Title

North Delta Arc Study 2018 Annual Report: Cache and Lindsey Slough Water Quality, Productivity and Fisheries

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Summary

The North Delta Arc, consisting of Suisun Marsh, the lower Sacramento River, the Cache-Lindsey Slough Complex, and Yolo Bypass, contains the best remaining habitat for native fishes in the northern San Francisco Estuary. In particular, the Cache-Lindsey Slough Complex represents the best opportunity for sustainable enhancement of native fish populations within the freshwater portion of the estuary. However, the CLC has been understudied relative to the main bays and rivers of the estuary, with only sparse, short-term data to gauge restoration success or to compare to the more data-rich bays and rivers.

To provide baseline data for restoration, to elucidate mechanisms supporting native and desirable fishes, and to document ecosystem responses to changes in both climate and water management, the North Delta Arc Study was initiated in 2012 and continues through to today. The study has used a diverse, flexible suite of both lab and field methods for improving knowledge about the entire ecosystem. Water-quality constituents, phytoplankton, and zooplankton have been collected, often at very high resolution, that have revealed both broad spatiotemporal patterns as well as clarifying vital drivers of native fish populations. Utilizing a suite of fish-sampling techniques, the study has also documented dramatic responses in the fish assemblage while also providing valuable data for adaptive management. When coupled, water-quality, plankton, and fish data from the study will be able to populate models that identify restoration designs most likely to succeed.

From 2012 to 2018, the estuary was subject to numerous challenging conditions: a prolonged, pervasive drought; extremely high water temperatures; and, later in the period, some of the highest flows and biggest floods in recent time. The North Delta Ac Study was in place to capture the response of the Cache-Lindsey Slough Complex to these challenges. Persistent low flows during the drought appeared to facilitate the spread and density of noxious aquatic weeds in the complex, which was accompanied by a notable increase in water clarity concurrent with a decline in suspended particles. Effects of a restoration implemented in this period on habitat conditions in adjacent sloughs were not observed. The fish assemblage changed with water-quality conditions and aquatic-weed growth, with decreasing native smelt numbers contrasted by increasing abundances of non-native sunfishes. Extremely high flows in 2017 appeared to only marginally affect the weeds and sunfishes, suggesting the complex had passed a threshold. Nevertheless, upstream reaches of small sloughs that received local stream flows maintained relatively high turbidities, high plankton abundances, and, consequently, high numbers of native and desirable fishes. Further, high-frequency sampling in the western complex around storms large enough to cause considerable runoff documented similar habitat conditions. The apparent importance of locally strong inflows in small sloughs in contrast to the observed weaker performance of the tidal restoration provides invaluable information for informing future management actions targeted at native and desirable fishes.

Introduction

The North Delta Arc ("Arc") forms a habitat corridor along the northern edge of the upper San Francisco Estuary that is the principle remaining refuge for many native species (Moyle et al. 2018). It includes freshwater and brackish-water habitats extending from Suisun Marsh to the Yolo Bypass via the Sacramento-San Joaquin Confluence, Cache and Lindsey sloughs, Prospect Slough, the Toe Drain, and the Deep Water Shipping Channel (Figure 1).

Hydrodynamic, landscape, geochemical and food-web processes in the Sacramento-San Joaquin Delta ("Delta") have been greatly altered, affecting ecosystem function (Lund et al. 2007). In the late 1800s, hydraulic-mining sediment elevated river channel beds and increased flooding (Thompson 1957), causing Delta landowners to dredge and levee waterways to protect their farms. Large-scale flood control projects that straightened and widened main river channels were mostly completed by the early 1900s. Dendritic sloughs bordered by marsh plains were replaced by deep, straightened channels buttressed by hardened levees (Thompson 1957), with most tidal wetlands converted to farms. After state-wide droughts during the 1920s and 1930s, the federal and state governments began building the Central Valley and State Water projects, a system of reservoirs and aqueducts designed to store and transfer water for municipal and agricultural use (Lund et al. 2018). Separation of aquatic and terrestrial processes, coupled with dams and diversions, diminished the influence of both floods and sediment transport on Delta landscapes.

Shifts in physical and biological conditions can create feedback loops that compound stressors. For example, sediment loss combined with intensive farming of peat soils has caused deep subsidence in some regions of the Delta (Mount and Twiss 2005). Increases in water clarity and altered hydrodynamics have created opportunities for invasive species, such as submersed aquatic vegetation, that further limit water movement and reduce turbidity (Durand et al. 2016). The combination of filter-feeding by invasive invertebrates, such as clams, and increased water export have reduced food abundance for planktivorous fish, leading to population declines in some species (Kimmerer 1996; Moyle et al. 2016). Food-web deficiencies coupled with water-quality and habitat degradation have reduced refuge and foraging opportunities for native fishes (Grimaldo et al. 2004; Feyrer et al. 2007). Many fishes are dwindling, and some are critically endangered, including delta smelt (*Hypomesus transpacificus*), winter-run Chinook salmon (*Oncorhynchus tshawytscha*), and green sturgeon (*Acipenser medirostris*).

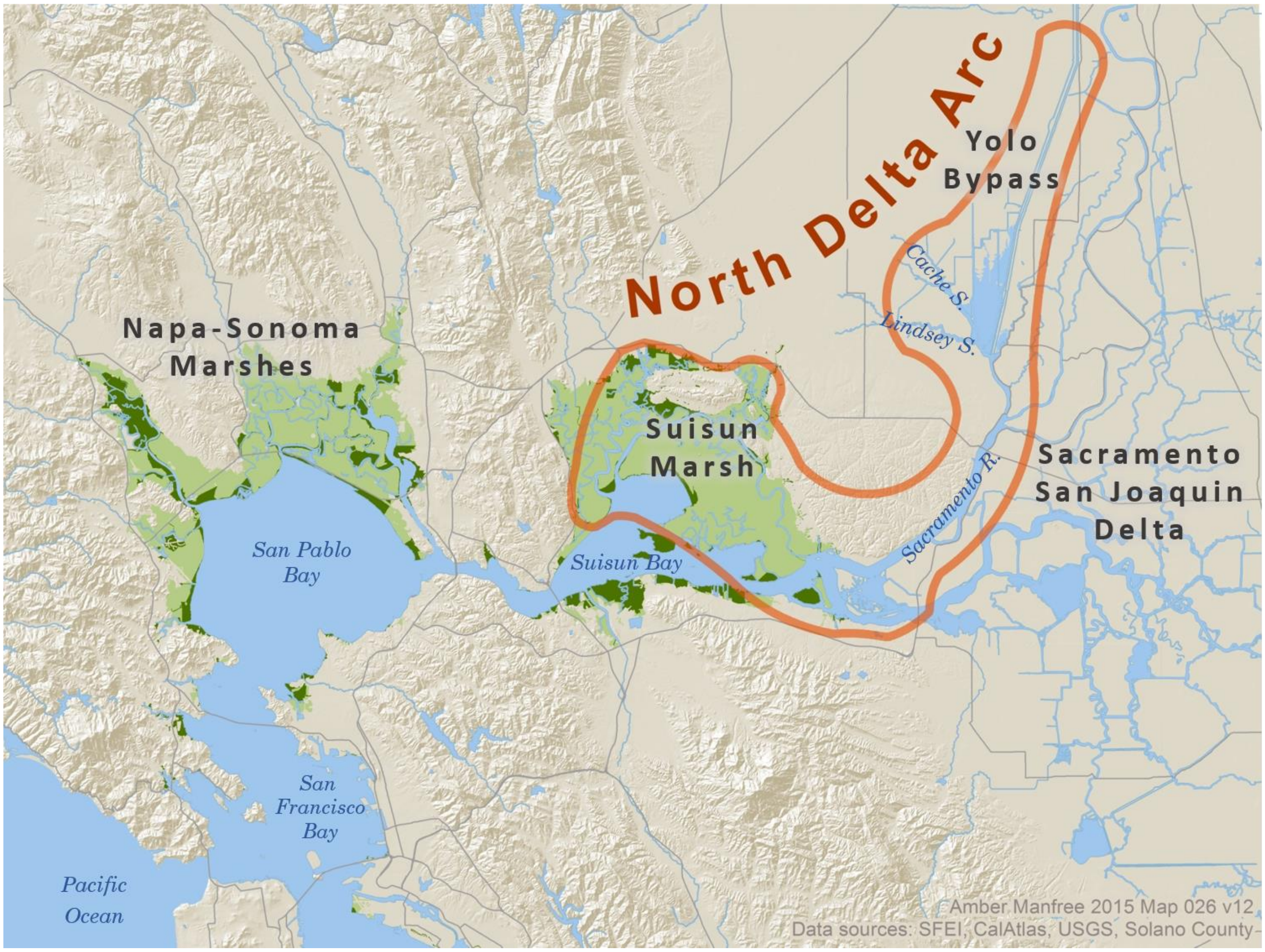


Figure 1. North Delta Arc, showing habitat corridor from Suisun Marsh to Yolo Bypass, including region of study at the Cache-Lindsey Slough Complex.

The Arc possesses the most potential for successful restoration in the Delta (Durand 2017; Moyle et al. 2018). Clay soils have resisted subsidence of reclaimed lands in the Arc, and a mosaic of shallow-water habitats, lost in other parts of the estuary, have been retained. Gradual upland elevations exist that can accommodate restoration and sea-level rise. Sediment from the Sacramento River and the Yolo Bypass results in higher seasonal turbidity than in other Delta regions. Historic riparian vegetation and emergent marsh are common features in several reaches of the Arc. Until recently, submersed and floating aquatic vegetation were less extensive in the Arc than in other areas of the Delta. The spatial complexity of the region; the connectivity to wetlands, floodplains, and streams; and high food concentrations support favorable seasonal and year-round habitats for both migratory and resident native fishes (Simenstad et al. 2000; Matern et al. 2002). There is thus broad interest in restoring large tracts of tidal habitat in the Arc (ICF International 2013).

Because of the promise of the region to support native organisms, the Arc is the focus of both scientific studies and restoration. The North Delta Arc Study was started in 2012 to describe the Cache-Lindsey Slough Complex (CLC) and to assess its response to environmental changes. The study's chief goals are to:

1) Use the Cache and Lindsey Slough complexes as comparative experimental systems to understand how variability in physical structure, management, water quality, and food-web production supports fish abundance and assemblage composition

2) Understand the effect of flow pulses from up-slough sources (e.g., overland flow, agriculture returns, and Ulatis Creek) on the longitudinal distribution of water-quality conditions and the pelagic food web

3) Understand impacts of drought, flood, and climate change on the environment and water-management needs and practices

4) Recommend actions to support successful restoration outcomes for food webs and desirable fishes

5) Recommend actions to manage invasive plants and animals

6) Recommend flow regimes and water-management practices to optimize water-quality conditions for consumptive use and environmental restoration

During the study, the region has been subject to drought, record water flows, experimental water releases, and tidal restoration. This seven-year time series provides understanding of the effects of these processes on estuarine ecosystem function while also supporting experiments that can resolve observational uncertainties.

Methods

Overview

The project employs an interdisciplinary approach that couples hydrodynamic and food-web models with empirical data on the distribution and abundance of phytoplankton, zooplankton, epibenthic invertebrates, and juvenile and adult fishes across habitat types. Water-quality sampling includes monthly water grabs that are analyzed for nutrient, chlorophyll-a, and organic carbon concentrations. Continuous water-quality probes are deployed on mobile platforms to create a synoptic monthly snapshot of fine-scale water-quality conditions across the region. Zooplankton tows are used to evaluate secondary production in response to water-quality and hydrologic conditions. Experimental water incubations allow us to estimate ecosystem metabolism, including the impact of phytoplankton production and zooplankton-grazing on food webs. Fish sampling includes biannual boat electrofishing, monthly otter trawling, and monthly beach seining.

Study Area

Sampling has been conducted since 2012 across the Arc but focusing on the CLC, which includes Cache and Lindsey sloughs and their smaller tributaries (Barker Slough, Calhoun Cut, Hass Slough, and Ulatis Creek; Figure 2). The study area encompasses numerous planned and implemented restoration sites, including the Calhoun Cut Ecological Preserve (for which the project has pre- and post-implementation data), the North Liberty Island Mitigation Bank and Beaver Ponds (*post-hoc* data), and the proposed Lookout Slough restoration (pre-implementation data). Since early 2015, electrofishing, water quality, and zooplankton surveys have included several sites beyond the CLC, including those in Shag and Prospect sloughs, and the Stairsteps (Figure 1). Sites in the Toe Drain of Yolo Bypass have been sampled only rarely during exploratory surveys. In this report, we refer to the following sites as associated with Cache Slough tidal channel network (including Ulatis Creek and Hass Slough): UL1, UL2, CA1, CA2, CA3, HS1, and HS2. The following sites as associated with Lindsey Slough tidal channel network (including Calhoun Cut and Barker Slough): CC1, CC2, BK1, BK2, LN1, and LN2. LNCA is the lowermost Lindsey Slough site, located at its confluence with Cache Slough (Figure 2).

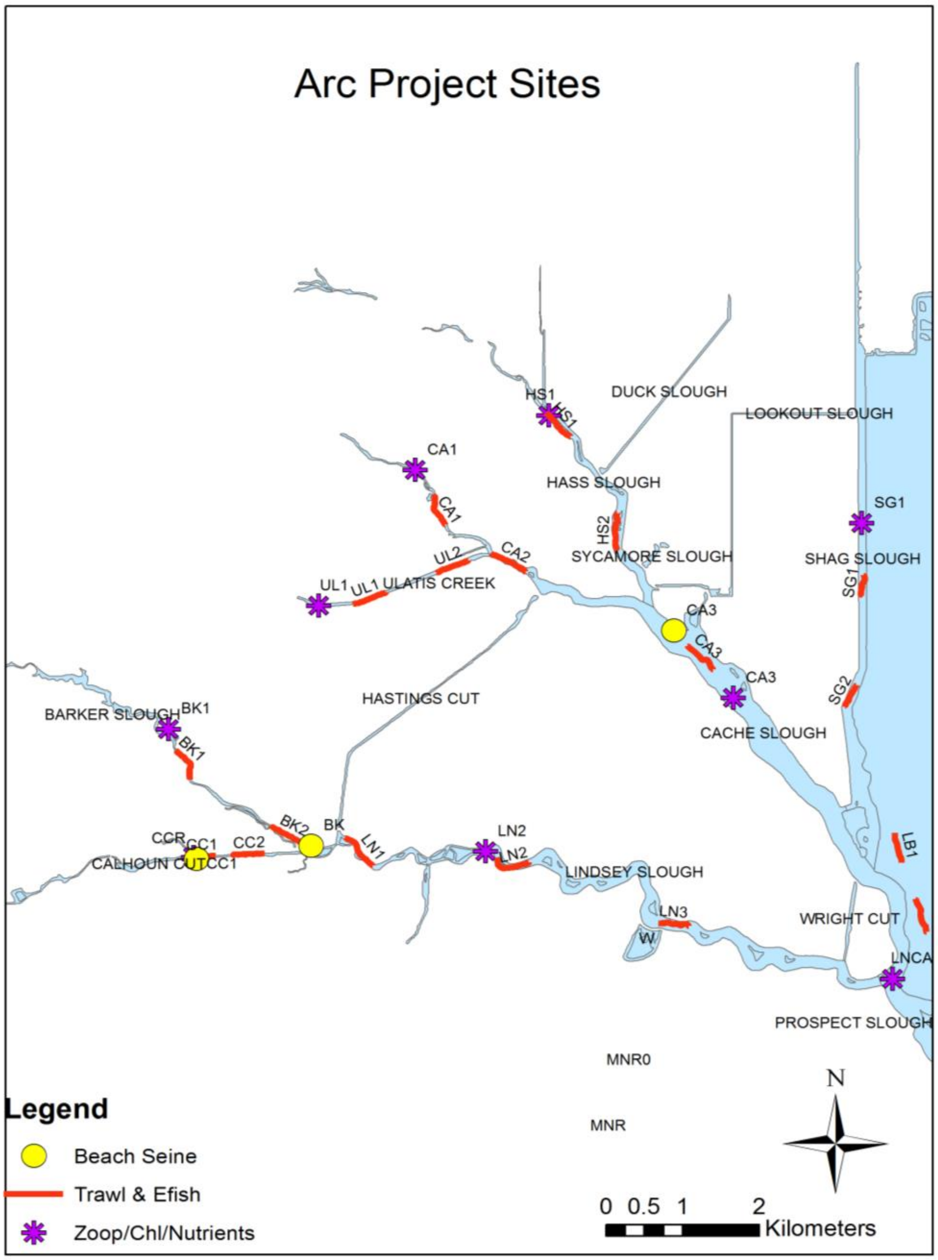


Figure 2. Primary monthly sample sites in Cache and Lindsey sloughs. Fish sample sites in yellow and red; water-quality grab sites in magenta.

A combination of historical whim and water-management decisions have endowed Cache and Lindsey Sloughs with very different features, despite their close geographic proximity. Both sloughs were connected historically to Maine and Jepson prairies, which drained much of Solano County east of the Vaca Mountains and north of the Montezuma Hills (along with Putah Creek to the north). Within and between the slough complexes are differences in hydrodynamics, water-quality characteristics, nutrient concentrations, and physical structure. For example, Lindsey and Cache sloughs exhibit clear differences in slough morphology and complexity, fine-scale attributes not included in Delta regional models that nevertheless form gradients affecting fish assemblages and abundances.

Cache Slough is steeply leveed and subject to periodic large flows from the upstream Ulatis Creek Watershed, which provides both local flood control and conveyance for irrigation tailwater. Urban, flood, and agricultural runoff, including flows from Vacaville's Easterly Wastewater Treatment Plant, are directed into Ulatis Creek. At times, Cache Slough holds a high proportion of native fishes, including delta smelt and other planktivores. Some reaches exhibit high turbidity year-round, and have less submersed and floating aquatic vegetation than other parts of the Delta.

