Title

North Delta Arc Study 2021 Annual Report: Cache-Lindsey Slough Complex water quality, productivity, and fisheries

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The data associated with this publication are available upon request.

North Delta Arc Study 2021 Annual Report: Cache-Lindsey Slough Complex 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 Complex (CLC), and Yolo Bypass – offers the best remaining opportunities for enhancing native fish populations within the upper San Francisco Estuary. Although the CLC is the subject of numerous restoration efforts, it remains understudied relative to the main bays and rivers of the estuary, with only sparse, short-term data to gauge restoration success.

The UC Davis North Delta Arc Study began in 2012 to provide baseline data for restoration, elucidate mechanisms supporting native and desirable fishes, and document ecosystem responses to climate change and water management. The study has used a diverse, flexible array of research approaches that include water-quality, phytoplankton, zooplankton, and fish sampling. This study has captured ecosystem responses to numerous environmental extremes: prolonged drought, record-high air and water temperatures, and record-high inflows. The study has also documented dramatic changes in ecosystem function, and provided recommendations for water management, fish and wildlife management, and restoration design.

The study revealed a major shift in conditions over the past nine years. Low flows during the 2012-2016 drought promoted the spread of noxious aquatic weeds, which was accompanied by an increase in water clarity and a decline in suspended particles. The fish assemblage changed with water-quality conditions and aquatic-weed growth. Native, cool-water smelts declined while non-native, warm-water sunfishes increased. High flows and storm runoff in 2017 ended the drought and altered water quality but did not limit weeds and sunfishes, suggesting the CLC had passed a threshold. However, 2021 marked the first year that a decrease in aquatic weeds was observed and was accompanied by an increase in some native species. Small sloughs with local inflows from streams, ponds, and agriculture drains, and high-to-variable water residence times in certain upstream reaches, generally maintained relatively low water clarity, high plankton biomass, and relatively high native fish abundance.

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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). The Arc includes freshwater and brackish-water habitats extending from Suisun Marsh to the Yolo Bypass via the confluence of the Sacramento and San Joaquin rivers, the Sacramento River from the confluence to Steamboat Slough, Cache and Lindsey sloughs, Prospect and Shag sloughs and Liberty Island, the Toe Drain, and the Deep Water Ship Channel (Figure 1).

