. However, ammonium concentration is usually high enough to limit nitrate uptake because of releases by wastewater treatment plants, and the quantity released has increased in parallel with changes in phytoplankton biomass and species composition (as well as numerous species introductions and other changes).

Third, there is also evidence that harmful algal blooms (HABs) may be increasing in the estuary, possibly as a result of increasing water clarity, changing nutrient concentrations, and changing water residence time (Lehman et al. 2005).

Species composition: Phytoplankton growth rates and their responses to environment (light, nutrients, temperature, salinity) are species-specific. For example, some species of diatom can grow very rapidly under conditions of high nitrate, low to moderate temperature, moderate light level, and moderate turbulence. Some cyanobacteria can fix nitrogen from atmospheric N_2 gas, and can therefore grow when nitrogenous nutrients are scarce. Motile species such as dinoflagellates, or buoyant forms such as the toxic cyanobacteria *Microcystis*, a HAB species, can move into favorable depths for light or nutrients. All of these differences make it very difficult to predict which species of phytoplankton will become abundant in blooms under current conditions or as a result of long-term change.

There has been a long-term trend in San Pablo Bay to the Delta toward smaller and possibly less nutritious phytoplankton species. This trend has been linked alternatively to size-selective grazing by the introduced clam *Potamocorbula amurensis* and changes in nutrient composition. Smaller cells are less available for grazing by zooplankton, with the result that foodweb efficiency has decreased. This, together with the overall low productivity of this part of the estuary, implies poor foodweb support for fish (Kimmerer et al. 2012, Cloern and Jassby 2012).

The expansion of *Microcystis* in the Delta roughly coincided with the pelagic organism decline in the upper estuary, indicating a possible link through the foodweb. Ongoing field-based experiments on the effects of *Microcystis* on zooplankton that are key foodweb organisms in the Delta will help to determine the effect of these blooms, although laboratory experiments suggest a strong negative effect on survival (Ger et al. 2010).

Temperature: Physiological rates of phytoplankton and other ectothermic organisms depend on temperature, generally increasing with temperature to a species-specific maximum and then declining sharply. Photosynthetic rate responds more strongly to ambient variation in light than variation in temperature, while respiration rate is strongly sensitive to temperature. There is no information on the temperature response specifically for phytoplankton in the San Francisco estuary.

Salinity: Phytoplankton move with the water and therefore do not experience changes in salinity the way that marsh or benthic organisms do. A given species is most abundant over a range of salinity and its abundance declines at higher and lower salinity. This pattern is due to some combination of salinity tolerance of individual species, which can affect growth, and factors that affect biomass (below).

Biomass accumulation or depletion depends on specific growth rate, grazing, and hydrodynamic transport to and from other regions of the estuary.

Grazing by zooplankton and bivalves removes most of the phytoplankton production in the estuary. In the northern estuary, and previously in South Bay, grazing by bivalves controls the accumulation of biomass (Cloern 1982, Lucas et al. 1999, Thompson 2005, Kimmerer and Thompson 2014). Grazing by the clam *Potamocorbula amurensis* has been high since its introduction in 1986, and phytoplankton biomass in the northern estuary has been high only during a few brief spring blooms (Kimmerer and Thompson 2014). Grazing by this clam has also depressed abundance of some copepod species and probably microzooplankton (Kimmerer et al. 1994, Greene et al. 2011).

Grazing by microzooplankton is also an important loss term for phytoplankton, and at times can exceed that by bivalves, while grazing by mesozooplankton such as copepods is the third most important grazing term (Kimmerer and Thompson 2014). In the South Bay grazing by clams declined sharply around 1999, resulting in an increase in phytoplankton biomass. The decline in clam abundance was apparently due to an influx of benthic-feeding fish which in turn resulted from a shift in ocean climate (Cloern et al. 2007).

The distribution of benthic grazers shifts rather slowly with seasonal movement of the salinity gradient, while the plankton move with the water and therefore most of the individuals in a population are not directly affected by salinity. However, an indirect salinity effect can arise when the temporal patterns of freshwater and tidal flow place a plankton population over a shoal or a channel, and in or out of contact with a clam bed.

<u>Transport</u> occurs through advection, i.e., the gradual seaward movement of the water due to river input, and dispersion or horizontal mixing, which moves salt, sediment, and plankton from areas of high abundance toward areas of low abundance. Mixing is largely effected by the tides and influenced by the salinity distribution (see section on salinity in Chapter 2 and on sediment movement in Chapter 4).

Transport can bring freshwater or oceanic phytoplankton into the estuary, mix phytoplankton between favorable and unfavorable salinity or depth regimes, and spread a buildup of biomass from shallow areas to deep areas where blooms are unlikely (Lucas et al. 1999). It can also bring phytoplankton into or out of proximity with benthic grazers, outfalls, water intakes, shoals, and other geographically static habitat elements that may affect biomass.

Zooplankton Production

Little is known about the long-term patterns of abundance or taxonomic composition of microzooplankton because, despite their importance in the estuarine foodweb, they have never been monitored. Microzooplankton consume bacteria, phytoplankton, and other microzooplankton. They are the second most important grazers in the northern estuary after clams (Kimmerer and Thompson 2014), and the most important food for some mesozooplankton (Rollwagen Bollens and Pen 2003, Bouley and Kimmerer 2006, Gifford et al. 2007).

As with phytoplankton, production of zooplankton is the product of biomass and growth rate. Under conditions of plentiful food, growth rate increases with increasing temperature below the upper thermal limit for each species, and also varies with species. Growth of microzooplankton presumably responds to temperature as well as phytoplankton or bacterial biomass, but previous experiments in the low-salinity zone showed relatively little response which was interpreted to mean that food is usually adequate for microzooplankton (York et al. 2011), and their biomass may be limited by consumption by clams (Greene et al. 2011). However, the growth rates of copepods including their nauplius larvae are chronically food limited (Kimmerer et al. 2005, W. Kimmerer, unpub.). This can be interpreted to mean that the availability of food for small fish is limited by the productivity of phytoplankton, at least in the upper estuary.