Lindsey Slough is mostly isolated from large flood flows, although connectivity to adjacent landscapes results in local inputs. Deep and leveed near the mouth, the slough expands into relatively extensive intertidal and riparian habitats in the upper reaches. Water inputs come mostly from Jepson Prairie overland flow, the Big Ditch, and the Barker Slough Watershed. Water quality in Barker Slough varies as a function of precipitation and export. Precipitation enters the slough via Campbell Lake and irrigation canals, with the resultant runoff water accumulating salts and sediment, and affecting water quality in the slough. Export pumping is continuously measured at the Barker Slough Pumping Plant (BSPP) and is slowed or stopped under two conditions: when water quality for municipal use declines during precipitation events, or when facility maintenance is needed. A major tidal restoration project was recently implemented in Calhoun Cut in 2015. Lindsey Slough supports many more non-native sunfishes, and a much higher proportion of submersed and floating aquatic vegetation than Cache Slough.

Physical and hydrodynamic differences between the two channel networks provide an opportunity to evaluate mechanisms that drive biological differences. Water withdrawals and inputs likely affect hydrodynamics, water quality, food-web production, and species composition of the CLC. Locally, elements with potential to affect the system are 1) Ulatis Creek inputs; 2) inputs from agricultural returns (for example, Hass Slough and the Big Ditch system); 3) overland flow (for example, at upper Lindsey/Calhoun and Barker sloughs); and 4) municipal and agricultural withdrawals, including the BSPP. More distant elements with potential to affect the CLC are 1) winter/spring Yolo Bypass flows during flood years; 2) fall Yolo Bypass planned releases from rice fields to support the Delta Smelt Resiliency Strategy; and 3) Sacramento River flows and changes in water quality (for example, due to changes resulting from the Sacramento Waste Water Treatment plant upgrade, expected in 2021-23).

Water Quality and Zooplankton Sampling

We used the Net Delta Outflow Index ("Delta outflow") as a general indicator of water conditions across the study period. Delta outflow was calculated by summing river flows entering the Delta, channel depletions, in-Delta diversions, and State Water Project, Central Valley Project, and Contra Costa Water District exports. Delta outflow was obtained from the California Department of Water Resource's (DWR) Dayflow website (DWR 2019).

Monthly sampling expeditions recorded conditions in the CLC, Shag Slough, the Stairsteps, and Prospect Slough. Water quality was measured with a combination of hand-held meters, multiparameter sondes, and whole water grabs for laboratory analysis. In water-years 2016 and 2018, water-quality surveys were conducted more frequently to measure the direct and immediate impact of flows from storm events on water quality and fish. Various flow events were used as triggers for increased sampling frequency, including any storms that resulted in greater than 0.5 inches of local precipitation, flow releases on Putah Creek or Cache Creek, and increased flows down the Toe Drain or across the Yolo Bypass. In 2018, changes in export of water at BSPP were used as an experiment to evaluate effects on water quality and the food web.

Water-quality multiparameter sondes were used (a Hydrolab datasonde-5 through October 2018 and a YSI EXO2 sonde since November 2018) to create monthly water-quality maps of the region. Sondes were outfitted with sensors for conductivity, turbidity, dissolved oxygen, pH, depth (stage), temperature, and chlorophyll-a fluorescence. A pump outfitted to an intake below the boat continuously drew water from the slough and over the sonde probes while transiting at moderate speed. Data were recorded on a portable computer and synchronized with simultaneously collected GPS data. At the end of each sample day, data were uploaded to a laboratory computer and backed up on local and remote servers. Satellite corrections were applied to the spatial data within a week of data collection. Turbidity and chlorophyll-a were validated and corrected using simultaneously collected water grabs for lab extraction and analysis. The field (sonde) and lab (grab) data were regressed for correction factors that were then applied to the daily sonde data. Phytoplankton samples were preserved in Lugol's solution and archived for later identification, as necessary.

Lab analyses on the whole water grabs were used to validate sonde sensor readings for chlorophyll-a and turbidity. Additional laboratory analyses on many water-quality constituents important for ecosystem function were performed by the Dahlgren geochemistry laboratory at UC Davis [using standard analysis techniques from Eaton et al. (1998)] and included the following:

- *pH*. Low pH indicates increased heterotrophy, or respiration; high pH suggests increased autotrophy, or carbon fixation.
- *Indicators of suspended sediment or detritus*. These can be useful to determine what organic or mineral material is suspended in the water column. Turbidity is an optical measurement of particle concentration; dissolved organic carbon (DOC) is a measurement of the total amount of dissolved carbon in the water; total suspended solids (TSS) is a measurement of the mass of suspended particles in the water (including carbon); and volatile suspended solids (VSS) is a measurement of the mass of suspended carbon in the water.

- *Nutrients*. Phosphorus was measured as phosphate (PO_4), total dissolved phosphorus (TDP), and total phosphorus (TP). Nitrogen was measured as nitrate (NO_3), ammonium (NH_4), total dissolved nitrogen (TDN), and total nitrogen (TN). The ratio of TN to TP is an indicator of when nutrient limitation might occur. At very high values, phosphorus might be limiting.
- *Chlorophyll.* Chlorophyll serves as a proxy for phytoplankton production, which fuels zooplankton. Chlorophyll-a is a measurement of chlorophyll from living cells. Pheophytin-a is a measurement of ambient chlorophyll from lysed cells.

Zooplankton samples were collected at the same sites where whole water grabs and phytoplankton samples were collected. Zooplankton were collected using a 50-micrometer (µm) mesh conical net with 0.5-meter (m) gape and 2-m length. A flowmeter was mounted in the center of the net mouth to estimate volume. The net was hand-towed for 20 m against flow. Samples were then stored in glass jars, stained with 1% rose Bengal, and preserved in 5% formaldehyde. Samples were sub-sampled and analyzed under a dissecting scope until 100-200 individuals were counted. All individuals were identified to gross stage (juvenile or adults), to species, and to gender for adults. Egg counts were performed on females of species with attached egg sacs. Species tallies were recorded for each sub-sample. Total counts were taken from the tallied sub-samples at the conclusion of each sample analysis. Total counts were multiplied by the inverse sample proportion and divided by tow volume to give the total number of organisms per cubic meter. Zooplankton from key sites were analyzed for 2013-2014 for this report, and included two sloughs from Suisun Marsh and several adjacent Interagency Ecological Program (IEP) sites for comparison.

Fish sampling

Fish sampling was conducted in diverse near-shore and channel habitats, using a combination of boat electrofishing, seining, and trawling. Periodic high-intensity sampling was conducted during key periods of hydrodynamic variability and fish recruitment, which occurred in select locations as frequently as once a week. All sampling was conducted from UC Davis boats, including a 21-foot-long Workskiff outfitted for fish trawling and water-quality sampling, and a customized Smith-Root electrofishing vessel.

Trawling was conducted using a four-seam otter trawl with a 1.5-m X 4.3-m opening, a length of 5.3 m, and mesh sizes of 35-millimeter (mm) stretch in the body and 6 mm stretch in the cod end. The otter trawl was towed at approximately 4 kilometers/hour for 5 minutes at 19 sites. Beach seines 10-m wide and having a stretched mesh size of 6 mm were pulled at two or three sites, pending site suitability (sites became periodically inaccessible because of aquatic weeds).

Electrofishing was conducted bi-annually (spring and fall) using a Smith-Root 7.5 GP boat-mounted electrofisher at a constant pulse width of 60 pulses per second and variable power so as to maintain a constant electrical current of 8 ± 1 amperes. Earlier electrofishing efforts were conducted more frequently (2014-16). Between 12 and 24 transects along approximately 300 m of shoreline at each site were sampled in the down-current direction, with effort being measured in both distance of shoreline and time spent electrofishing. Stunned fish were collected using long-handled dipnets and placed in an aerated live-well prior to identification, and released upon recovery. Sampling was conducted within restoration project areas where possible, as well as in close vicinity of the projects, to detect possible influences on fish and food webs.

For each site, temperature (degrees Celsius, °C), dissolved oxygen (DO, milligrams per liter (mg/l), and % saturation), and specific conductance (microSiemens, µS) were recorded with a Yellow Springs Instruments PRO2030 handheld device. Water transparency (Secchi depth, centimeters (cm)), tidal stage (ebb, flood, high, low), and water depths (m) were also recorded.

Contents of each trawl or seine were placed into large containers of water. Fishes were identified to species using Wang (1986) and Moyle (2002), measured to the nearest mm standard length, and returned to the water. Sensitive native species were processed first and immediately released. Numbers of Siberian prawn (*Palaemon modestus*), red swamp crayfish (*Procambarus clarkii*), and Asian clam (*Corbicula fluminea*) were also recorded. Amphipods were pooled into one category and given an abundance ranking. Volume of debris, including aquatic vegetation, was estimated from each trawl to scale invertebrate density.

To evaluate changing fish assemblies, we chose the most abundant species from trawls and electrofishing, grouped them by guild, and then graphed them (Figure 16 and 17). The guilds encompass fish species with similar feeding strategies, habitat associations, and taxonomy. Grouping fishes by guilds offers a way to delineate patterns more easily without being overwhelmed by the complexity of viewing many individual species.

The Pelagic Organism Decline (POD) guild is comprised of fish that are planktivorous during at least one point in their life history and rely on estuarine conditions to carry out their life cycle. It includes striped bass (*Morone saxatilis*), delta smelt, longfin smelt (*Spirinchus thaleichthys*), wakasagi (*Hypomesus nipponensis*), threadfin shad (*Dorosoma petenense*), and American shad (*Alosa sapidissima*).

The centrarchid guild is comprised of non-native sunfishes introduced for sport fisheries from the southeastern United States. Centrarchids favor fresh water, warm temperatures, low flows, weedy habitats, and eat various invertebrates and fishes. It includes bluegill (*Lepomis macrochirus*), redear sunfish (*Lepomis microlophus*), largemouth bass (*Micropterus salmoidees*), white crappie (*Pomoxis annularis*), and black crappie (*Pomoxis nigromaculatus*).

The native-fishes guild includes a suite of the most abundant remaining native fishes in the Delta. These fishes favor fresh to brackish water and respond well to wet years with increased river and Delta flows, and includes tule perch (*Hysterocarpus traski*), Sacramento splittail (*Pogonichthys macrolepidotus*), hitch (*Lavinia exilicauda*), Sacramento sucker (*Catostomus occidentalis*), and Sacramento pikeminnow (*Ptychocheilus grandis*).

The benthic fishes guild includes bottom fishes that feed largely on invertebrates, including one native, prickly sculpin (*Cottus asper*), and two non-natives, yellowfin goby (*Acanthogobius flavimanus*) and shimofuri goby (*Tridentiger bifasciatus*).

Results

Mean Daily Outflow

The study began in the winter of 2012, which was the onset of a drought. Delta outflow was rather low in 2013, and was very low in 2014 and 2015, which were the driest years of the drought. In the winter of 2016, Delta outflow increased as the drought began to lessen (Figure 3). The following year, 2017, was extremely wet, and much of the Delta was flooded, causing an interruption to some sampling. Subsequent years (both 2018 and 2019) have continued to be above-average water years, allowing ecosystem recovery from the drought and an opportunity for this study to evaluate that process.

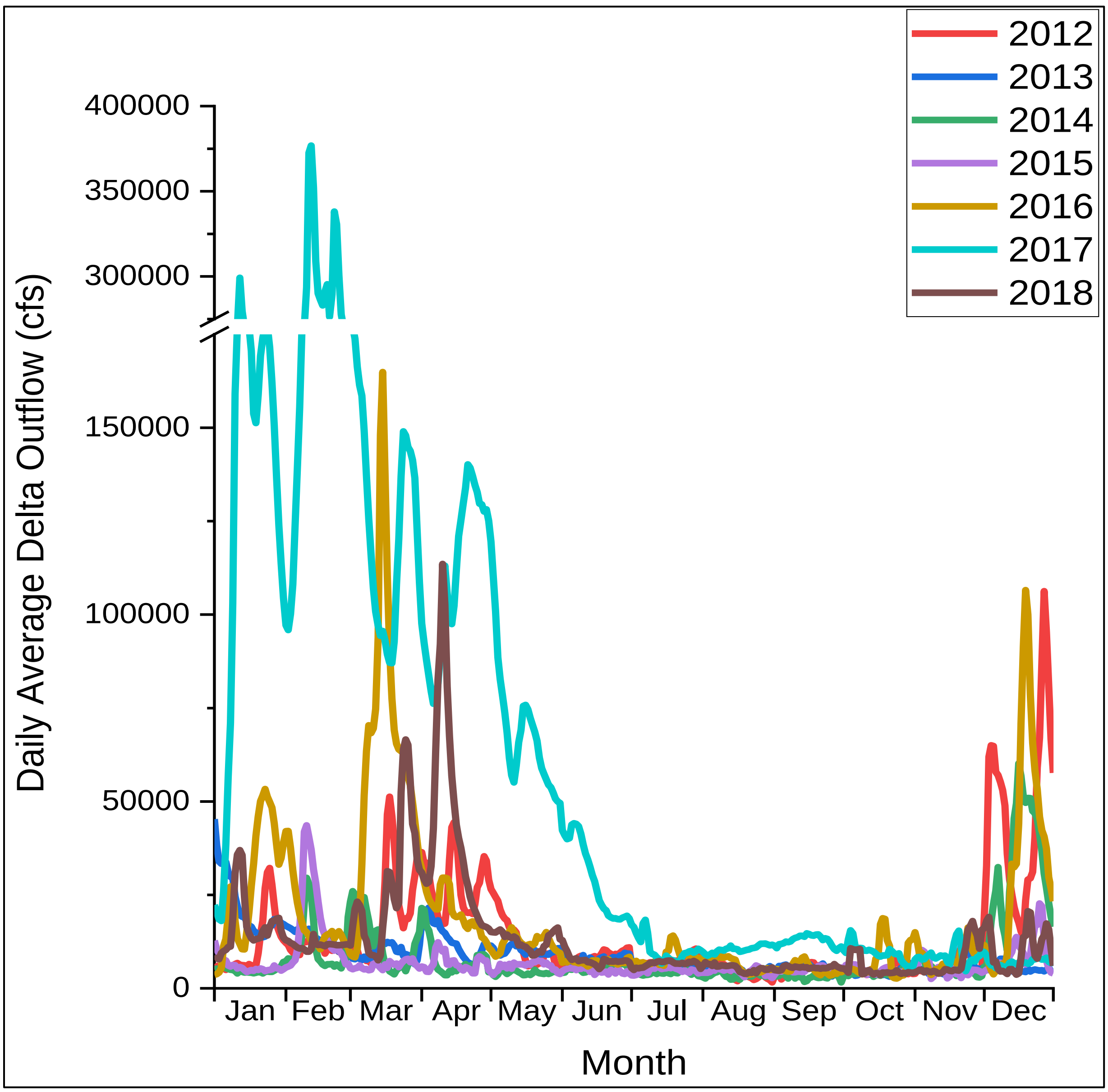


Figure 3. Mean Daily Delta outflow for 2011-2018 (DWR 2019).

Water Quality (handheld meters)

Temperature - Temperatures were typical of California's Mediterranean climate, with hot summers and cool winters (Figure 4). Limited cooling marine influence in the CLC allowed summer temperatures to exceed 20°C for prolonged periods. Summers in 2014 and 2015 were among the hottest on record, and had the highest number of months with mean water temperatures above 20°C. Differences in mean annual temperature among sample sites were minimal, although the terminal end of Cache Slough (CA1) and Ulatis Creek had slightly higher maxima in most years.

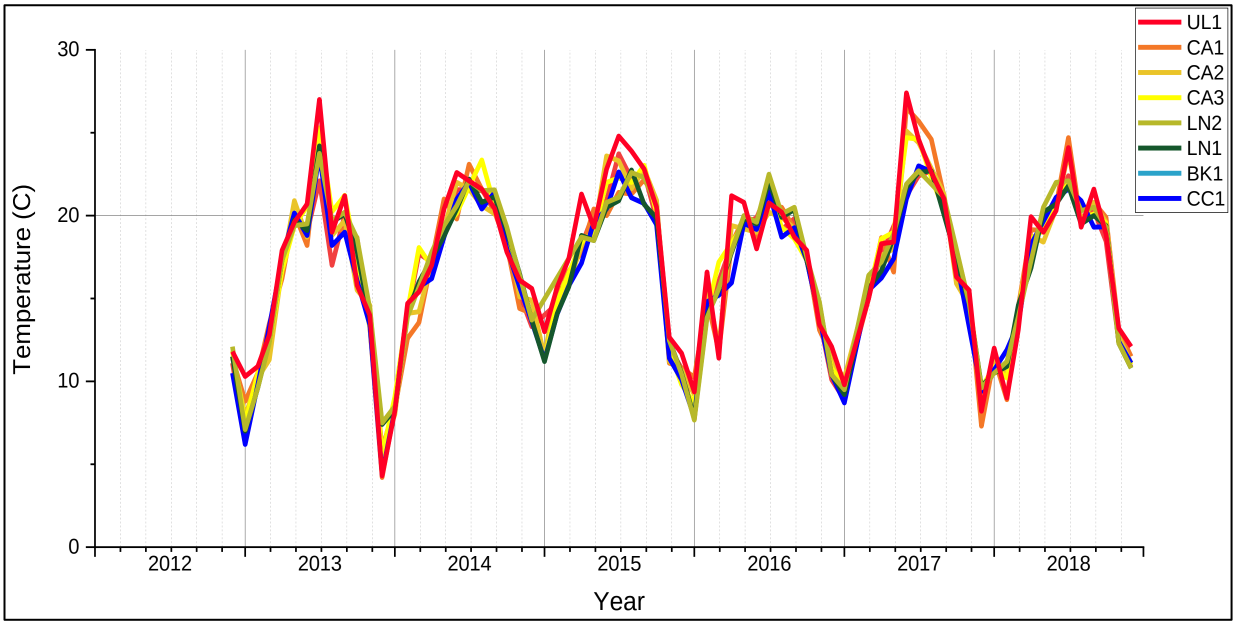


Figure 4. Monthly mean water temperature by site.