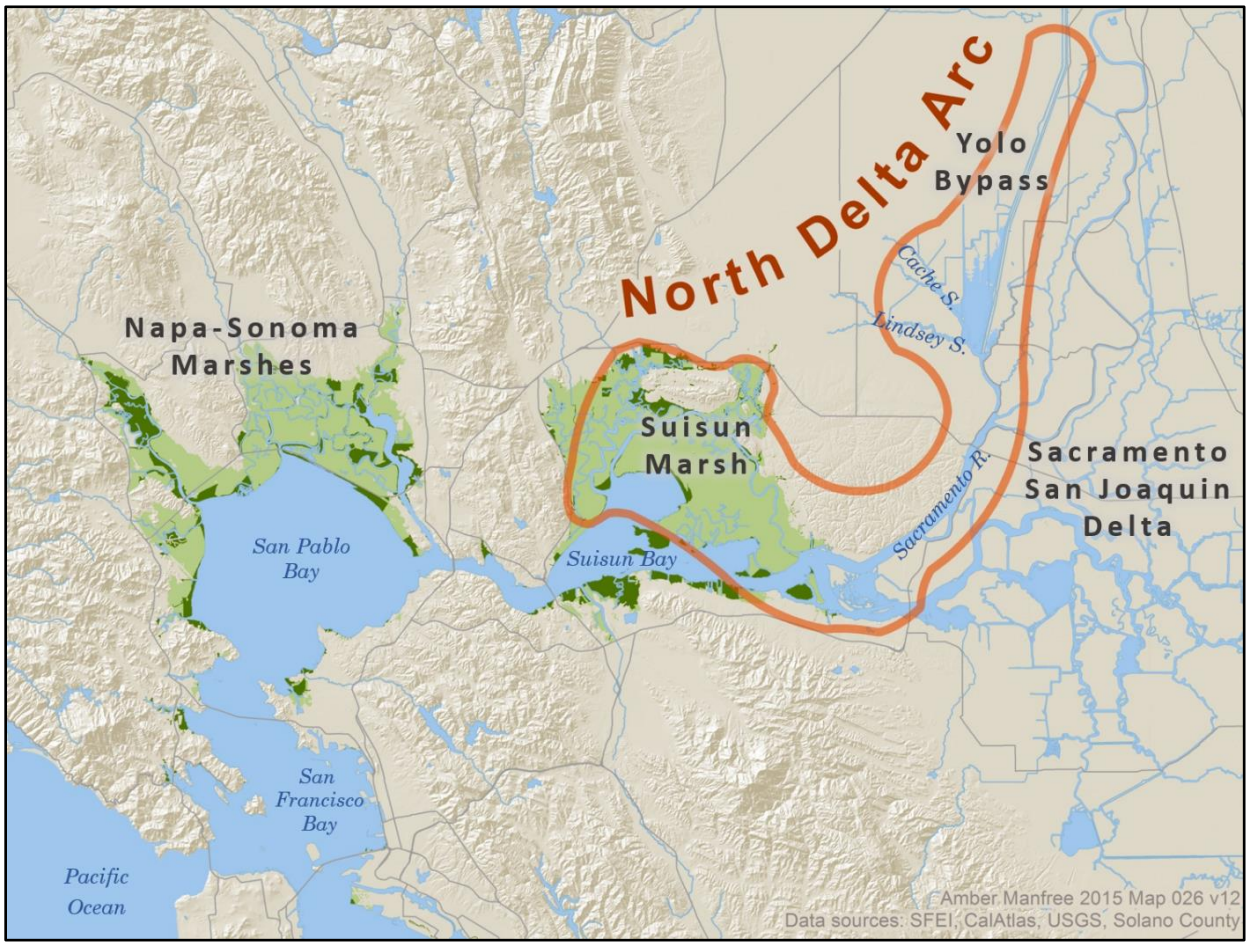

Figure 1. North Delta Arc, showing habitat corridor from Suisun Marsh to Yolo Bypass, including region of study at the Cache-Lindsey Slough Complex.

Hydrodynamic, landscape, geochemical, and food-web processes in the Sacramento-San Joaquin Delta ("Delta"; Figure 1) 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 in the region (Thompson 1957). In response, Delta landowners dredged and leveed 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 wetlands were replaced by deep, straightened channels buttressed by hardened levees, with most wetlands converted to farms (Thompson 1957). After state-wide droughts during the 1920s and 1930s, the federal government began building the Central Valley Project, followed by the construction of California's State Water Project several decades later. These form a system of reservoirs and aqueducts designed to store and transfer water for municipal and agricultural use (Lund et al. 2018). Dams, dikes, and diversions have commonly separated aquatic and terrestrial processes, diminishing the influence of both floods and sediment transport on Delta landscapes.

These physical and biological changes have created novel environments, sometimes with feedback loops that amplify new conditions. Sediment loss combined with intensive farming of peat soils has caused deep and continuing subsidence in leveed Delta islands, increasingly compromising levee integrity (Mount and Twiss 2005). Flow reductions and sediment-trapping by dams have reduced turbidity, favoring proliferation of non-native submersed aquatic weeds, which then further slow and clear the water (Durand et al. 2016). Filter-feeding by invasive invertebrates, combined with increased water export, have reduced plankton abundance for pelagic crustaceans and fishes, leading to food limitation and population declines in many species (Kimmerer 1996; Moyle et al. 2016, Hammock et al. 2019).

Food-web, water-quality, and habitat degradation have reduced refuge and foraging opportunities for pelagic and native fishes (Grimaldo et al. 2004; Feyrer et al. 2007). Many once-common fishes are dwindling, such as striped bass (*Morone saxatilis*), and some are critically endangered, including delta smelt (*Hypomesus transpacificus*), winter-run Chinook salmon (*Oncorhynchus tshawytscha*), and green sturgeon (*Acipenser medirostris*). Major changes to the system are needed to aid the recovery of these species.

The CLC possesses considerable potential for successful restoration in the Delta (Durand 2017; Moyle et al. 2018). In contrast to other regions of the Delta, clay soils in the CLC have resisted subsidence in reclaimed lands, allowing potential re-creation of tidal marsh. Gradual upland slopes exist that can accommodate restoration and sea-level rise. Sediment transported from the Sacramento River, Yolo Bypass, and Ulatis Creek produces higher seasonal turbidity than in other Delta regions. Historic riparian vegetation and emergent marsh are common features in several reaches of the CLC. Until recently, submersed and floating aquatic weeds were less extensive in the CLC than in other areas of the Delta. The spatial complexity of the region; the connectivity to marshes, floodplains, and streams; and

high food concentrations support seasonal and year-round habitats for migratory and resident native fishes (Simenstad et al. 2000). Thus, broad interest exists in restoring large tracts of tidal habitat in the CLC (ICF International 2013).