Micro- and mesozooplankton are also subject to transport by tidal and net (river-derived) currents but the larger organisms (> ~0.5 mm) are capable of tidal and daily migrations that effect retention within some region of the estuary (Kimmerer et al. 2002, Kimmerer et al. in prep.). Microzooplankton are also removed through grazing by clams, and this can be a significant loss to the populations despite strong escape responses of the larger organisms (Kimmerer et al. 1994, Greene et al. 2011).

REVIEW OF LONG-TERM EFFECTS

Many of the controlling factors discussed above are likely to change in the long run with changing climate and human interventions. The long-term changes likely to have the greatest effect on phytoplankton are:

<u>Changing water clarity</u> due to shifts in the estuary-wide sediment budget, with potential contributions from changing wind speed, tidal prism, and water depth. Although the main concerns with increasing clarity are for eutrophication and harmful algal blooms, Suisun Bay and the western Delta are currently in a state of low productivity, and a trend toward eventual eutrophication would have to pass through a period of moderate to high production before production becomes excessive. Thus, for that region, which seems most affected by the increase in water clarity, the concern over eutrophication may be premature. However, the trajectory of phytoplankton production depends on the continued high impact of grazing by introduced clams, and if that grazing were to be reduced (as it was in South San Francisco Bay), the trophic status of the estuary would shift toward eutrophication.

<u>Changing nutrient inputs</u> with increases in human population and improved treatment. This effect is likely to be strong locally, but the broader-scale implications of a significant reduction in total nutrient inputs, or in ammonium inputs specifically, are uncertain. Equally uncertain is the likely response of blooms of harmful algae such as *Microcystis*. Some of these species do well in high-nutrient conditions, but the level of nutrient concentrations that would inhibit these blooms is unknown.

<u>Changes in the coastal ocean</u>: Plankton move between the coastal ocean and the Bay, affecting species composition and thereby responses to environment within the Bay. Any changes in the coastal ocean through, e.g., changes in upwelling intensity, local current patterns, or temperature will likely affect the species composition and condition of plankton entering the Bay. However, the likely magnitude and direction of such changes are poorly understood.

<u>Species introductions</u>, particularly of bivalves or other filter-feeders or their predators, or of some species of zooplankton. These shifts could occur naturally through range expansions and shifts in ocean climate, or through human activities. For example, the anticipated changes in the salinity distribution (section 2.F) will lead to shifts in species distributions with consequences that would be difficult to predict.

Particular concerns for species invasions to the estuary are quagga and zebra mussels, which are likely to arrive in the estuary soon. Although these are considered freshwater species, they can tolerate some salinity. Furthermore, if established they would consume the freshwater phytoplankton that now provide a subsidy to the brackish parts of the estuary where grazing by *Potamocorbula* has suppressed phytoplankton biomass, leading to further declines in the brackish foodweb. Previous studies of zooplankton in ballast water, a likely vector for introducing planktonic organisms, did not reveal species that would be likely to have a major impact in the estuary (Choi et al. 2005), although that does not rule out future high-impact invasions through ballast-water discharge.

<u>Changing water circulation</u> due to a reduction in freshwater flow into the estuary during summer may make parts of the Delta less physically dynamic. This would make the Delta more suitable for blooms of

Microcystis, which could affect foodwebs in Suisun Bay, and also of the waterweed *Egeria densa*, which may remove nutrients from the water.

Temperature effects at the ecosystem scale are difficult to predict because the responses are species-specific. Some harmful algal species (possibly *Microcystis*) may be more suited to high temperature than low. Most of the introduced zooplankton species are most abundant in summer, suggesting tolerance to high temperature. The reproductive season of these zooplankton and some benthic grazers will likely be extended, extending the time during which net phytoplankton growth is negative.

OTHER STRESSORS

Contaminants such as herbicides may affect phytoplankton in the estuary. One study showed this effect to be episodic and patchy during 1997 in the Delta, where large quantities of herbicides are applied (Edmunds et al. 1999). Effects of a variety of contaminants on zooplankton have been reported, but these also appear to be sporadic (Werner et al. 2000).

FACTORS THAT MAY AFFECT SPECIES RESILIENCE

Individual species may or may not be resilient to changes in their immediate environment. The assemblages along the salinity gradient comprise a variety of species with overlapping salinity and seasonal distributions. This diversity of forms and responses to environment mean that foodweb support by plankton should be resilient to most kinds of change. However, the assemblage present in the northern estuary in 1986 appeared resilient, but by 1993 it had been completely altered by clam grazing and introductions of several copepods, and possibly also by a changing nutrient regime.

LIKELY CLIMATE CHANGE IMPACTS AND RISKS

The most significant impacts are likely to come not from climate but from species introductions and increasing water clarity. The risks cannot be calculated.

MANAGEMENT ACTIONS TO BE CONSIDERED

Anticipate and plan for the likely impacts of quagga and zebra mussels in the Delta. Maintain the Interagency Ecological Program's monitoring for lower trophic levels and water quality variables in the upper estuary. Expand or supplement that monitoring program to include South and Central Bay and expand coverage of San Pablo Bay. Add a microzooplankton component.

UNCERTAINTY AND KNOWLEDGE GAPS

- Thresholds for harmful algal blooms and effects on zooplankton.
- Likely effects of quagga and zebra mussels.
- Distribution, abundance, and trajectory of microzooplankton throughout the estuary.

- Distribution, abundance, and trajectory of mesozooplankton in the lower estuary.

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