Dissolved oxygen- Highest and lowest DO values occurred in landward slough sites such as UL1 (red), CA1 (orange), and CC1 (blue) (Figure 5). Timing of minimum DO differed between the two slough complexes. In general, DO in Cache Slough was highest in winter and spring, and decreased throughout the summer and fall. Lindsey Slough had highest values in the fall, which then decreased and stabilized during winter, spring, and summer.

Specific conductivity- Cache Slough generally had more elevated specific conductivity (SC) than Lindsey Slough (Figure 6). Specific conductivity was highest at UL1 and decreased downstream toward CA3. Increases were seasonal, with SC decreasing during summer months when runoff or agricultural inputs were low. In Lindsey, SC was low throughout summer and fall, elevating only slightly in winter.

Secchi depth- Secchi depth, or water clarity, increased throughout the study, especially in Lindsey Slough and lower Cache Slough (Figure 7). Sites with the least increase in water clarity were UL1 and CA1. As water clarity increased in some sites, so too did an annual pattern of increasing clarity in the late summer and fall, followed by an abrupt decrease in the winter.

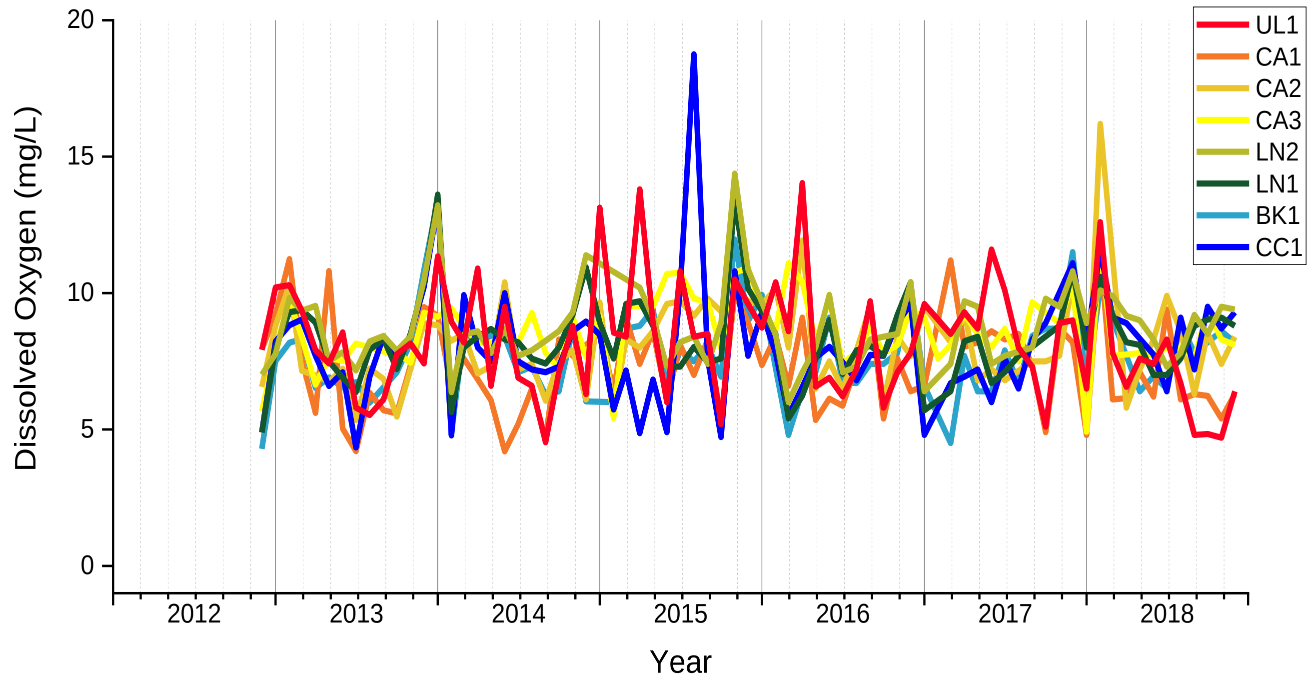


Figure 5. Monthly mean dissolved oxygen by site.

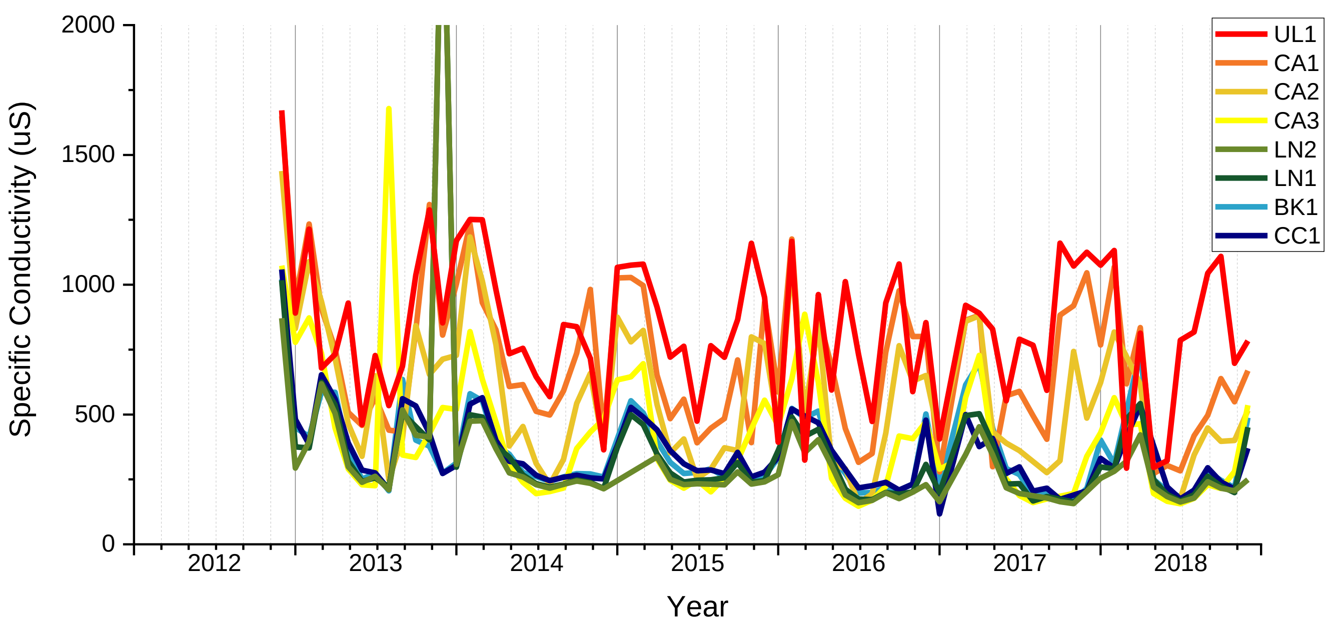


Figure 6. Monthly mean specific conductivity by site.

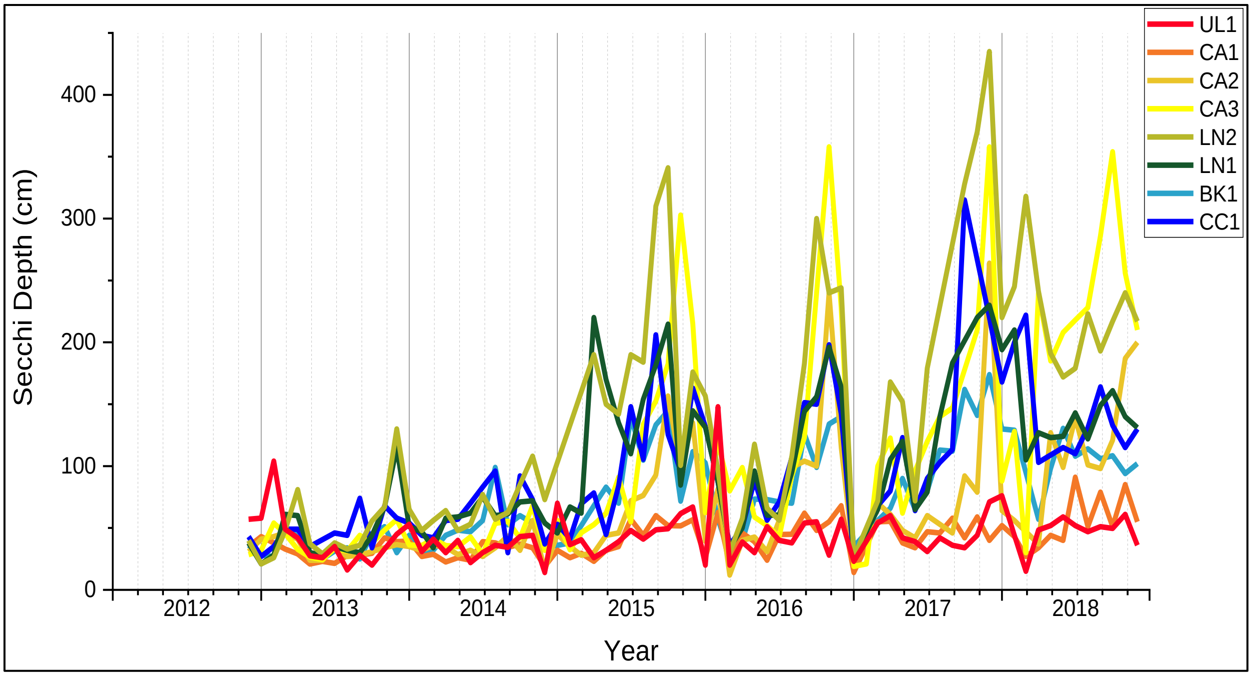


Figure 7. Monthly mean Secchi depth by site.

Water Quality (water grabs)

pH- pH was generally lower during the beginning of the study, with increased pH in spring of most years (Figure 8). UL1 consistently had the highest pH of all sites. Since late 2016, the entire region had become more alkaline, suggesting a decrease in respiration and an increase in autotrophy.

Indicators of suspended detritus or sediment- All measurements showed similar spatial differences, with the highest measurements of each recorded at UL1, CA1, and HS1. Samples close to the confluence of Cache and Lindsey sloughs, and samples from Lindsey Slough, all had considerably lower values (Figure 9). All sites showed seasonal changes, with increases in values occurring early in the year, especially during the very wet winter of 2017. Other changes occurred over the course of the study for turbidity, VSS, and TSS. Sites near the confluence and in Lindsey Slough all had decreasing values for turbidity, VSS, and TSS throughout the study. Water clarity and suspended solids all decreased after 2014, and remained that way since then, even through the wetter years following the drought. In contrast, DOC values did not appear to have changed much over the study period.

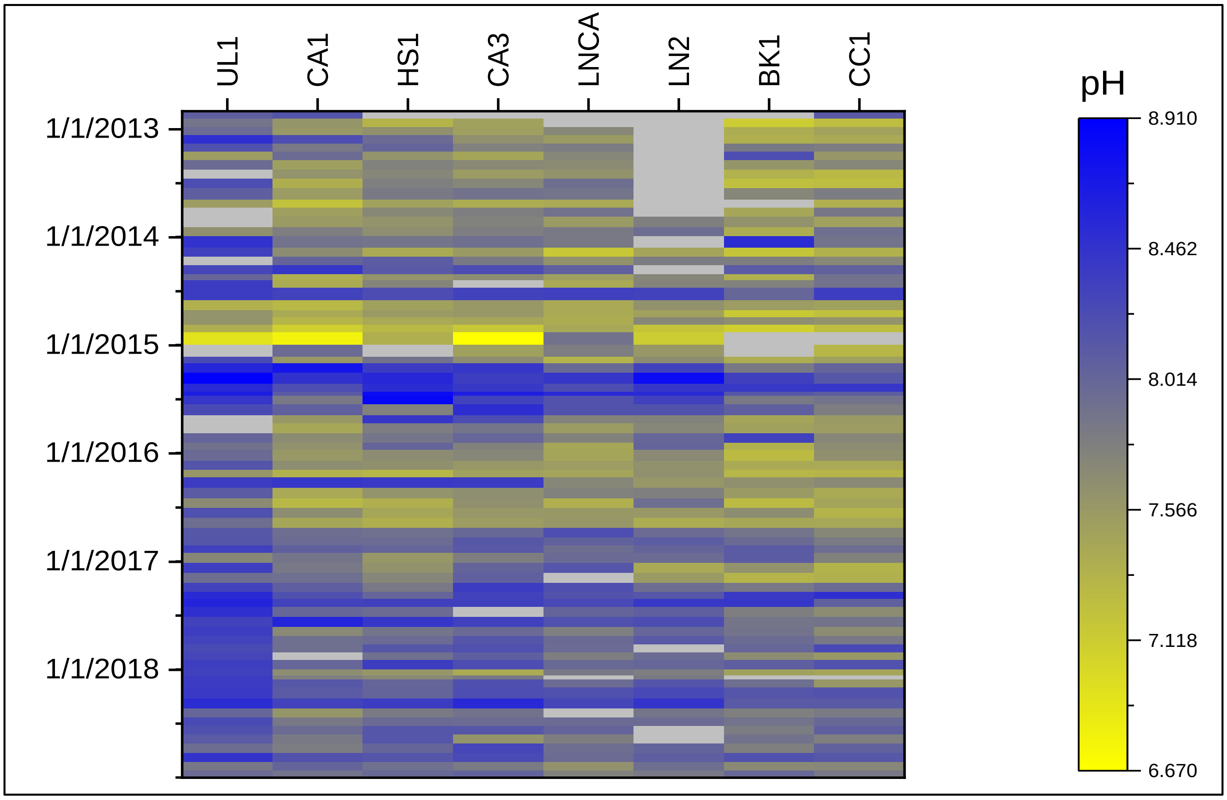


Figure 8. Monthly mean pH by site.

<u>Phosphorus-</u> All measurements showed similar seasonal and spatial patterns (Figure 10). Landward sites (UL1, CA1, and to a lesser degree, HS1) had the highest phosphorus concentrations. At all other sites, phosphorus was very low, except from late winter to early spring, corresponding with changes in suspended and dissolved materials.

<u>Nitrogen-</u> Relative patterns of nitrogen concentrations were similar for NO3, TDN and TN (Figure 11). Landward sites in Cache Slough (UL1, CA1, and HS1, in descending order) had the highest concentrations. Seasonal increases occurred during the winter and spring across all sites. Patterns of NH_4 were somewhat different. The highest concentrations were found in the landward CA1 site and the most downstream site, LNCA. The highest concentrations occurred later in the year than for suspended sediment metrics or phosphorus, appearing generally to be at highest levels in summer.

<u>Total Nitrogen/Total Phosphorous (TN/TP)-</u> High values occurred mostly at the mouth of the sloughs, with the highest ratios in LNCA, followed by CA3 and LN2 (Figure 12). UL1 also showed some periodically high ratios, particularly in the winter.

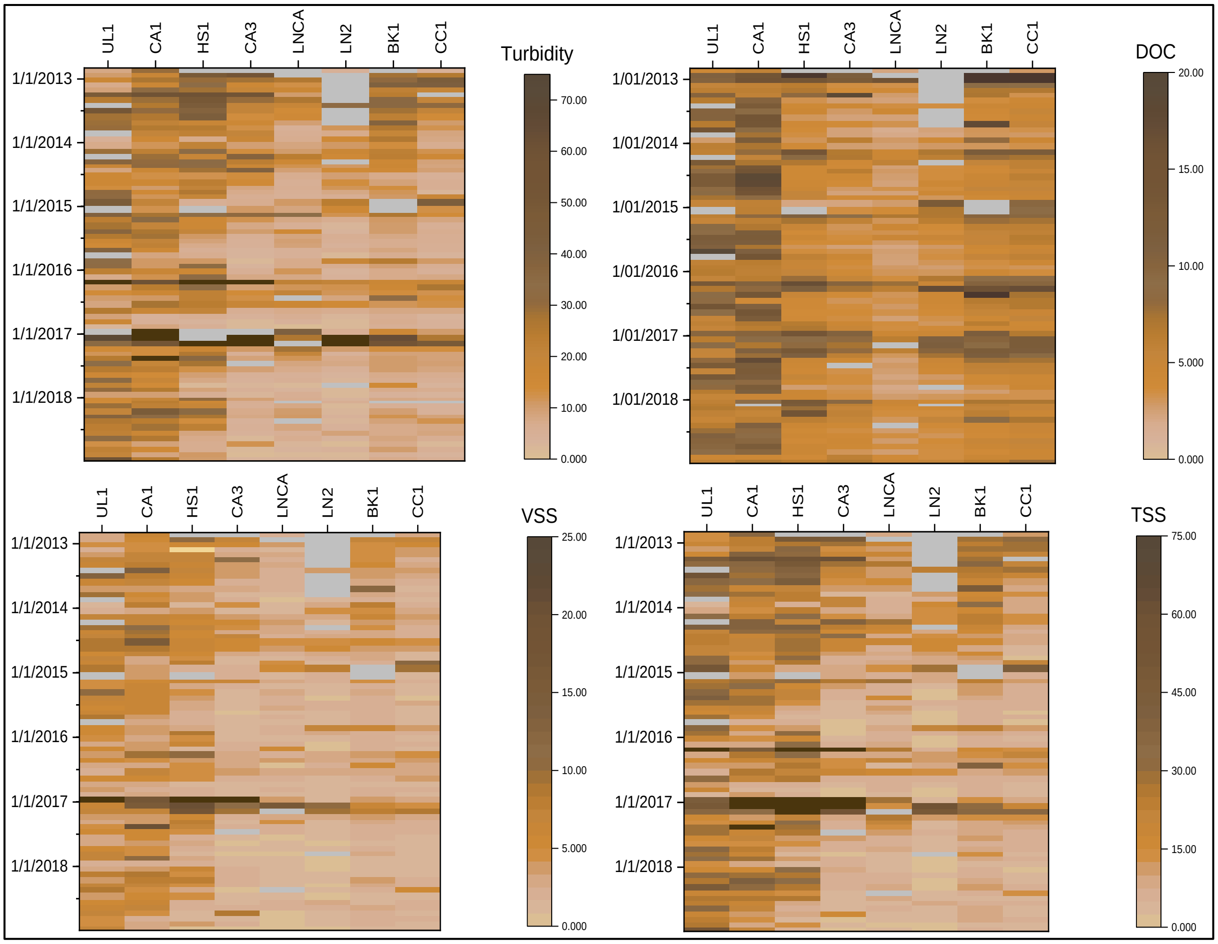


Figure 9. Indicators of suspended detritus or sediments. Monthly mean turbidity, DOC, VSS, and TSS.