Because the CLC showed promise for restoration but was the subject of minimal study, the North Delta Arc Study began in 2012 to describe its aquatic ecosystem, to assess its response to environmental changes, and to update and inform restoration design and management. The study was updated in 2014 with grants from the State and Federal Contractors Water Agency, in 2016 with a California Department of Fish and Wildlife (CDFW) Proposition 1 grant, and in 2017 with a grant from Solano County Water Agency.

The study's chief objectives have been to:

(1) Understand temporal changes in water-quality conditions, plankton production, and invertebrate and fish assemblages in Cache and Lindsey sloughs resulting from tides, seasonal flow pulses, regional water diversion, and periods of drought and flood

(2) Understand spatial differences in ecosystem function between distinct slough networks within the CLC

(3) Compare water quality and fish assemblages among restored and adjacent sites, particularly the CDFW Lindsey Slough/Calhoun Cut Restoration and the Wildlands North Liberty Island Mitigation Bank

(4) Develop a hydrodynamic model of water age and residence time to understand advection and dispersion in the North Delta, including the CLC

We completed interdisciplinary work that fulfilled or partially fulfilled several of the study's objectives and published our findings in a previous report (Durand *et al.* 2020). Partially fulfilling objective number one, an investigation of water quality and zooplankton in the CLC found that sites with higher conductivity generally supported higher chlorophyll-*a* concentrations and zooplankton densities, and that both primary and secondary productivity may have been tied to nutrient loading from treated urban wastewater and upland agriculture runoff (Jasper 2020). Current studies are experimentally comparing the rate of production relative to environmental conditions. Fulfilling objective number two, we reported on a comparison between dead-end-slough and mainstem-river/slough sites within the Arc for 2013 and 2014 that determined that both chlorophyll-*a* concentration (proxy for phytoplankton) and zooplankton biomass were much higher at upstream sites (Montgomery 2017). A current study is

expanding this analysis both spatially and temporally to better understand habitat function and zooplankton abundance in response to changing environmental conditions such as drought and flood. Partially fulfilling objective number three, a study comparing restoration and adjacent slough sites found lower abundance and a similar proportion of native fishes in the Lindsey Slough Restoration Project**,** and higher abundance and proportion of natives in the North Liberty Island Mitigation Bank (NLIMB) in 2015 and 2016 (Durand *et al.* 2020). A current study is comparing distribution of key common fishes found in the surveys across space through periods of drought and flood. Fulfilling objective number four, a hydrodynamic model was produced that identified upper Cache Slough to have higher water age (residence time) than downstream sites and that the Lindsey Network has a higher proportion of Sacramento River water compared to the upper Cache Network (Gross *et al.* 2019, Durand *et al.* 2020). Findings from these studies have enhanced our understanding of how the CLC functions and led to further research.

The following report details data collected throughout the duration of the Arc Study in pursuit of further fulfilling study objectives. Timeseries data are presented from water-quality, aquatic vegetation, and fishes sampled from December 2012 through December 2021. Results from the current study of spring zooplankton from 2013 to 2021 are included. Additionally, preliminary results from a study on rates of pelagic primary production and respiration are presented. These data show spatial and temporal patterns of ecosystem function within the CLC and have led us to several conclusions and management recommendations.

Methods

Study Area

The CLC includes two distinct slough networks: (1) the Cache Network, which includes upper Cache Slough, Hass Slough, and Ulatis Creek; and (2) the Lindsey Network, which includes Lindsey Slough, Barker Slough, and Calhoun Cut. A combination of historical endeavors and water-management decisions have endowed each network with very different features despite their close geographic proximity. Both networks were historically connected 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 networks are differences in hydrodynamics, nutrient concentrations, and physical structure that affect water quality and fish assemblage.

The Cache Network is steeply leveed and subject to large seasonal flows from Ulatis Creek, receiving urban, flood, and agricultural runoff – including effluent from Vacaville's Easterly Wastewater Treatment Plant. Some upstream reaches, including Ulatis Creek and Cache Slough, exhibit high turbidity year-round, and have less submersed aquatic weeds than elsewhere in the Delta.