<u>Primary production-</u> Generally paralleling suspended-sediment and nutrient concentrations, both chlorophyll types were highest in landward sites of the Cache Slough Complex (CA1 and UL1, followed by HS1; Figure 13). Concentrations at the Cache-Lindsey confluence and in Lindsey Slough were consistently low, with the exception of two small blooms that raised chlorophyll-a across the region, one in December 2014, and the other in spring 2016.

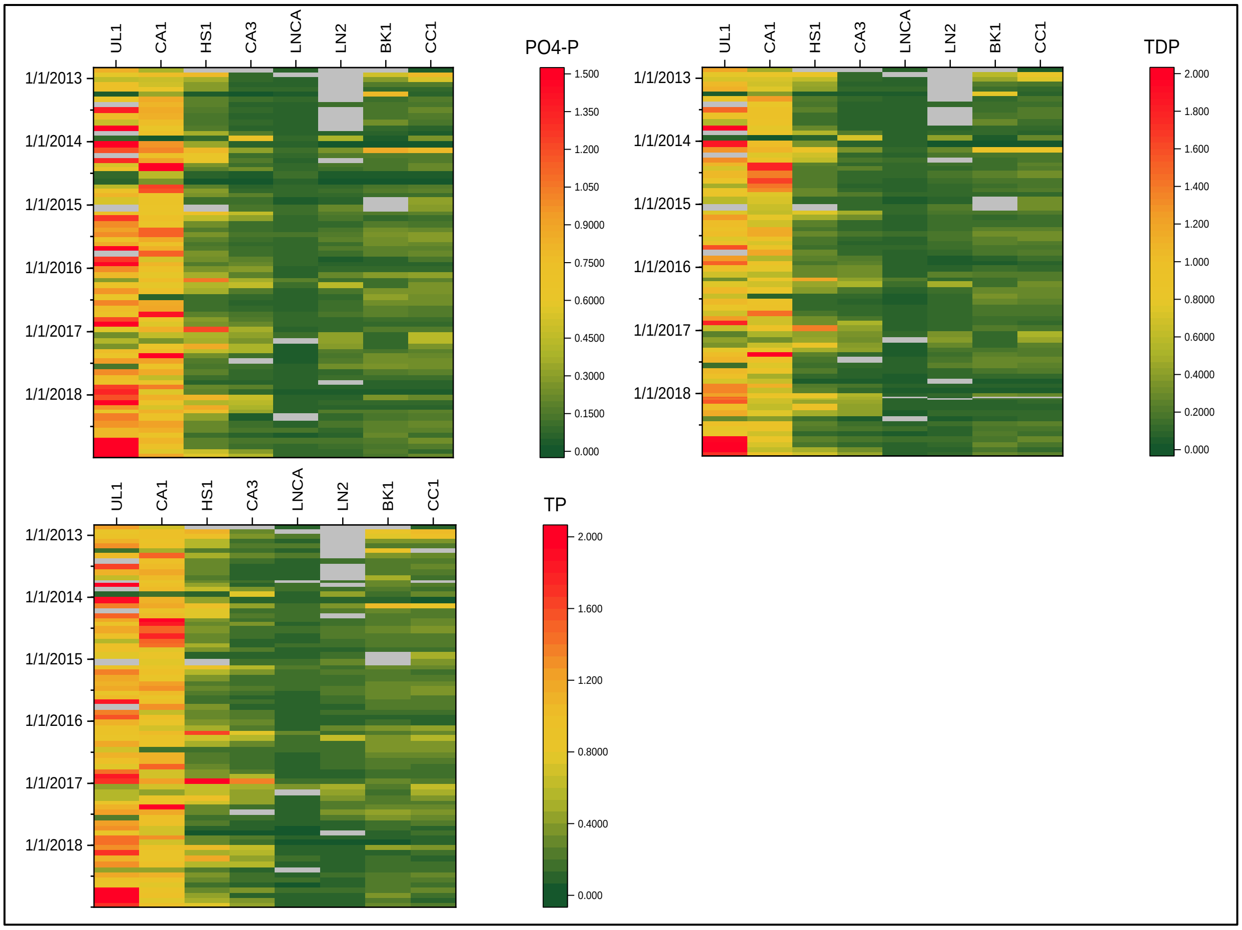


Figure 10. Monthly mean phosphorus as PO_4, TDP, and TP, in mg/L.

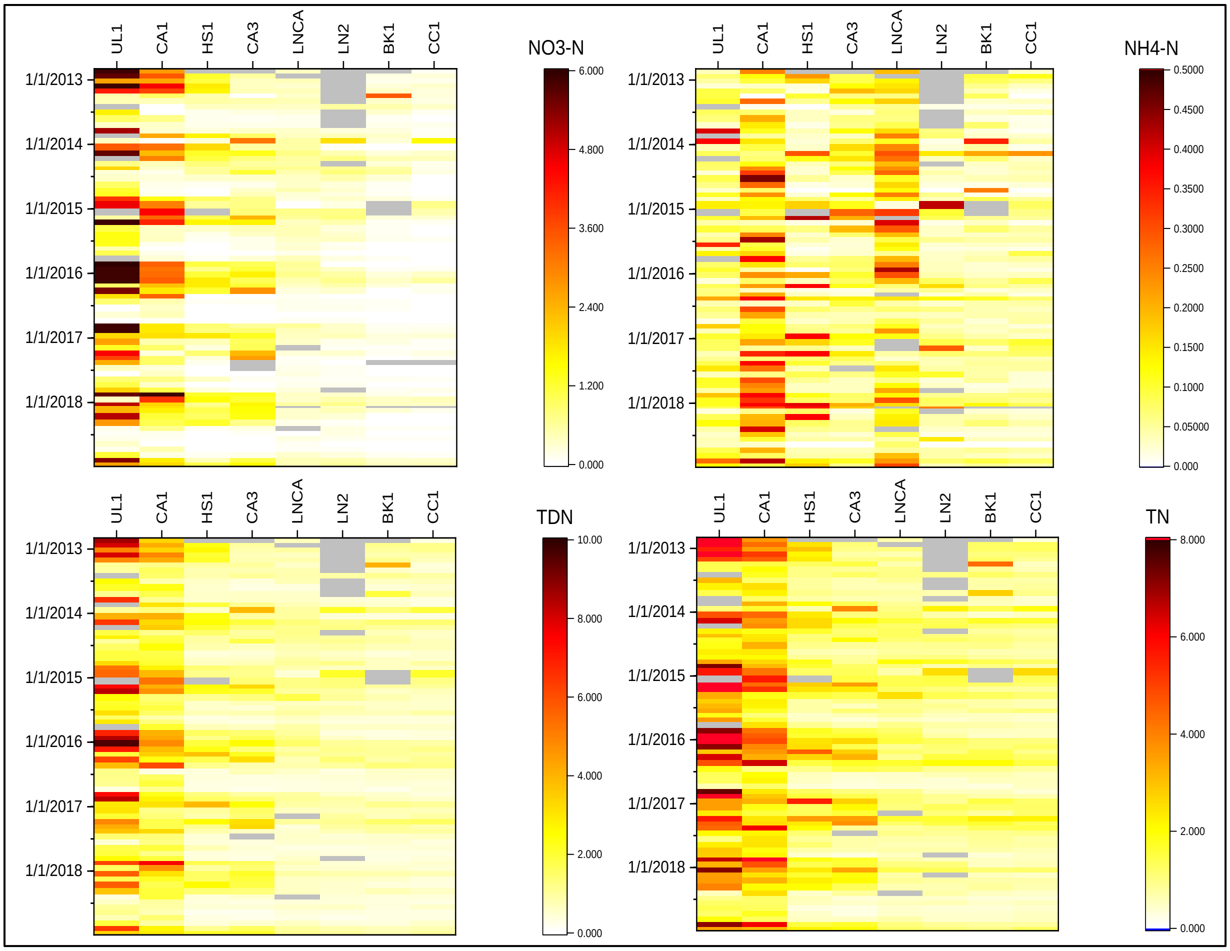


Figure 11. Monthly mean nitrogen as nitrate (NO_3), ammonium (NH_4), total dissolved nitrogen (TDN), and total nitrogen (TN), in mg/L.

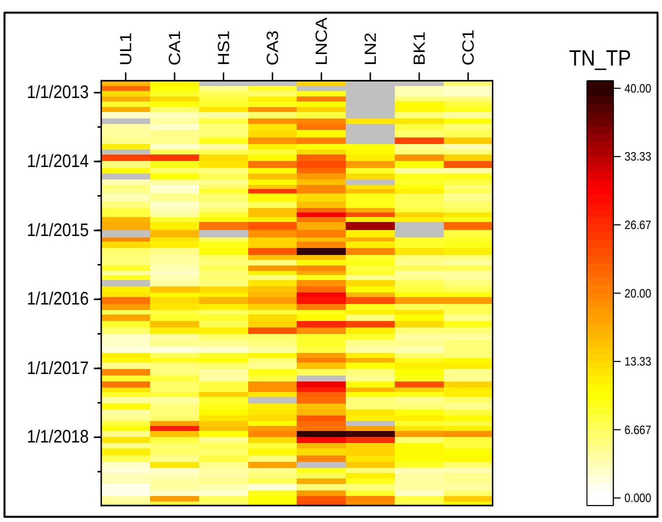


Figure 12. Ratio of total nitrogen to phosphorus (TN:TP) based upon monthly mean values.

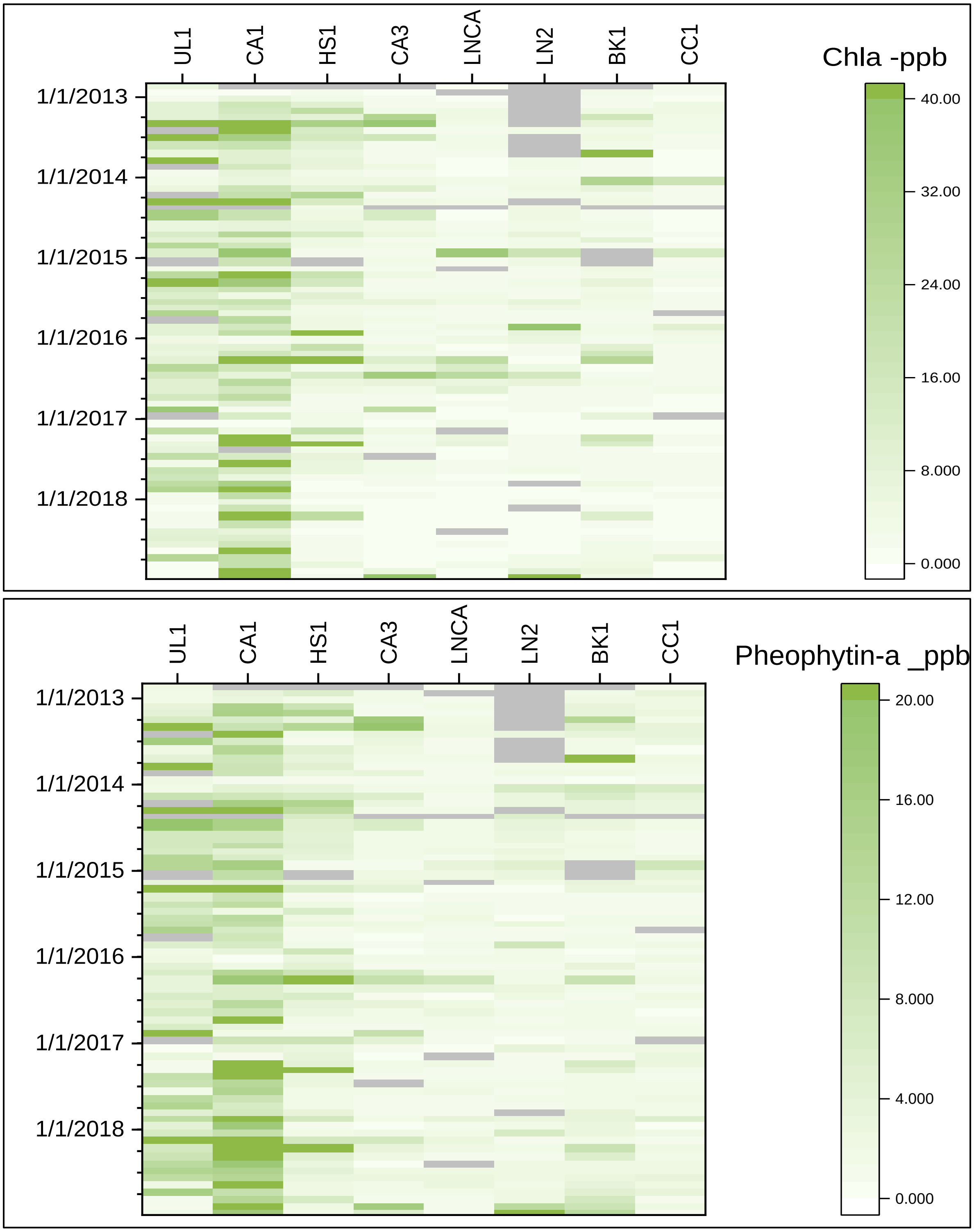


Figure 13. Monthly mean primary production as chlorophyll-a (Chla) and pheophytin-a, in parts per billion (ug/L).

Zooplankton

Highest mean zooplankton biomass were found in three CLC sites (CA1, CA3, and LN2) and one Suisun Marsh site (DV1; Figure 14). CA1, in upper Cache Slough, had the highest variability in biomass and provided samples with the highest biomass. The upper Calhoun Cut site (CC1) off Lindsey Slough and the MZ1 site in Suisun Marsh had the lowest mean biomass. CA1 and DV1 are both near the terminal ends of sloughs. LN2 is located far from the terminal end of the slough and is adjacent to a downstream outfall of a large pond (Big Ditch); MZ1 is in Montezuma Slough, the largest distributary channel in Suisun Marsh. IEP stations, when compared to Arc stations, showed low zooplankton biomass, comparable to the lowest values sampled in the Arc study.

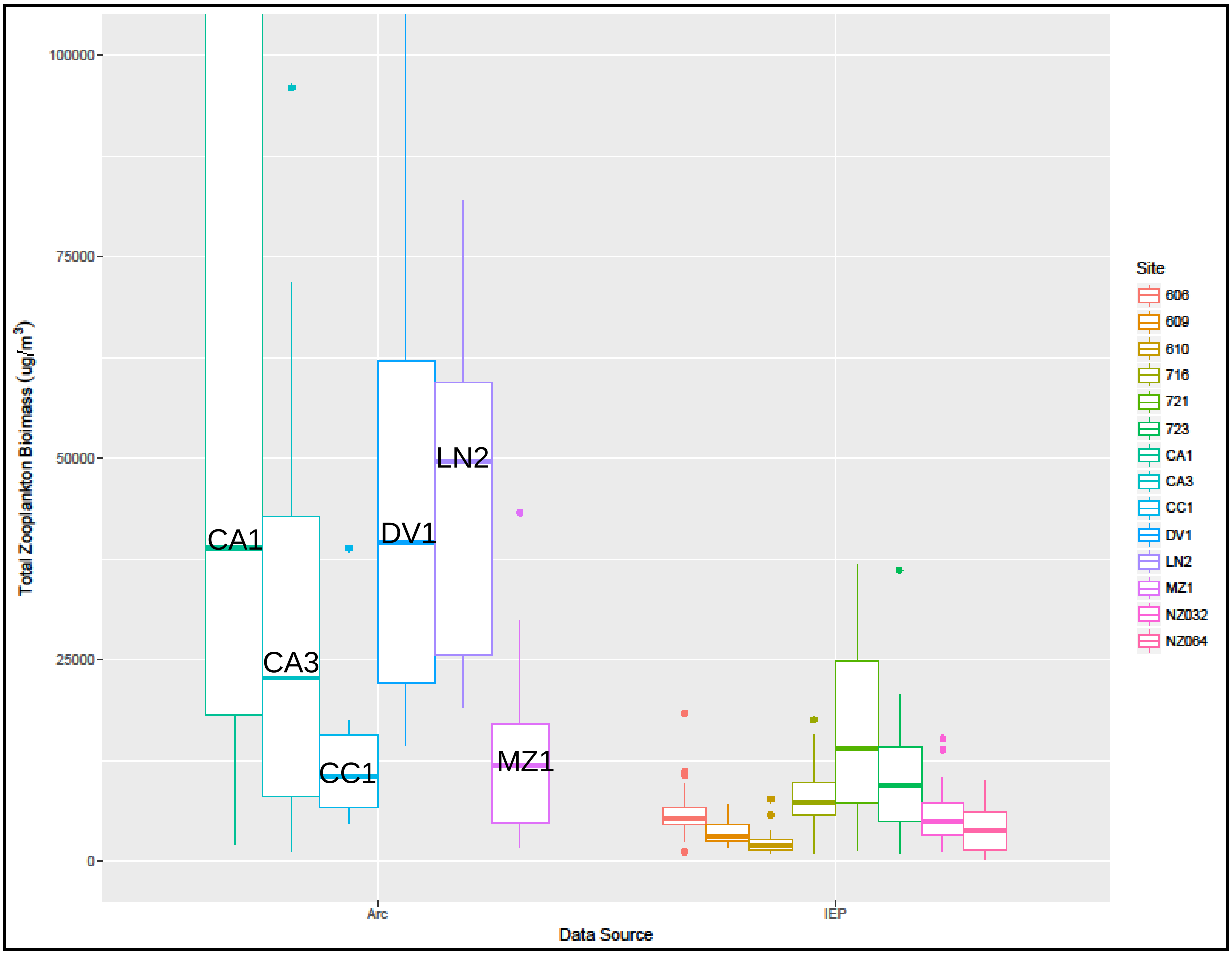


Figure 14. Comparison of 2013-2014 zooplankton biomass data from Arc study sites (on left) and eight relevant IEP Zooplankton Study, Summer Townet Survey, and Fall Midwater Trawl sampling sites (on right). Y-axis is cut off at 100,000 µgC/m^3 to show detail at lower values. CA1, CA3, CC1 and LN2 are current study sites in the Cache-Lindsey complex. DV1 and MZ1 are sites in Suisun Marsh, part of the Suisun Marsh Fish Study (O'Rear *et al.* 2019). Numbered sites are IEP sites.