The Lindsey Network is mostly isolated from large flood flows but receives some water from local sources. Deep and leveed near the mouth, the slough expands into extensive intertidal and riparian habitats in the shallow upper reaches of the main tributaries, Barker Slough and Calhoun Cut. Water inputs come mostly from Jepson Prairie overland flow, the Big Ditch, and the Barker Slough Watershed. Water quality in Barker Slough is largely affected by runoff from Campbell Lake, which accumulates salts and sediment, and by water exports for agriculture and the North Bay Aqueduct. Water export by the Barker Slough Pumping Plant is continuously measured and slowed or stopped under several conditions: when water quality declines due to runoff, when demand is low, or when facility maintenance is needed. Agricultural withdrawals occur mostly in summer and are largely unmonitored. The Lindsey Slough Tidal Habitat Restoration was implemented in Calhoun Cut in 2015, connecting the historic upper slough channel of Lindsey Slough to Calhoun Cut and Lindsey Slough.

Physical and hydrodynamic differences between the Lindsey Network and Cache Network provide an opportunity to study mechanisms that drive biological differences. Water withdrawals and inputs affect hydrodynamics, water quality, food-web production, and species composition of the CLC. Locally, elements that affect the system are (1) Ulatis Creek inflows; (2) agriculture runoff (for example, Hass Slough and the Big Ditch system); (3) overland flow (for example, at upper Lindsey/Calhoun and Barker sloughs); (4) municipal and agricultural withdrawals, including the Barker Slough Pumping Plant; and (5) restoration projects. Regionally, elements with potential to affect the CLC are (1) winter/spring Yolo Bypass flows during flood years; (2) autumn 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, the Sacramento Regional Wastewater Treatment Plant upgrade in 2021).

Climatic Conditions

We used the Net Delta Outflow Index ("Delta outflow") as an indicator of water conditions across the study period and watershed (Kimmerer 2004, Feyrer *et al.* 2015). 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 Resources (DWR 2022).

Sampling

Sampling has been conducted monthly since December 2012 across the Arc, with a focus on the CLC, which includes Cache and Lindsey sloughs and their smaller tributaries (Barker Slough, Calhoun Cut, Hass Slough, and Ulatis Creek; Figure 2). Originally, otter trawls were conducted around Liberty Island, but these were discontinued due to floods in 2017 that introduced bottom hazards to the region; biannual electrofishing sites and monthly water-quality transects were continued, however. The study area encompasses numerous planned and implemented restoration sites, including the Lindsey Slough