Aquatic Vegetation

Aquatic vegetation sampled as by-catch in otter trawls increased throughout the study (Figure 15). Most samples were dominated by the invasive Brazilian waterweed (*Egeria densa*). The largest samples occurred at sites closer to the confluence and in Lindsey Slough: CA3, CC1, and BK1. The largest increases over time occurred at CA3 and BK1. Several sites had little to no aquatic vegetation at the outset of the study, including UL1, CA1, CA2, CA3, and LN2, but all contained submersed aquatic vegetation by 2018.

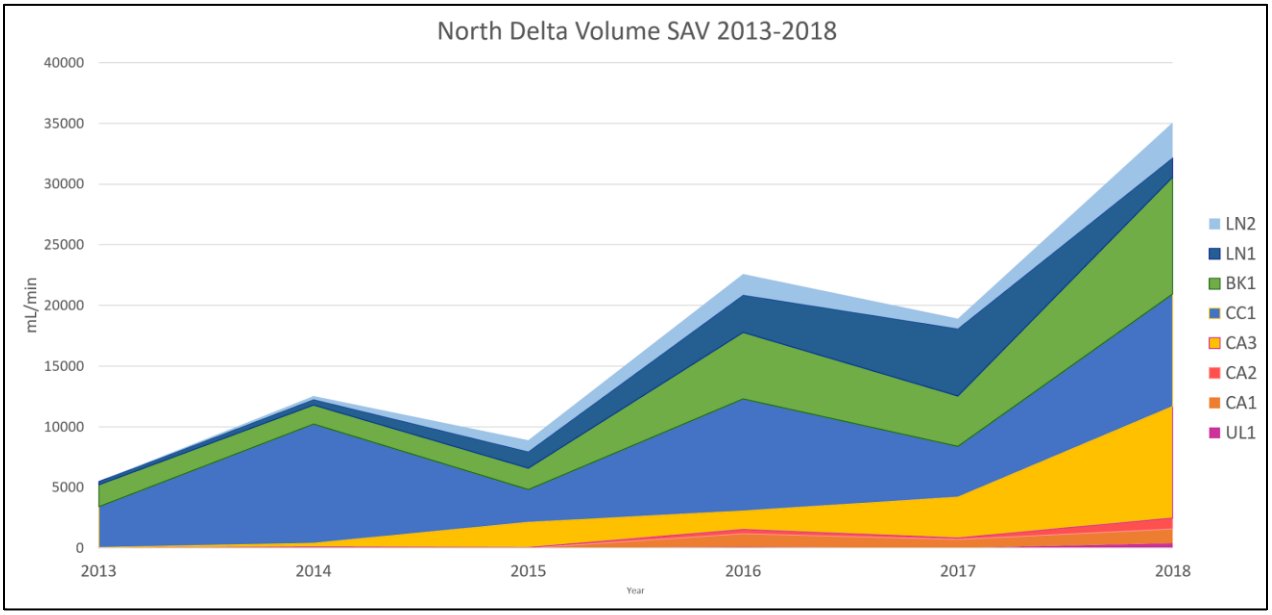


Figure 15. Annual CPUE of submersed aquatic vegetation (ml/min) retrieved in otter trawls at different sites from 2013-2018.

Fish Assemblage Composition

Temporal patterns

Otter-trawl catch in the CLC was dominated by POD and centrarchid guilds (Figure 16 and 17), with the centrarchid guild generally increasing over the study period. Abundances of these two guilds were somewhat seasonal, more commonly dominating catches during the latter half of the year. In contrast, the native and benthic guilds were more evenly distributed across time and among seasons.

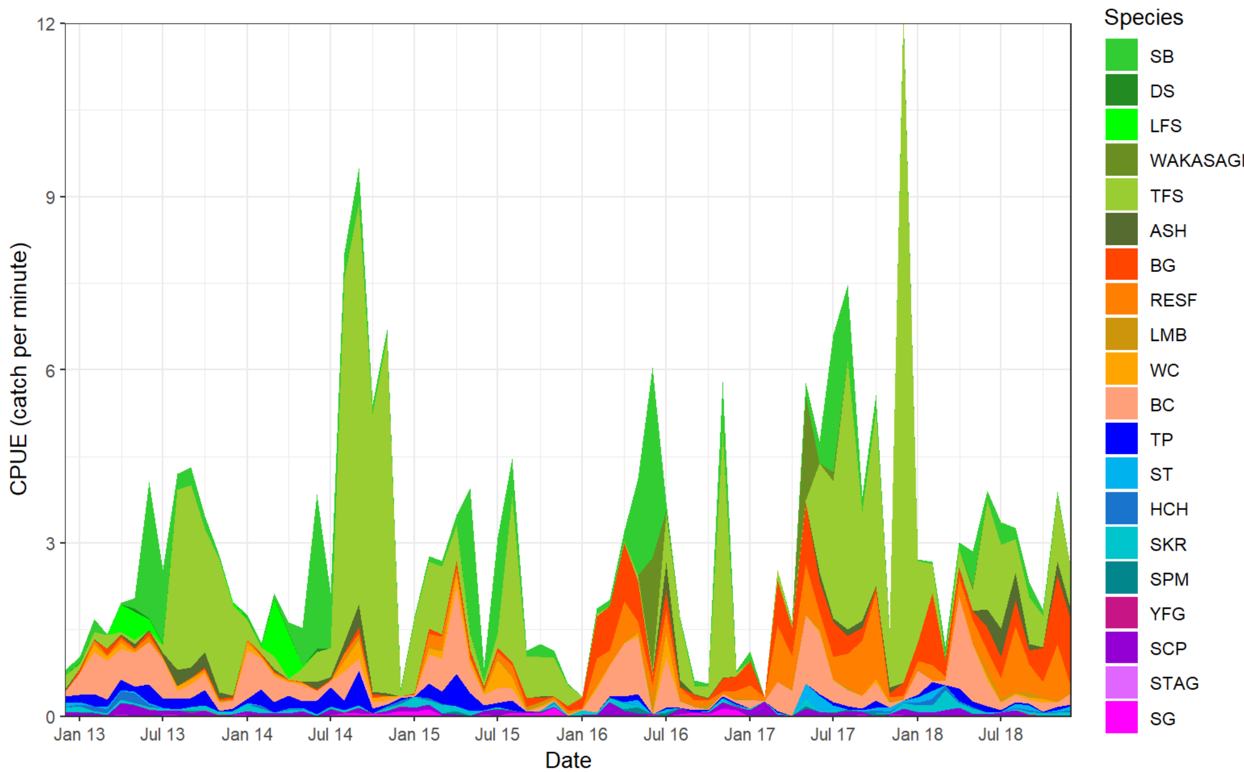


Figure 16. Total monthly CPUE of guilds from otter trawls (POD guild = greens, centrarchid guild = oranges, native fishes guild = blues, and benthic fishes guild = purples).

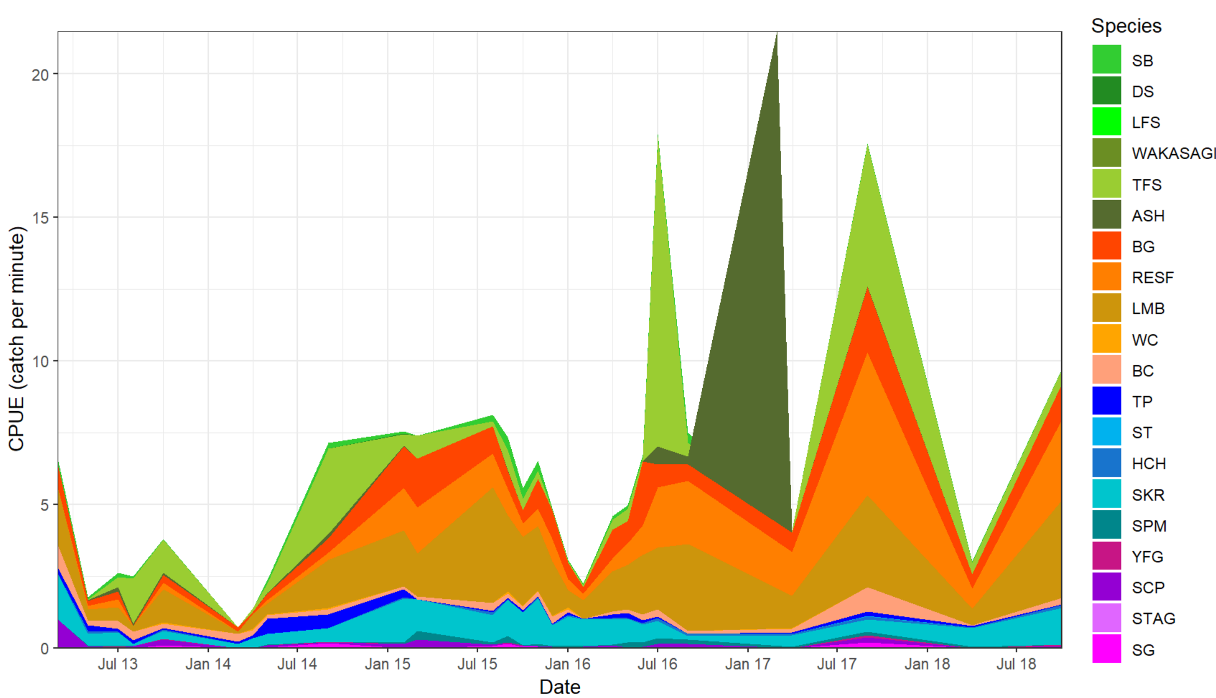


Figure 17. Total monthly CPUE of guilds from electrofishing (color codings same as Figure 16).

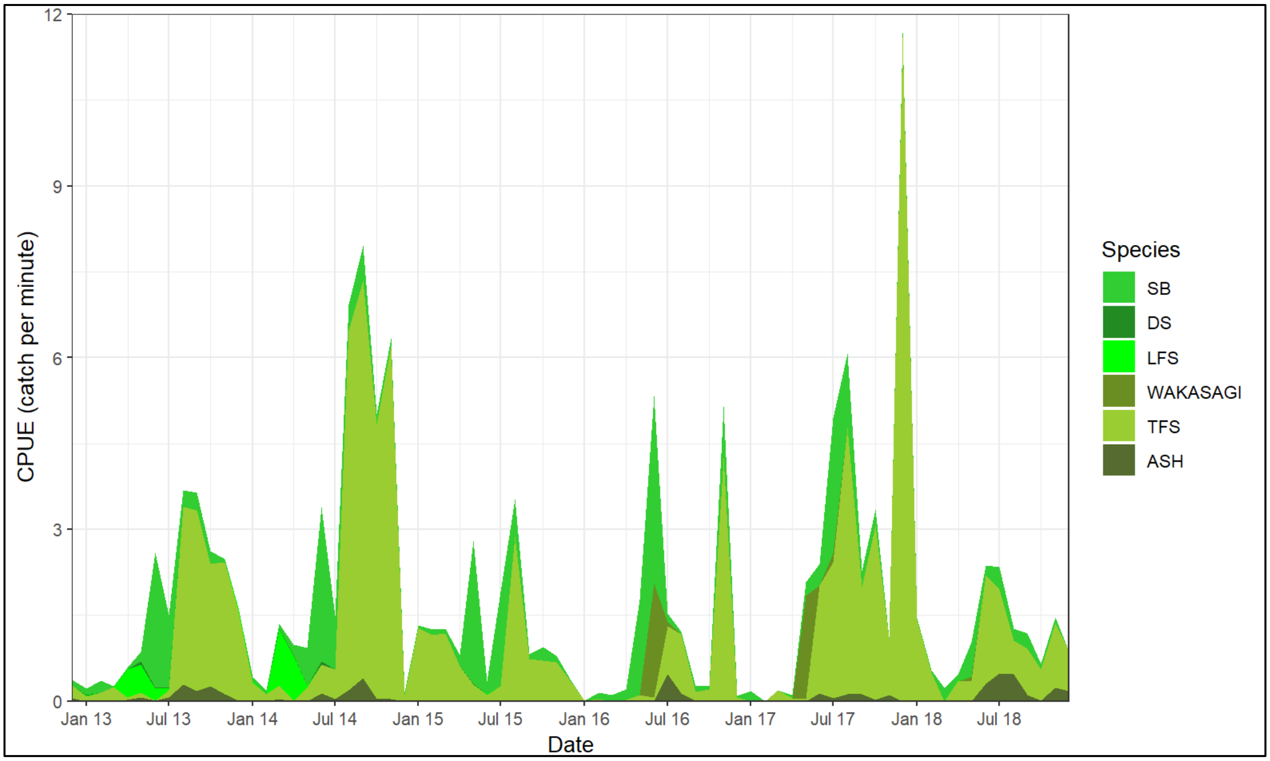


Figure 18. Total monthly CPUE of POD species from otter trawls.

The POD species were largely dominated by threadfin shad (Figure 18), which increased in late summer and early fall, reflecting both recruitment of young-of-year fish and co-occurrence with higher zooplankton numbers. Also seasonally abundant were striped bass, which appeared mostly in early summer. While striped bass and threadfin shad remained abundant throughout the study (Figure 19), delta smelt and longfin smelt mostly disappeared after 2015. Delta smelt were never abundant during the study, and the last capture occurred in May 2015. Longfin smelt were captured at a slightly higher rate, but only rarely after March 2014 (Figure 20).

Non-native centrarchids increased across the study period (Figure 16 and 17). Representing a relatively small fraction of the catch in 2012-13, they came to dominate catches by 2015, and continued increasing in abundance thereafter. In comparing the otter-trawl catch of the most abundant centrarchids (bluegill, redear sunfish, and largemouth bass) with the ecologically similar native tule perch (Figure 21), tule perch became rare in catches after summer of 2015 while redear sunfish and bluegill increased dramatically. Increasing Secchi depths represented a change in water-quality conditions to those favored by centrarchids (Figure 21). Electrofishing confirmed these trends but captured many more largemouth bass as a proportion of the overall catch (Figure 22).

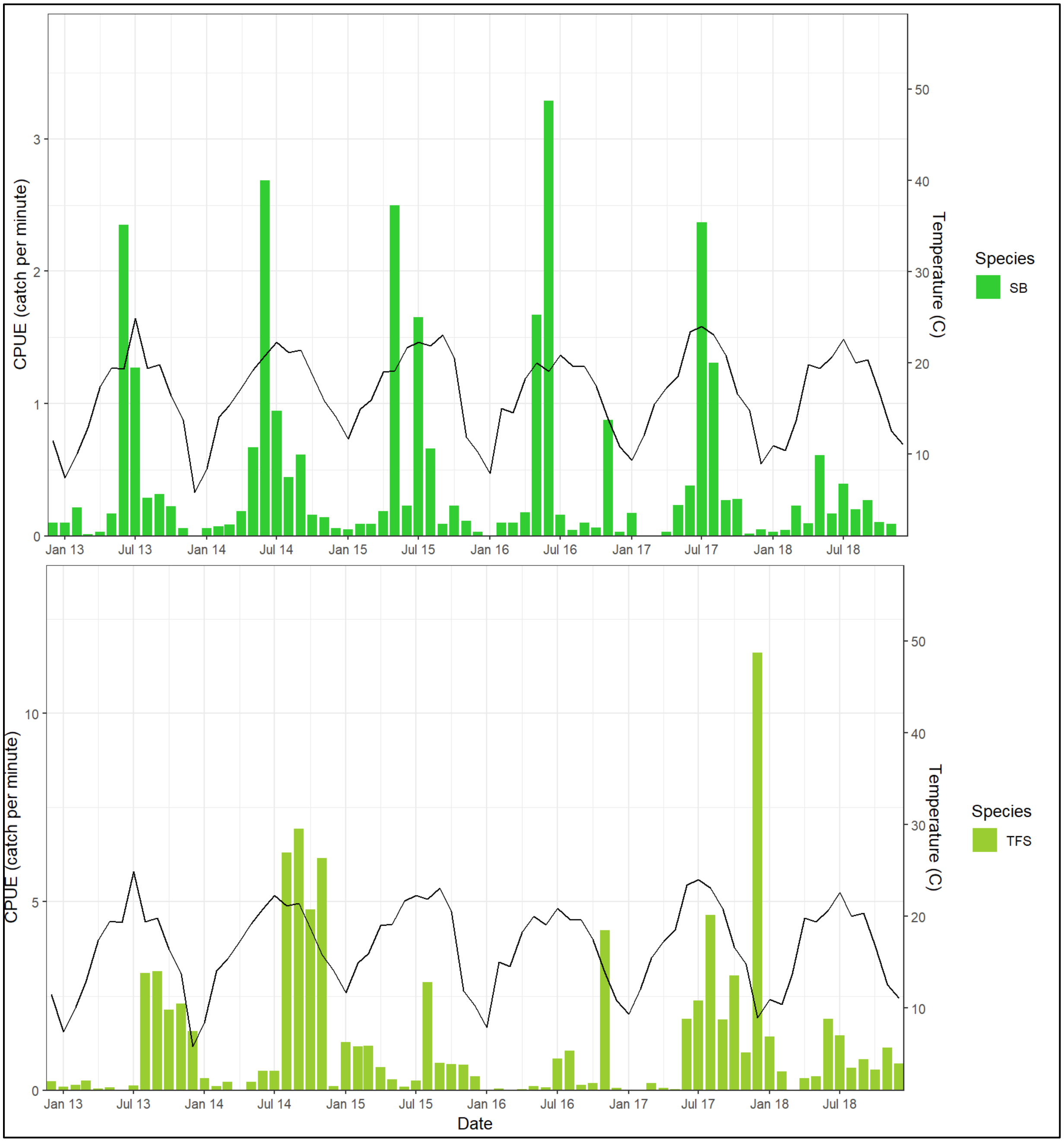


Figure 19. Total monthly otter-trawl CPUE of striped bass (top) and threadfin shad (bottom). Temperature on right axis.

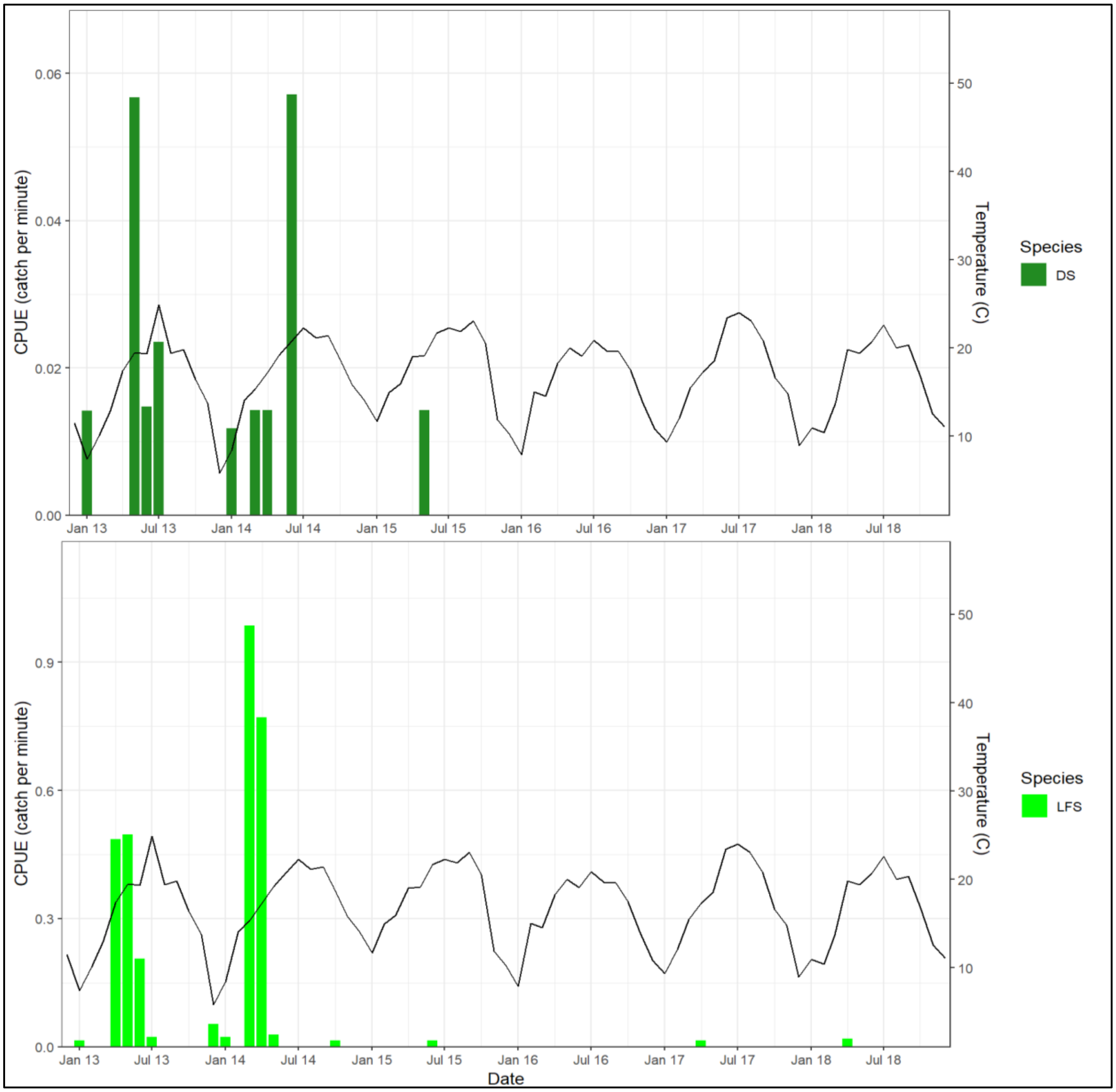


Figure 20. Total monthly otter-trawl CPUE of delta smelt (top) and longfin smelt (bottom). Temperature on right axis.

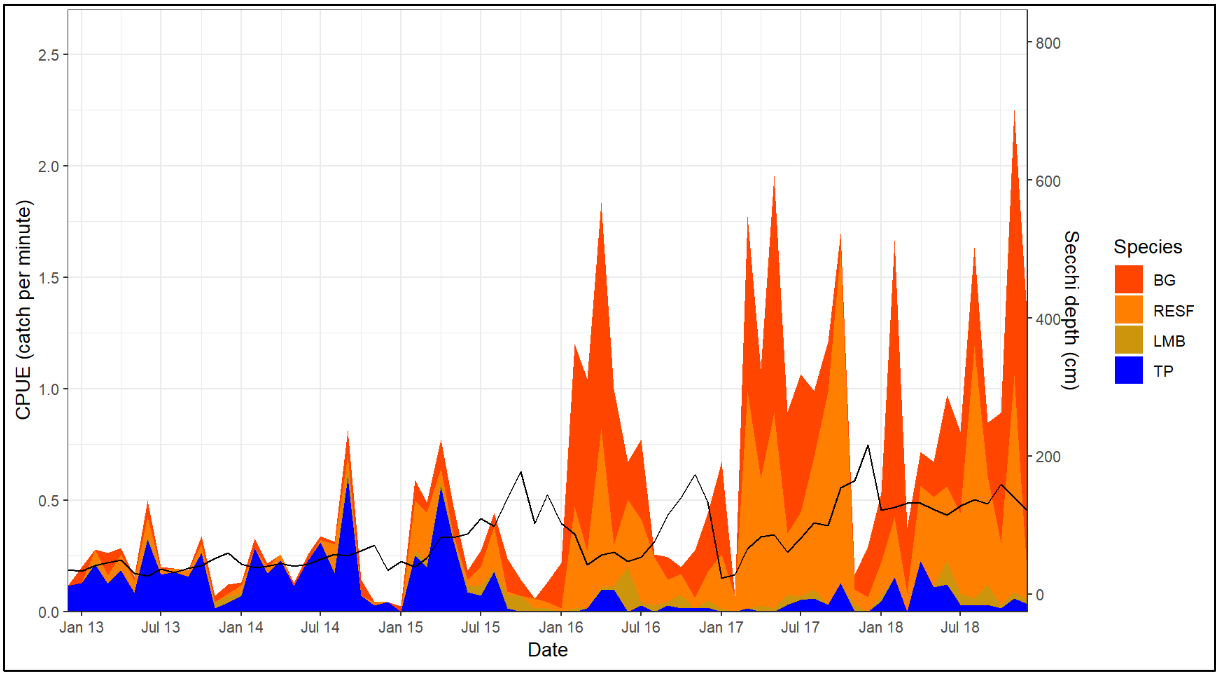


Figure 21. Monthly CPUE from otter trawling among four resident species: non-native centrarchids (bluegill, redear sunfish and largemouth bass) and native tule perch.

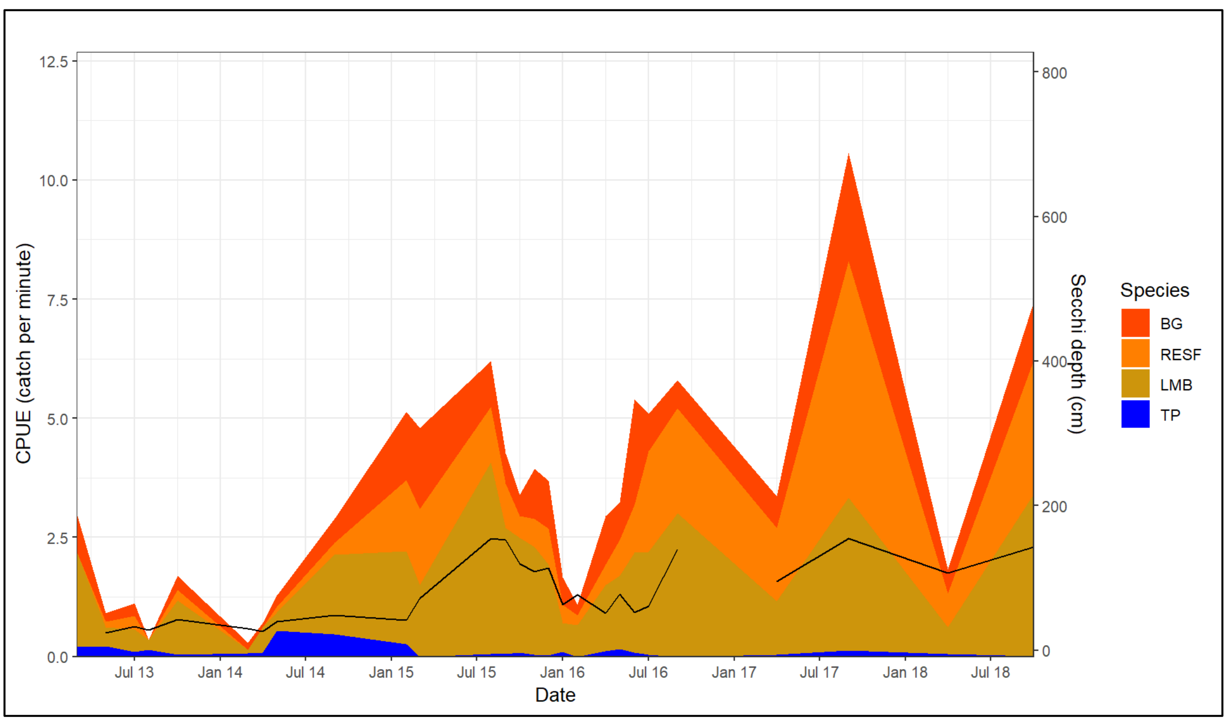


Figure 22. Monthly CPUE from electrofishing among four resident species: non-native centrarchids (bluegill, redear sunfish and largemouth bass) and native tule perch.

Spatial Differences

Spatial differences in catch were pronounced between the two slough systems (Figure 23). POD species were more abundant in Cache Slough than in Lindsey Slough (Figure 24). The two dominant species, threadfin shad (Figure 25) and striped bass (Figure 26), were most abundant in the upper reaches of Cache Slough. Longfin smelt and American shad were most frequently captured in Cache Slough and Barker Slough. Wakasagi were captured almost exclusively in Barker Slough.

Of the centrarchids, black crappie were caught most often in Cache Slough and Barker Slough (Figure 26, upper plot). Electrofishing data showed that largemouth bass and redear sunfish were most abundant in Lindsey Slough sites (Figure 27, lower plot). Bluegill appeared to be fairly evenly distributed across all sites.

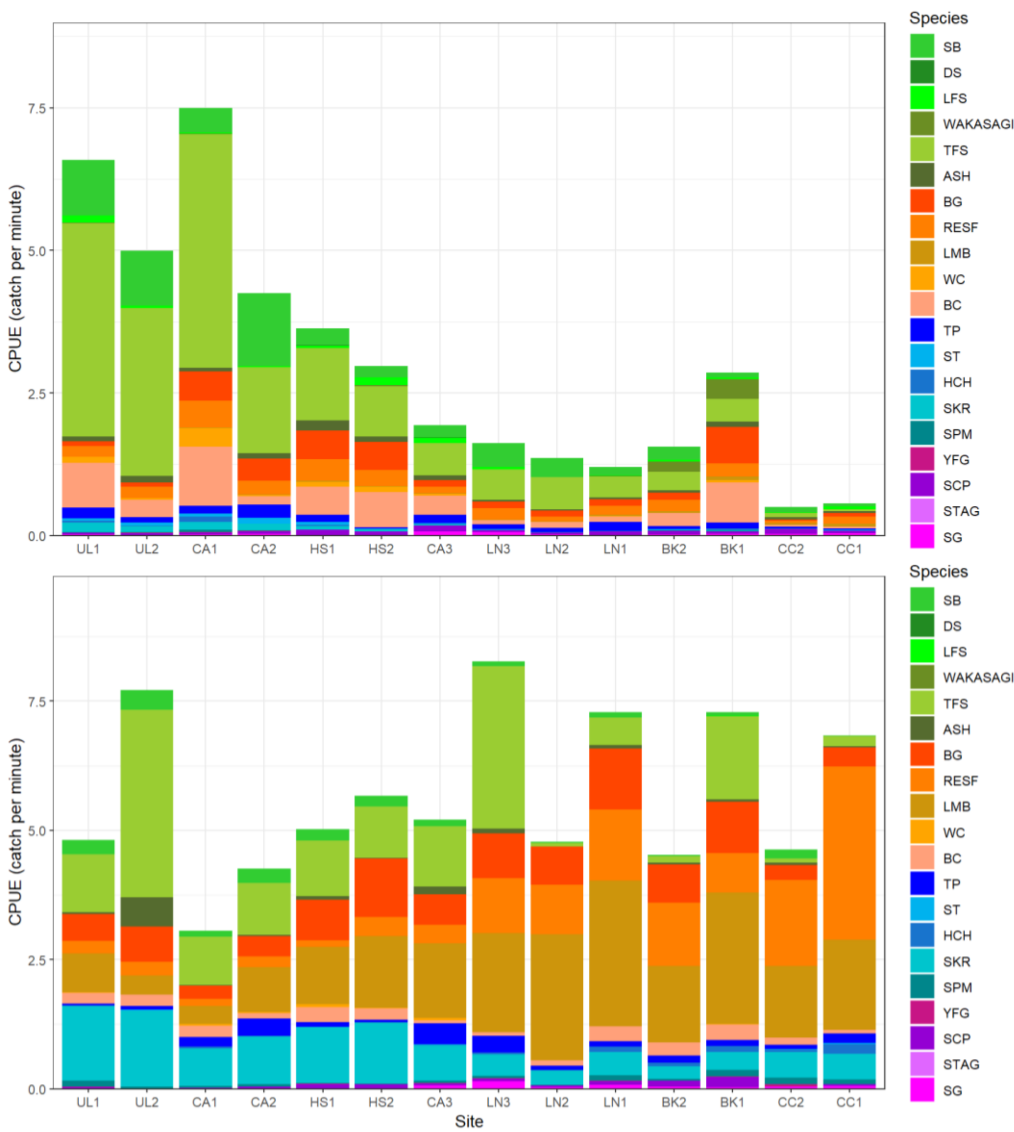


Figure 23. Total CPUE of most abundant species by site. Otter trawl data above, electrofishing data below.

Native fishes mostly favored Cache Slough, particularly splittail and Sacramento suckers (Figure 28). Tule perch tended to be well-distributed across all sites. Sacramento pikeminnow was caught most frequently landward. Hitch were most abundant in Cache sites in the otter trawl data, but most abundant in Lindsey sites in the electrofishing data.

Benthic fishes tended to be most abundant in Lindsey Slough, with SG slightly more prevalent near the mouth, and prickly sculpin more prevalent landward (Figure 23).