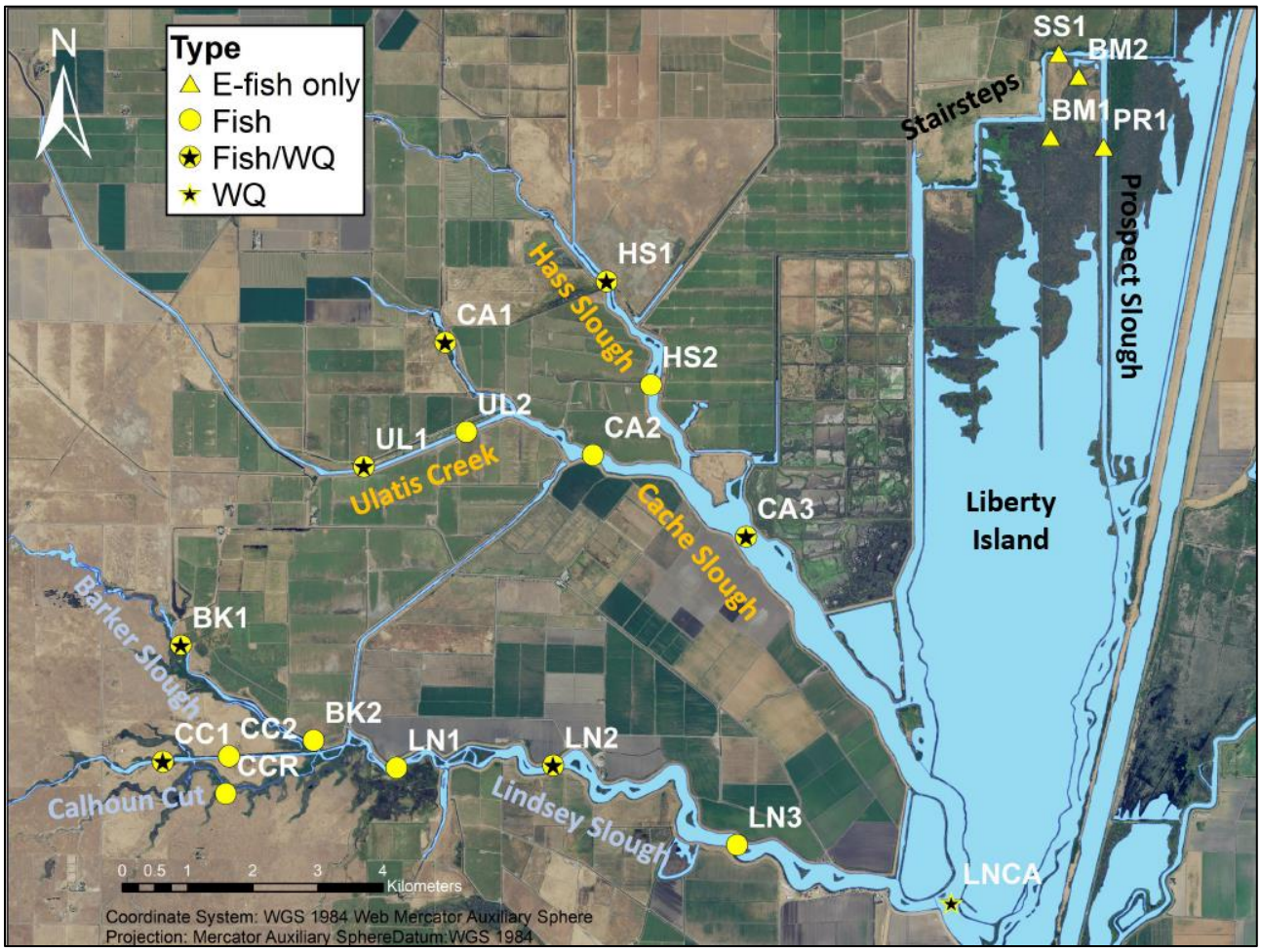

Figure 2. Current sample sites in the Cache-Lindsey Slough Complex. Yellow triangles indicate electrofishing only sites, circles indicate trawl and electrofishing sites (fish), and black stars indicate water-quality and zooplankton collection sites (WQ). Cache Network sites are labeled in light orange; Lindsey Network sites are labeled in light blue.

Restoration Project (for which the study has pre- and post-implementation data), the North Liberty Island Mitigation Bank, the Beaver Ponds (post-implementation data), the Lower Yolo Ranch Tidal

Restoration (pre- and post-implementation 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 in the Stairsteps. Sites in the Toe Drain of Yolo Bypass were sampled only rarely during exploratory surveys. Due to the COVID-19 pandemic, electrofishing did not occur in 2020; otter-trawling did not occur April, May, and June 2020; and water-quality/zooplankton sampling did not occur in April and May 2020.

In this report, the following sites are associated with the Cache Network (including Ulatis Creek and Hass Slough): UL1, UL2, CA1, CA2, CA3, HS1, and HS2. The following sites are associated with the Lindsey Network (including Calhoun Cut and Barker Slough): CC1, CC2, BK1, BK2, LN1, and LN2, and LN3. Site numbers indicate location of site along slough, with "1" being furthest upstream and "3" being furthest downstream. A single water-quality/zooplankton sampling site was located at the confluence of Cache and Lindsey sloughs (LNCA). Discrete water quality was sampled in all upper reaches (UL1, CA1, HS1, CC1, BK1), two mid-slough reaches (CA3, LN2), and a site at the confluence of the two slough networks (LNCA). In addition, biannual electrofishing surveys were conducted at each of these sites, plus sites around Liberty Island, and included SG1, SG2, BP1, BP2, SS1, BM1, BM2, PR1, and PR2. We include several of these sites around Liberty Island to compare a restoring wetland (BM1 and BM2) to adjacent waterways (SS1 and PR1). Site data are tabulated in Appendix I.

Water Quality, Pelagic Metabolism, and Zooplankton Sampling

Water Quality

Water-quality data were collected monthly with handheld meters (concomitant with fish sampling) and whole water grab analysis. In 2016, 2018, and 2019, water-quality surveys were conducted more frequently to measure the immediate impact of flows from storm events on water quality. 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 Yolo Bypass.

For each fish-sampling event, temperature (degrees Celsius, °C), dissolved oxygen (DO, milligrams per liter (mg/L), and % saturation), and specific conductivity (microSiemens, µS) were recorded with a Yellow Springs Instruments (YSI) PRO2030 handheld device. Water clarity (Secchi depth, centimeters (cm)), tidal stage (ebb, flood, high, low), and water depths (m) were also recorded. Data from each site were graphed through time.

Water grabs were taken at eight sites within the CLC. Phytoplankton samples were also collected, preserved in Lugol's solution, and archived for later identification. Lab analyses of water grabs for water-quality constituents 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 can indicate 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/how much 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 concentration of organic carbon dissolved 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), dissolved inorganic nitrogen (DIN; $NO_3 + NH_4$), and total nitrogen (TN). The ratio of DIN to PO_4 is an indicator of which nutrient is limiting primary production.
- *Chlorophyll.* Chlorophyll serves as a proxy for phytoplankton density. Chlorophyll *a* is a measurement of chlorophyll from living cells. Pheophytin *a* is a measurement of ambient chlorophyll from dead cells.