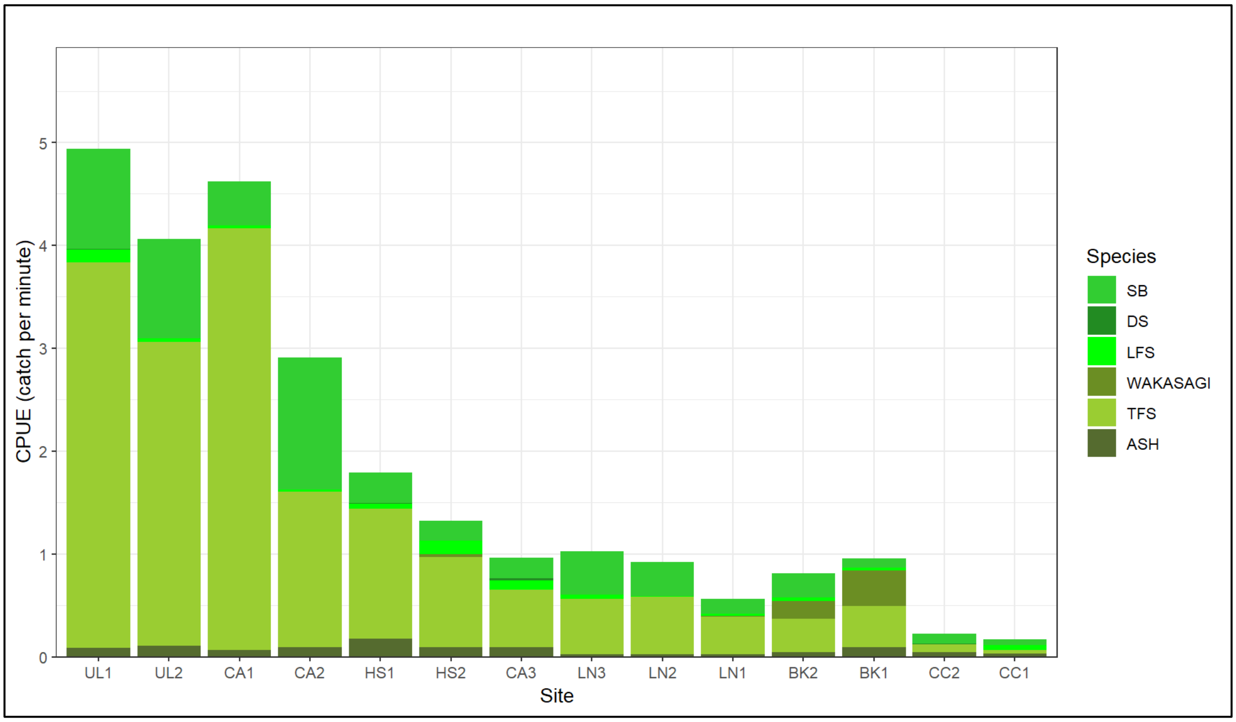


Figure 24. Total CPUE of POD species from otter trawls, by site.

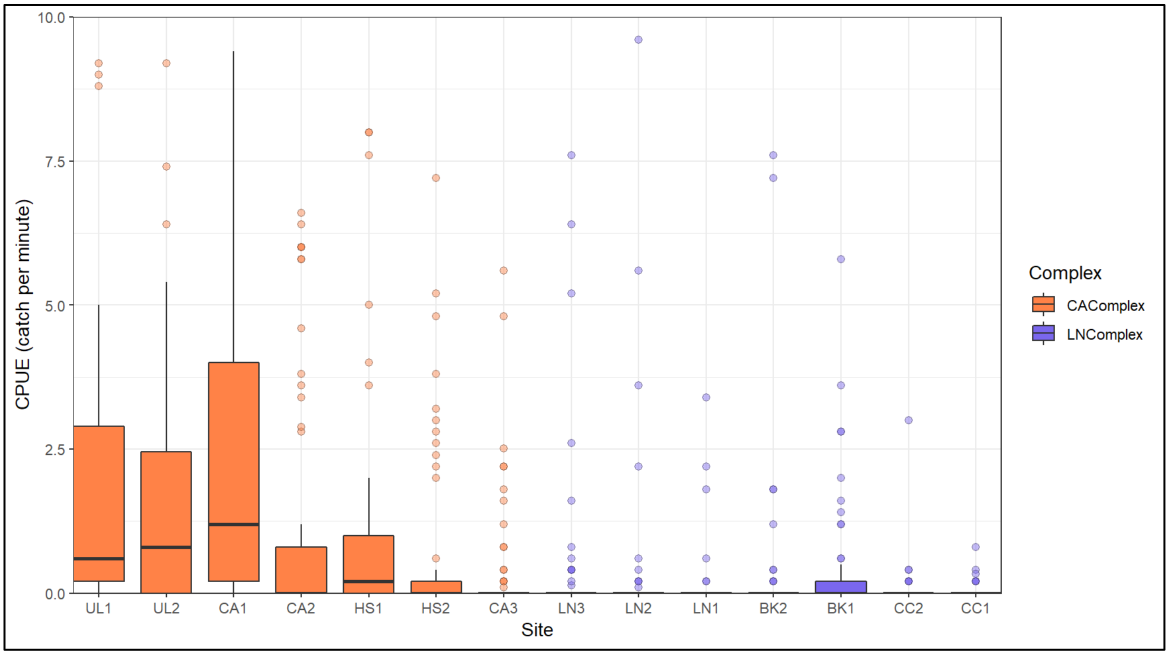


Figure 25. Mean total CPUE of threadfin shad from otter trawls, by site. Means represented by horizontal black line, boxes represent second and third quartiles, whiskers extend to highest value within 1.5 times of interquartile range, and points are outliers.

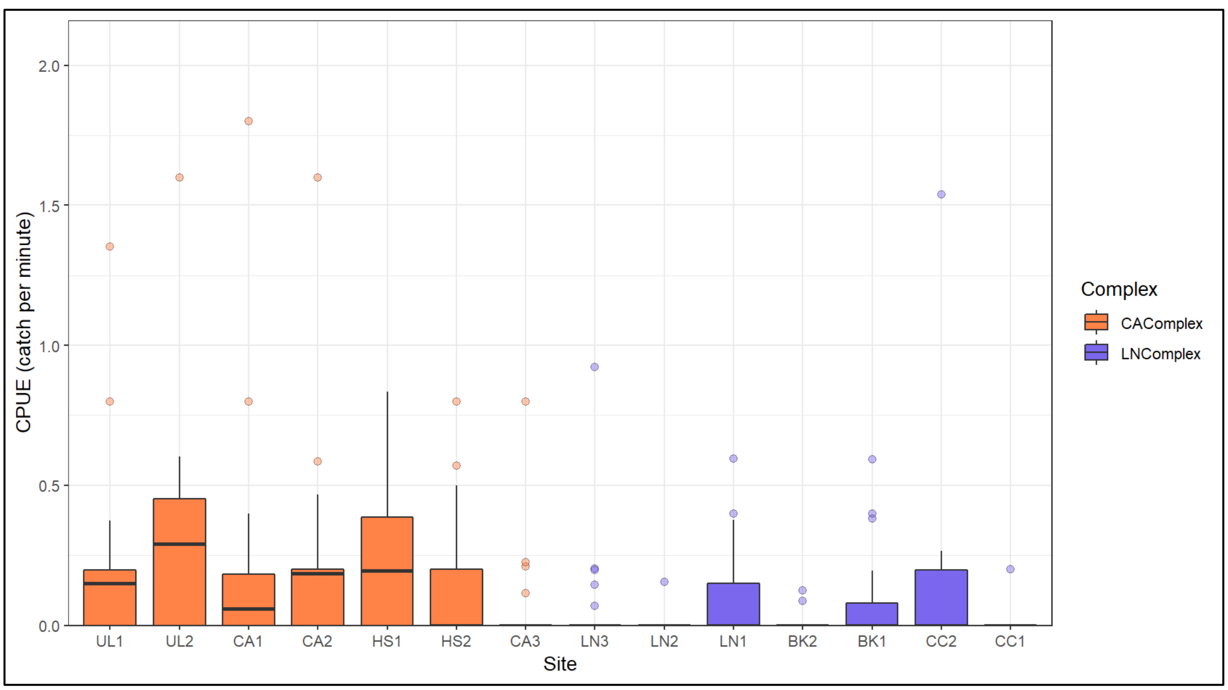


Figure 26. Mean total CPUE of striped bass from electrofishing, by site. Means represented by horizontal black line, boxes represent second and third quartiles, whiskers extend to highest value within 1.5x of interquartile range, and points are outliers.

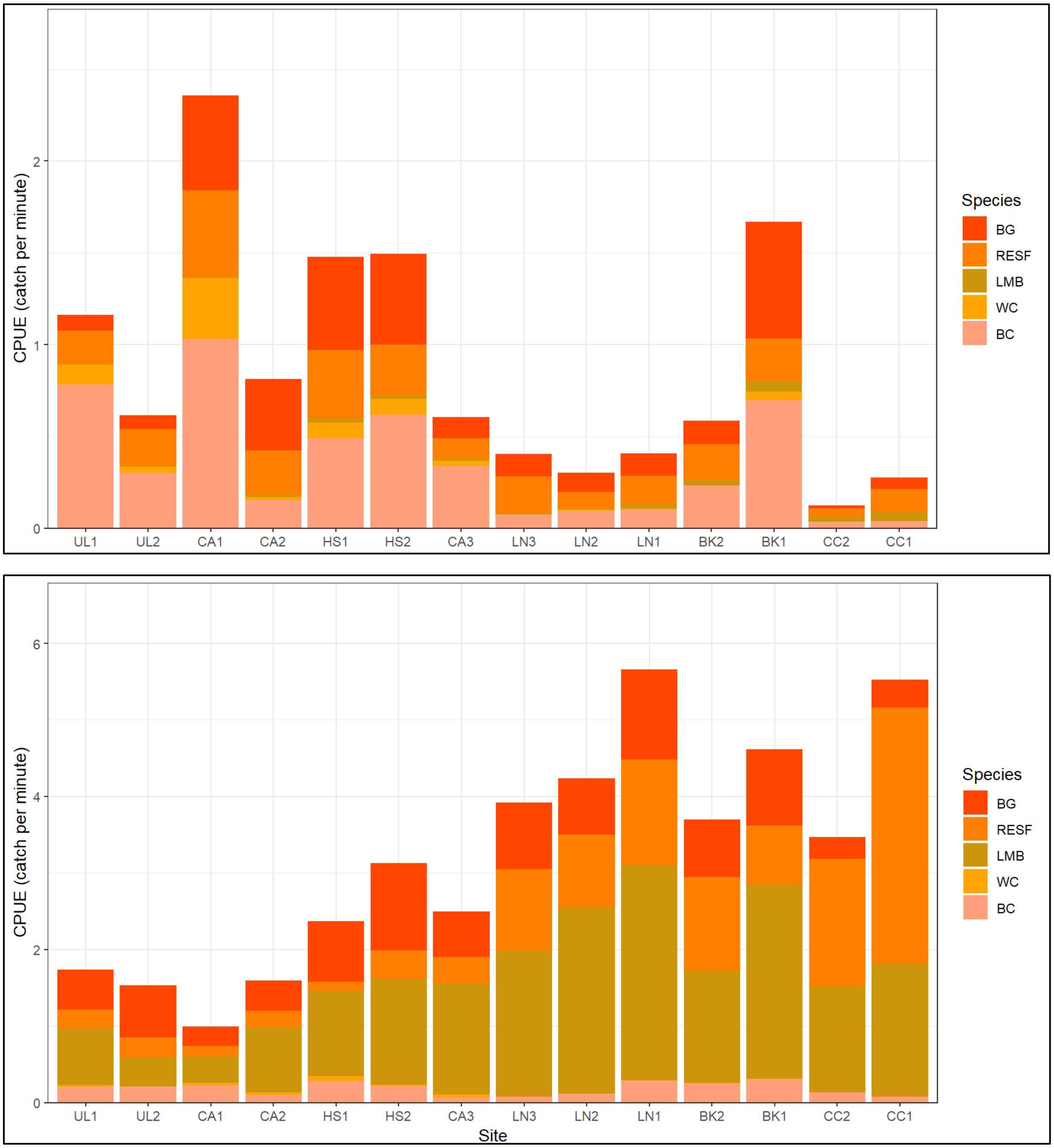
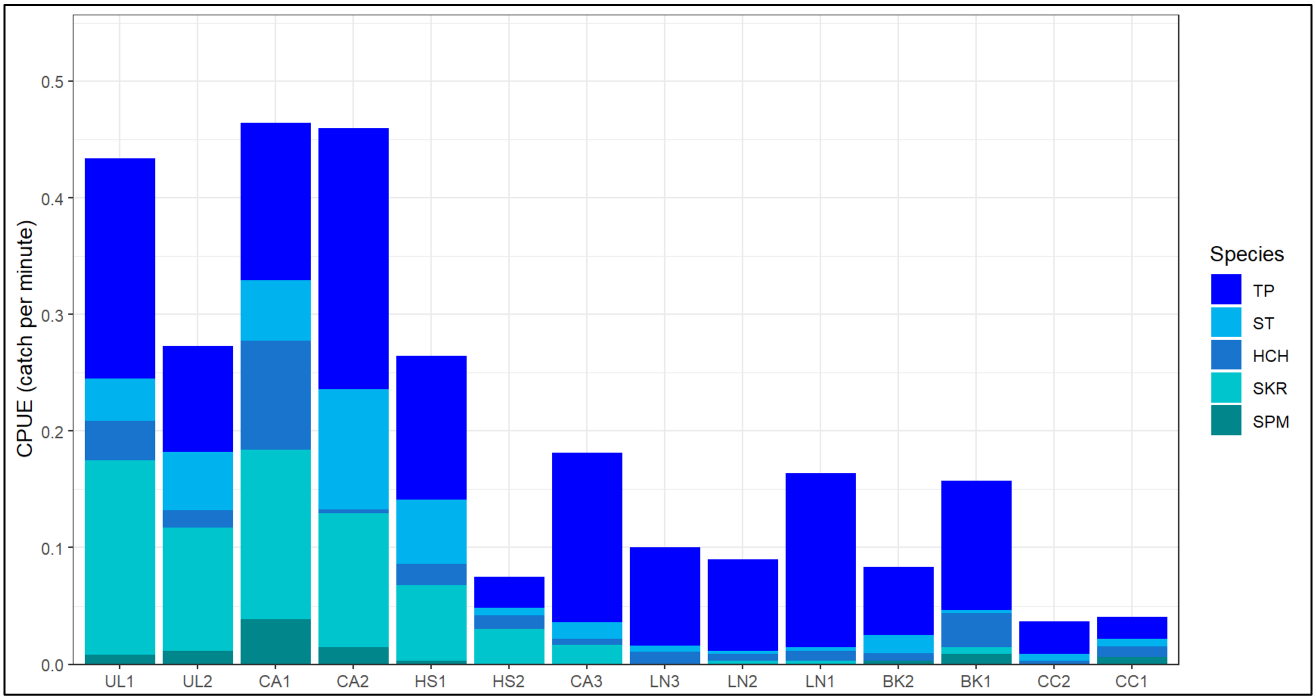


Figure 27. Total CPUE of centrarchids by otter trawl (above) and electrofishing (below) across sites.



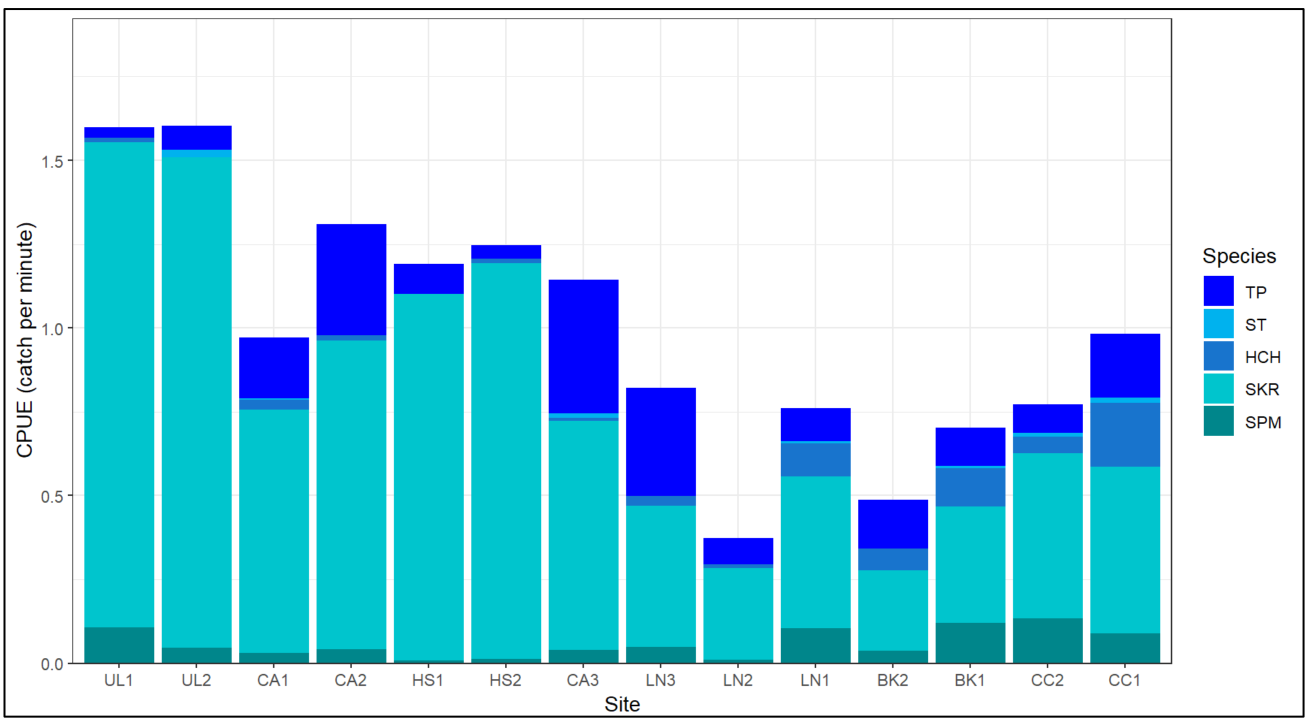


Figure 28. Total CPUE of native species by otter trawl (above) and electrofishing (below), across sites.