Special Study: Pelagic Metabolism

Concurrent with water grabs at five sites (UL1, CA1, HS1, BK1, CC1) from January 2021 to June 2021, surface water samples were collected for bottle incubations to measure rates of pelagic community metabolism (*i.e.*, how much photosynthesis and respiration are occurring from phytoplankton and bacterioplankton). Water was collected in a thoroughly rinsed 5-gallon bucket, poured through a 150-micrometer (μm) filter to exclude zooplankton, placed in thoroughly rinsed opaque bottles, and placed on ice. Water samples were transported to the laboratory and placed in a temperature-controlled grow chamber where they were allowed to equilibrate to chamber temperature (15 °C) in the dark. Water from each site was poured into four replicate 1-pint mason jars and DO concentration was measured using a fibox5 (Presens) fiberoptic oxygen sensor. The jars were randomly placed under fluorescent grow lights and exposed to 12 hours of light followed by 12 hours of dark. DO

was recorded for each jar before the lights turned on at the end of the 12-hour light period and at the end of the 12-hour dark period. We assumed respiration to be the same in both the light and dark bottles and calculated the metabolism rate as follows:

Net Community Production (NCP)

NCP (mg DO/hour/L) = (light period final DO [mg/L] – light period initial DO [mg/L])/time [hours]/volume of jar [L]

Community Respiration (CR)

CR (mg DO/hour/L) = (dark period final DO [mg/L] – dark period initial DO [mg/L])/time [hours]/volume of jar [L]

Gross Primary Production (GPP)

GPP (mg DO/hour/L) = NCP + CR

Gross primary production is the rate of oxygen production from planktonic photosynthesis, community respiration is the total amount of oxygen consumed from respiration (both phytoplankton and bacteria), and net community production (community metabolism) is the difference between the amount of oxygen produced and oxygen consumed. Higher gross primary production corresponds to a greater amount of energy in the form of phytoplankton available to zooplankton and other algae consumers. Because community respiration includes respiration by phytoplankton, it will increase with increasing gross primary production. Greater amounts of organic carbon, mainly from detrital sources, will also increase the amount of respiration by bacterioplankton and cause an increase in community respiration. Net community production indicates if the community is net autotrophic or net heterotrophic. Autotrophic systems fix more carbon from photosynthesis than is respired, indicating energy being produced within the system by phytoplankton. Heterotrophic systems respire more carbon than is being fixed, indicating more energy flow through detrital pathways, from carbon that was created in a different location or time. To normalize rates for differing amounts of phytoplankton, NCP, CR, and GPP were divided by the chlorophyll-*a* concentration at the time of collection.

Zooplankton

Zooplankton were collected using a 50-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 high-density polyethylene bottles, stained with 1% rose Bengal, and preserved in 5% formaldehyde. In the laboratory, samples were sub-sampled and analyzed under a dissecting scope until a total of 100 individuals were counted for three different zooplankton genera. All individuals were identified to life stage (juvenile or adults) and genus, and egg counts were performed on females. Genera 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. A corrected tow volume was created and used to calculate all densities to account for error in the flowmeter, which could skew densities. All calculated sample tow volumes between 1 m^3 and 4 m^3 were averaged and produced a corrected tow volume of 2.436 m^3. Calculated volumes below 1 m^3 were not used because they resulted in unrealistically high densities, a result of the flowmeter propeller becoming fouled by debris. Volumes greater than 4 m^3 were removed because that is the maximum volume that can be generated when pulling a 20-m tow with the propeller spinning its fastest. Zooplankton assemblages were broken down into taxonomic clades: Calanoida, Cladocera, and Cyclopoida.

Trends in zooplankton densities were assessed using 94 samples collected from 2013 to 2021, focusing on spring months (March, April, and May) when zooplankton are important to native fish recruitment. Dead-end slough sites (BK1, CA1, CC1, HS1, and UL1; Figure 2) were selected to determine which sites within the CLC were the most productive. No samples were available from HS1 and UL1 in 2013, and from all sites during April and May in 2020.

Zooplankton were compared across years, months, sites, and were calculated as follows:

Sample Count

(Total Sample Volume/ Subsample Volume) * (# of organisms)

Sample Density

Sample Count/Sample Volume (m^3)

Fish and Aquatic Vegetation Sampling

Fish sampling was conducted in diverse near-shore and mid-channel habitats. To account for different habitat types, boat electrofishing and otter-trawling were used for sampling. All sampling was

conducted from UC Davis boats, including a 21-foot-long Workskiff outfitted for trawling and water-quality sampling, and a custom 18-foot-long Smith-Root electrofishing vessel.

Trawling targeted mid-channel habitats and was conducted monthly 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 a speed of approximately 4 kilometers/hour (relative to the water) for 5 minutes at 14 or more sites. Contents of each trawl 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. Siberian prawn (*Palaemon modestus*), red swamp crayfish (*Procambarus clarkii*), Asian clam (*Corbicula fluminea*), and Mississippi grass shrimp (*Palaemonetes kadiakensis*) were also identified and counted. Amphipods in the suborders Gammaroidea or Corophiida were given an abundance ranking. Other invertebrates, including insects, isopods, mysids, and snails, were also given a ranked abundance. Volume of debris, including aquatic vegetation, was also estimated for each trawl. Aquatic vegetation was identified to genus or species and estimated volumetrically. Catch per unit effort (CPUE) of trawl catches was calculated by dividing catch by minutes trawled.

Electrofishing targeted near-shore habitats and was conducted biannually (spring and autumn) since 2013, with some sites sampled more frequently from 2013 to 2016. Electrofishing was conducted with a Smith-Root 7.5 GPP boat-mounted electrofisher at a constant pulse width of 60 pulses per second and variable power to maintain a constant electrical current of 8 ± 1 amperes. 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 time spent electrofishing. Stunned fish were collected using long-handled dipnets and placed in an aerated live-well; once recovered, they were identified, measured, and released. Sampling was conducted within restoration project areas where possible, as well as in close vicinity of the projects, to detect possible influences of restoration on fish assemblages. CPUE was calculated by dividing catches by time spent electrofishing.

To evaluate changes in fish assemblages, we chose the most-abundant species from trawls and electrofishing, grouped them by habitat association or origin (native or non-native), and then graphed them. The habitat associations indicate if a species spends most of its lifespan in benthic, pelagic, or littoral (*i.e.*, near-shore) habitat. Grouping fishes by habitat association offers a way to delineate patterns more easily without being overwhelmed by the complexity of viewing many species at once (See Appendix II).

Species associated with benthic habitat include bottom fishes that feed largely on invertebrates. Eleven species comprise the benthic group, including three natives — prickly sculpin (*Cottus asper*), Sacramento splittail (*Pogonichthys macrolepidotus*), and Sacramento sucker (*Catostomus occidentalis*) — and eight non-natives — bigscale logperch (*Percina macrolepida*), channel catfish (*Ictalurus punctatus*), brown bullhead (*Ameiurus nebulosus*), black bullhead (*Ameiurus melas*), white catfish (*Ameiurus catus*), common carp (*Cyprinus carpio*), yellowfin goby (*Acanthogobius flavimanus*), and shimofuri goby (*Tridentiger bifasciatus*).

Fish associated with pelagic habitat are often planktivorous during at least one stage in their life history and occupy open-water habitat. We identified eight species as pelagic, including the pelagic organism decline (POD) species (Sommer *et al.* 2007)—striped bass (*Morone saxatilis*), Delta smelt, longfin smelt (*Spirinchus thaleichthys*), American shad (*Alosa sapidissima*), and threadfin shad (*Dorosoma petenense*)— and other species—wakasagi (*Hypomesus nipponensis*), Sacramento pikeminnow *(Ptychocheilus grandis*), hitch (*Lavinia exilicauda*), and Chinook salmon *(Oncorhynchus tshawytscha*).

We identified ten species that are associated with littoral habitat. Most of this group is comprised of non-native sunfishes (Centrarchidae) that were introduced for sport fisheries from the Mississippi River Watershed and southeastern United States, including bluegill (*Lepomis macrochirus*), redear sunfish (*Lepomis microlophus*), largemouth bass (*Micropterus salmoides*), white crappie (*Pomoxis annularis*), and black crappie (*Pomoxis nigromaculatus*). Sunfishes favor fresh water, warm temperatures, low flows, weedy habitats, and eat various invertebrates and fishes. The rest of the littoral group is made up of two native species – tule perch (*Hysterocarpus traski)* and threespine stickleback (*Gasterosteus aculeatus*) - and three non-native species – golden shiner (*Notemigonus crysoleucas*), Mississippi silverside (*Menidia audens*), and western mosquitofish (*Gambusia affinis*).