Special Study: Barker Slough

Monthly water-quality sampling showed an inverse relationship between rate of export pumping from Barker Slough with SC and TN (Figure 29). During periods of no pumping SC and TN were elevated. Water grab samples taken just downstream of the BSPP from late 2012 through 2018 were notably higher in conductivity and nitrogen values during periods of low export rates. Conversely, periods of high export rates co-occurred with reduced turbidity, conductivity, and nitrogen values.

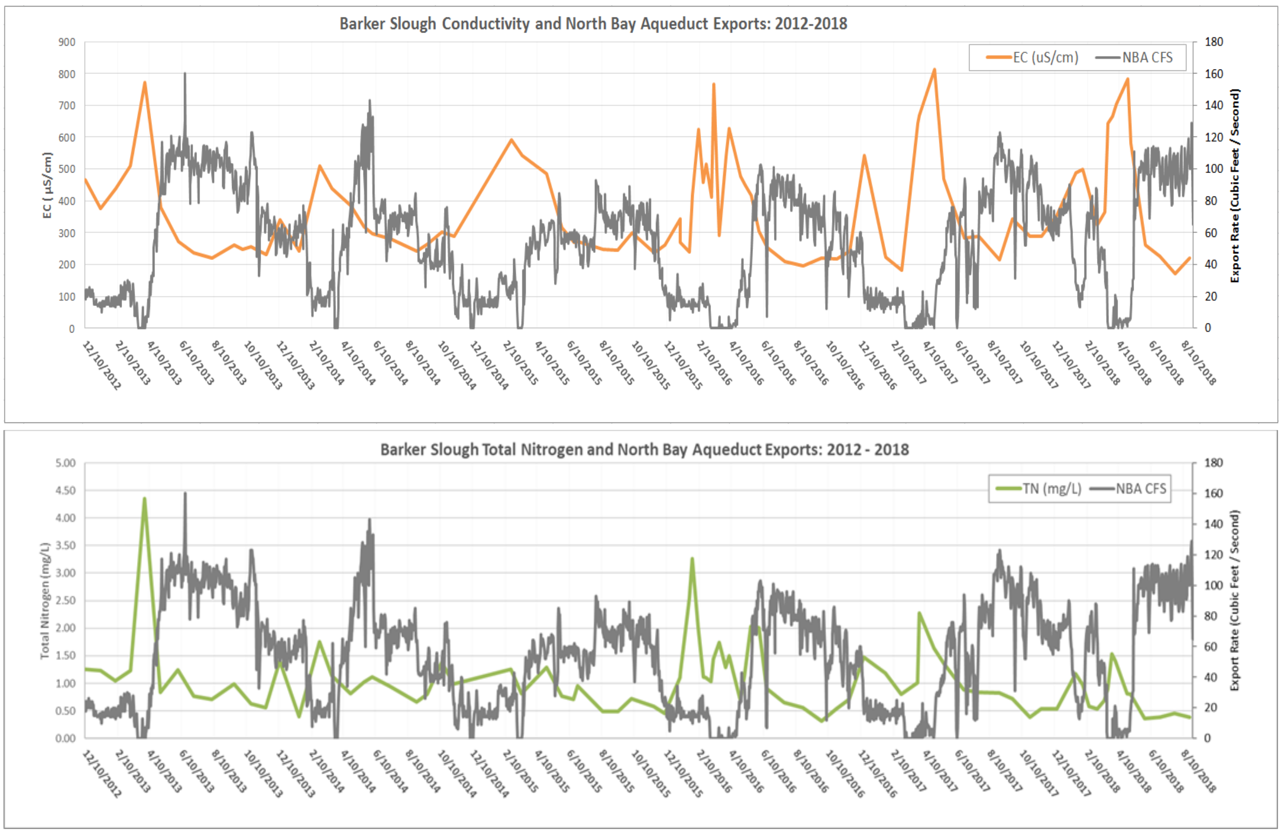


Figure 29. Barker Slough Pumping Plant export rate (cfs) plotted on right axes, with electroconductivity (uS/cm, top) and total nitrogen (mg/L, bottom) plotted on left axes, from monthly water grabs at BK1 from 2012-18.

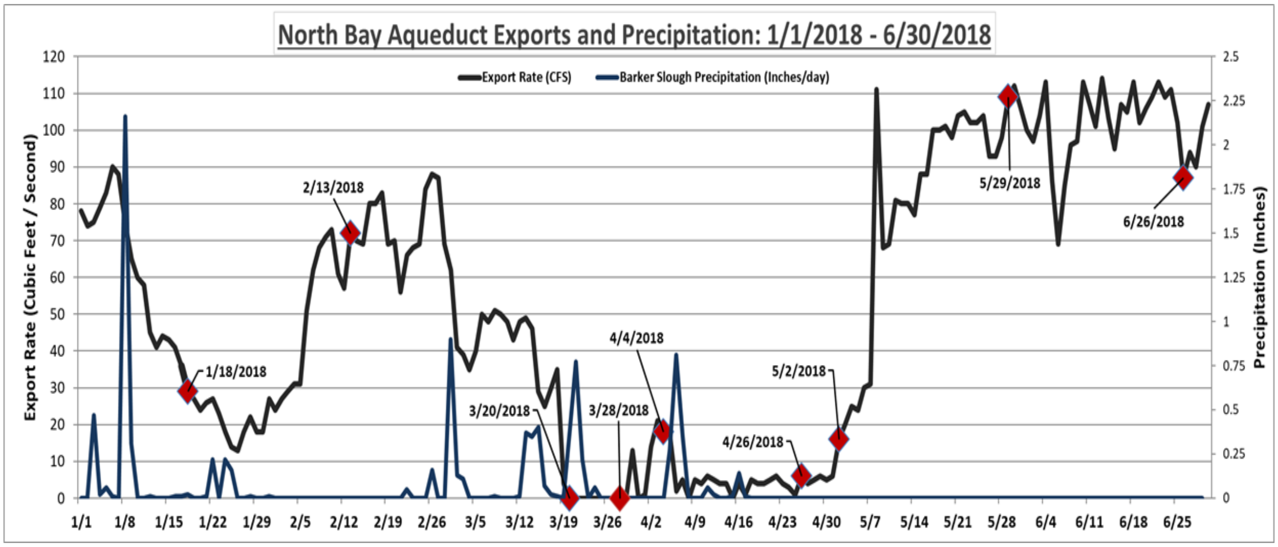


Figure 30. Barker Slough Pumping Plant export rate (cfs, black line), plotted on left axis, with local precipitation (inches/day, dark blue line) plotted on right axis for 2018. Red diamonds indicate nine sampling dates, some of which coincided with increased precipitation and reduced export.

Additional water-quality sampling was conducted in early 2018, with increased frequency of sampling before, during, and after the BSPP shutdown in 2018 (Figure 30). Water-quality values decreased from upland input sources, to termini of sloughs, to larger main channels throughout the year (Figure 31). However, the values were higher and the differences more extreme during export closures. Highest values were collected at Campbell Lake (CLDS), historic Barker Slough at the Dozier railroad track crossing (DOZ), and Calhoun Cut upstream of Highway 113 (CCWH). Values decreased from the terminus of Barker Slough (BK1) and upper Calhoun Cut (CC1), to middle Lindsey Slough (LN2), and to the confluence of Lindsay and Cache sloughs (LNCA).

Following a rain event at the beginning of the BSPP shutdown period (between March 20 and March 28 sampling events), total nitrogen increased by nearly 65% at BK1 and CC1. However, during a similar period from April 4 and May 2, total nitrogen decreased. During summer, with limited inputs and regular export pumping , values of water-quality constituents were greatly reduced at all slough sample locations.

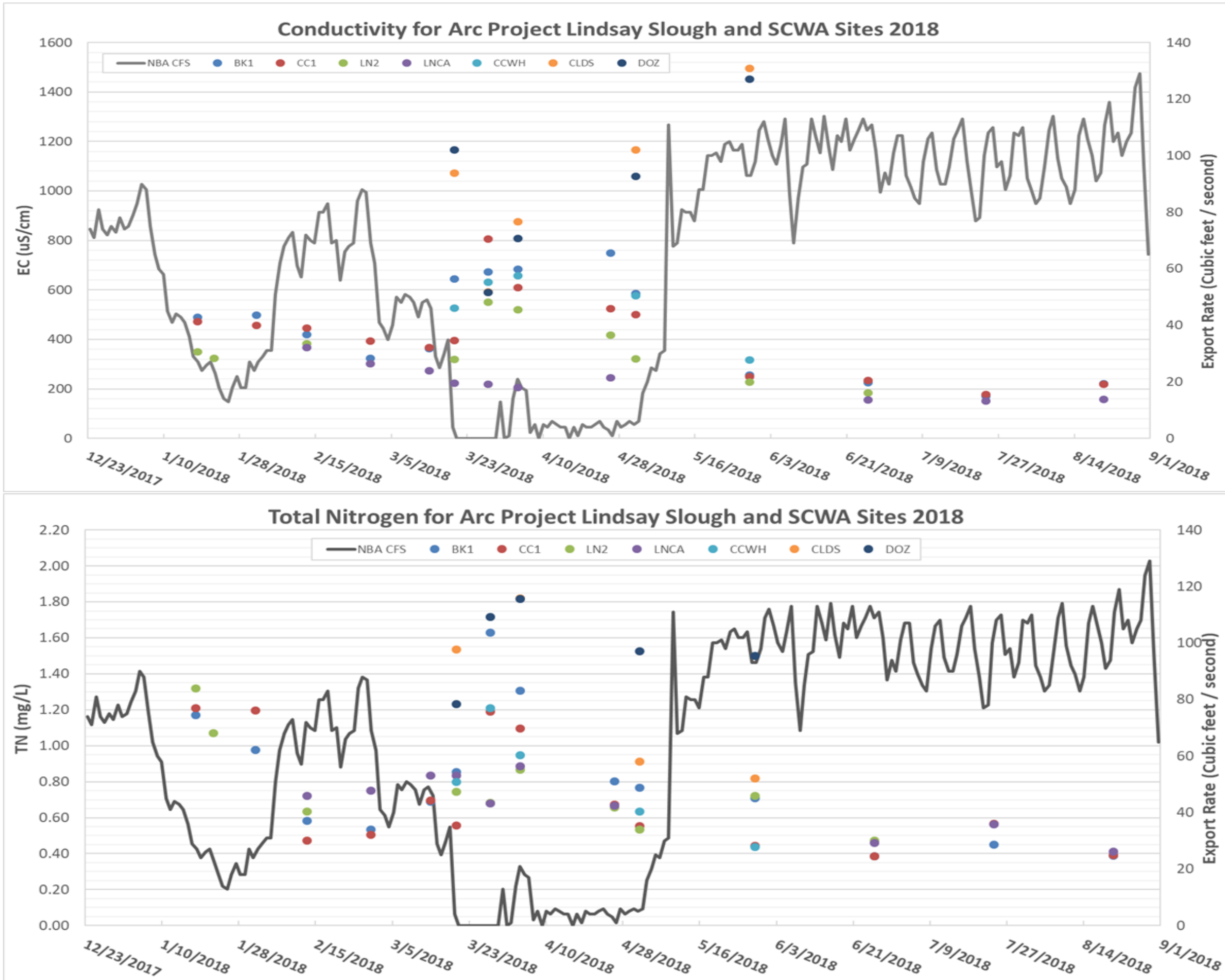


Figure 31. Barker Slough Pumping Plant export rate (right axis, cfs, black line) plotted with electroconductivity (upper plot, left axis, uS/cm) and total nitrogen (lower plot, left axis, mg/L) from water grabs taken at several upstream and down-slough locations (colored circles, see key).

Discussion

Temporal and spatial changes

The data analyzed for this report covered a period of severe drought and subsequent ecosystem recovery from 2012-18. During that time, the water quality and species composition of the CLC shifted.

In particular, water quality changed substantially in Lindsey Slough and near the confluence, with decreases in turbidity, VSS, and TSS, all measurements of suspended material in the water column. These water-quality changes were likely driven by the expansion of submersed aquatic vegetation (SAV) in the area, especially in Lindsey Slough. While proximity of the CLC to Yolo Bypass, Putah Creek, and Ulatis Creek (all of which provide detritus, sediment, and scouring flows) may have helped delay the spread of aquatic vegetation, the long drought of 2012-2016, which limited flooding on the Bypass and reduced flows, may have facilitated the establishment of aquatic weeds. Submersed vegetation like Brazilian waterweed is thought to be responsible for increasing water clarity throughout the southern Delta by slowing water movement and impeding sediment transport.

The rapid colonization of the CLC by Brazilian waterweed during the drought may have initiated changes in fish assembly over the study period. Historically, the Delta was much more turbid than it is today, and native fishes, including delta and longfin smelt, are adapted to these conditions. Increasing water clarity tends to decrease habitat for native species while optimizing conditions for many non-native fishes, especially centrarchids like bluegill, redear sunfish, and largemouth bass. Consistent with this, the CLC displayed a loss of native smelt species concurrent with a considerable increase in centrarchid abundance. Tule perch, a normally ubiquitous species in lowland rivers and estuaries in California, declined dramatically during the study. Abundances of other common species tolerant of warm water remained somewhat stable over time, including striped bass, threadfin shad, splittail, and Sacramento sucker.

Spatial differences in water quality between the two sloughs existed before the recent drought, underlain by differences in physical structure and water movement. The landward ends of the Cache Slough Complex, particularly Ulatis Creek, upper Cache Slough, and Hass Slough remained more resilient to changes than Lindsey Slough and the confluence. Water pH, turbidity, VSS, TSS, phosphorus, nitrogen, and chlorophyll were all considerably higher in the landward reaches of thee Cache Slough Complex, and remained so during and after the drought. This was somewhat surprising because Cache Slough lacks the complex physical structure and habitat (emergent wetlands, riparian vegetation, and a new restoration site) of Lindsey Slough. Notably, tidal restoration appeared to have no effect on water quality in Lindsey Slough, although the restoration is still young. In contrast, Ulatis Creek provides Cache Slough with fresh water, detritus, and nutrients, and may have helped limit the encroachment of submersed vegetation into the slough's upper reaches.

Plankton production was much higher in Cache Slough as well. Chlorophyll was found at very high concentrations throughout spring, decreased somewhat through summer, and rose again in fall, possibly when inputs from Ulatis Creek increased. While phytoplankton and zooplankton density tended to increase toward the landward ends of the CLC, the freshwater source may have stimulated more production in Cache Slough.

The differences in water quality and food production between the Cache and Lindsey Sloughs were paralleled by fish catch and community composition. POD species, which are reliant upon zooplankton for at least part of their life cycle, were most abundant in the upper portion of Cache Slough while being rarer in all of the Lindsey Slough sites. The most abundant POD species in the region was threadfin shad, which moved seasonally into the upper reaches of Cache Slough where zooplankton concentrations were higher. The second most abundant POD species was juvenile striped bass, which also were seasonally more abundant in Cache Slough. Catch of centrarchids by electrofishing tended to be highest in Lindsey Slough, especially for redear sunfish and largemouth bass, probably because of the increased edge structure from riparian and aquatic vegetation. Bluegill were somewhat more evenly distributed, and black crappie tended to be more prevalent in Cache Slough, probably because they are more well-suited for open water, turbid conditions, and abundant zooplankton. The somewhat higher otter-trawl catch of centrarchids in the Cache Slough Complex was likely due to higher turbidities coupled with less submersed vegetation, resulting in movement of centrarchids away edges and into the channel thalweg where the trawl sampled (Todd and Rabeni 1989, Abrahams and Kattenfeld 1997, Ahrenstorff *et al.* 2009).

Special Study: BSPP Shutdown WQ Shifts and Fish Response

Over the study period, Barker Slough was sampled during various water-year conditions and export regimes from the BSPP. Every year in March, the BSPP is shut down for two weeks for system maintenance, providing a unique opportunity to study how Barker Slough water quality responds both to reduced exports, and to inputs of fresh water from upland flows.

Water-quality conditions beneficial to ecosystems can be detrimental to municipal water supplies. As a result, BSPP slows or stops pumping at time when precipitation runs off from upland areas around Campbell Lake, degrading export water quality for municipal use. Thus pumping decreases when freshwater inputs increase, making it difficult to determine which factor most influences environmental conditions in the slough. To achieve higher resolution of this event, we are replicating the study in 2019. SCWA has been collecting samples at CLDS, DOZ, and CCWH since the beginning of this year, allowing us to properly track changes to water quality at locations that we cannot access by boat preceding the annual NBA shutoff event. Chlorophyll and zooplankton samples are currently being processed to link primary and secondary productivity to the observed inputs of total nitrogen and dissolved organic carbon. These data will be used to model linkages between precipitation, Campbell Lake overtopping events, and pumping rates with changes in nutrients concentration and productivity. With a more refined understanding of these linkages, a fish assemblage predictive model can be created around altered pumping regimes.

Conclusion

The CLC ecosystem is undergoing rapid change that was likely exacerbated by the drought. Whereas the region was once a stronghold for native species, that resiliency shows signs of weakening. In particular, the spread of non-native and invasive organisms are sentinels of an ecological shift that may be difficult to return from without substantial and persistent intervention. Tidal restorations, while providing habitat for some native species, may also support invaders. Such restorations may be limited in effectiveness if conditions are unfavorable in open-water channels that provide connectivity to other parts of the Delta.

Some useful lessons may be learned from the upper Cache Slough sites, which are affected by periodic high freshwater flows, have a well-developed pelagic food web, and are not yet heavily invaded by aquatic vegetation.

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