Results

Climatic Conditions: Mean Daily Outflow

The UC Davis North Delta Arc Study began in the winter of 2012, at the onset of a drought. Delta outflow was rather low in 2013 and very low in 2014 and 2015, which were the driest years of the drought. In 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. 2018 was a drier year, followed by a wet year in 2019, but 2020 marked the onset of another severe California drought that continued through 2021.

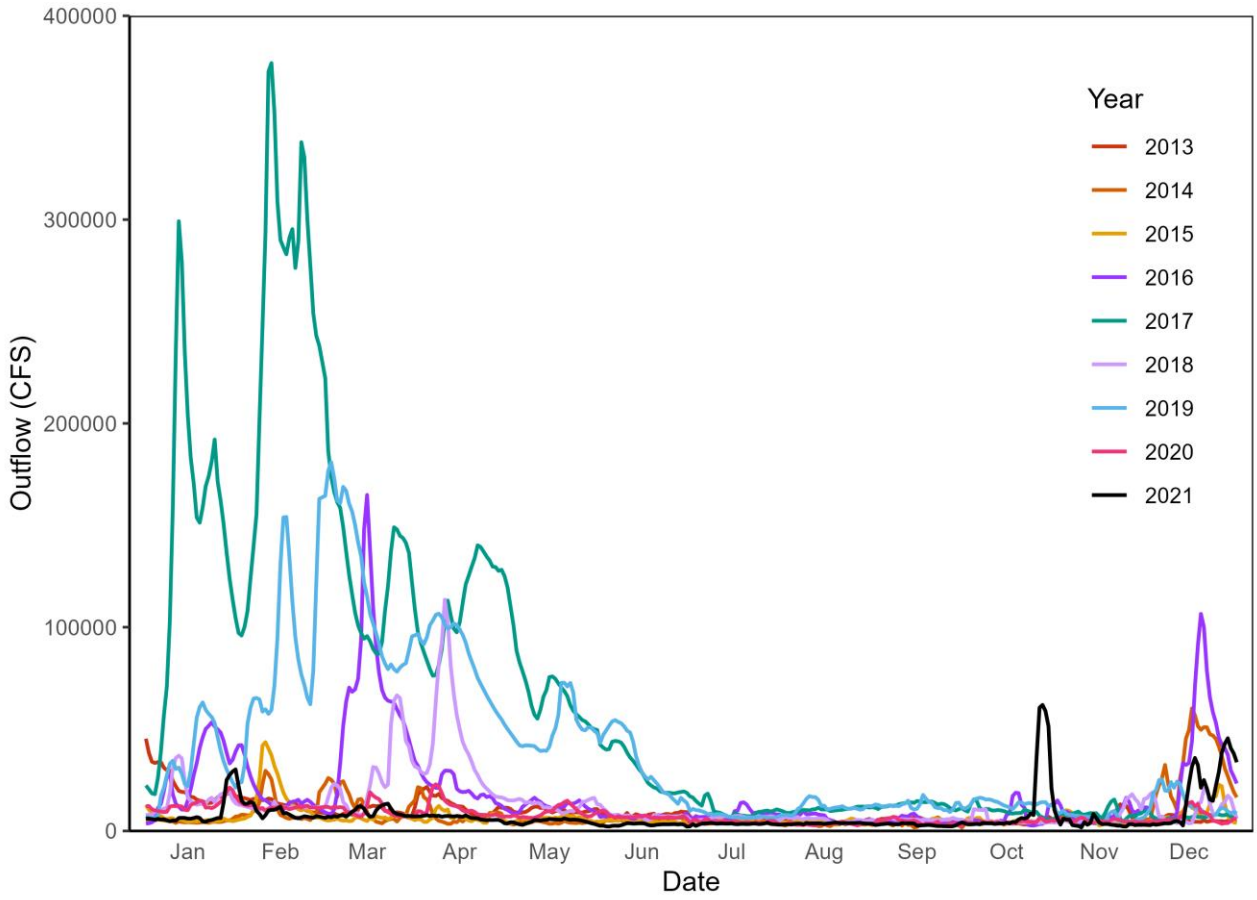

Figure 3. Mean daily Delta outflow (CFS) for 2013 to 2021 (DWR 2022).

Water Quality

Water Quality at Otter Trawl Sites (Handheld Measurements)

Temperature - Temperatures were typical of California's Mediterranean climate, with hot summers and cool winters (Figure 4). Due to its inland location, limited marine cooling 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 (UL1) had slightly higher maxima in most years. In 2021, maximum summertime water temperatures we measured were lower than 2017, 2018, and 2019, and minimum temperature never fell below 8°C.

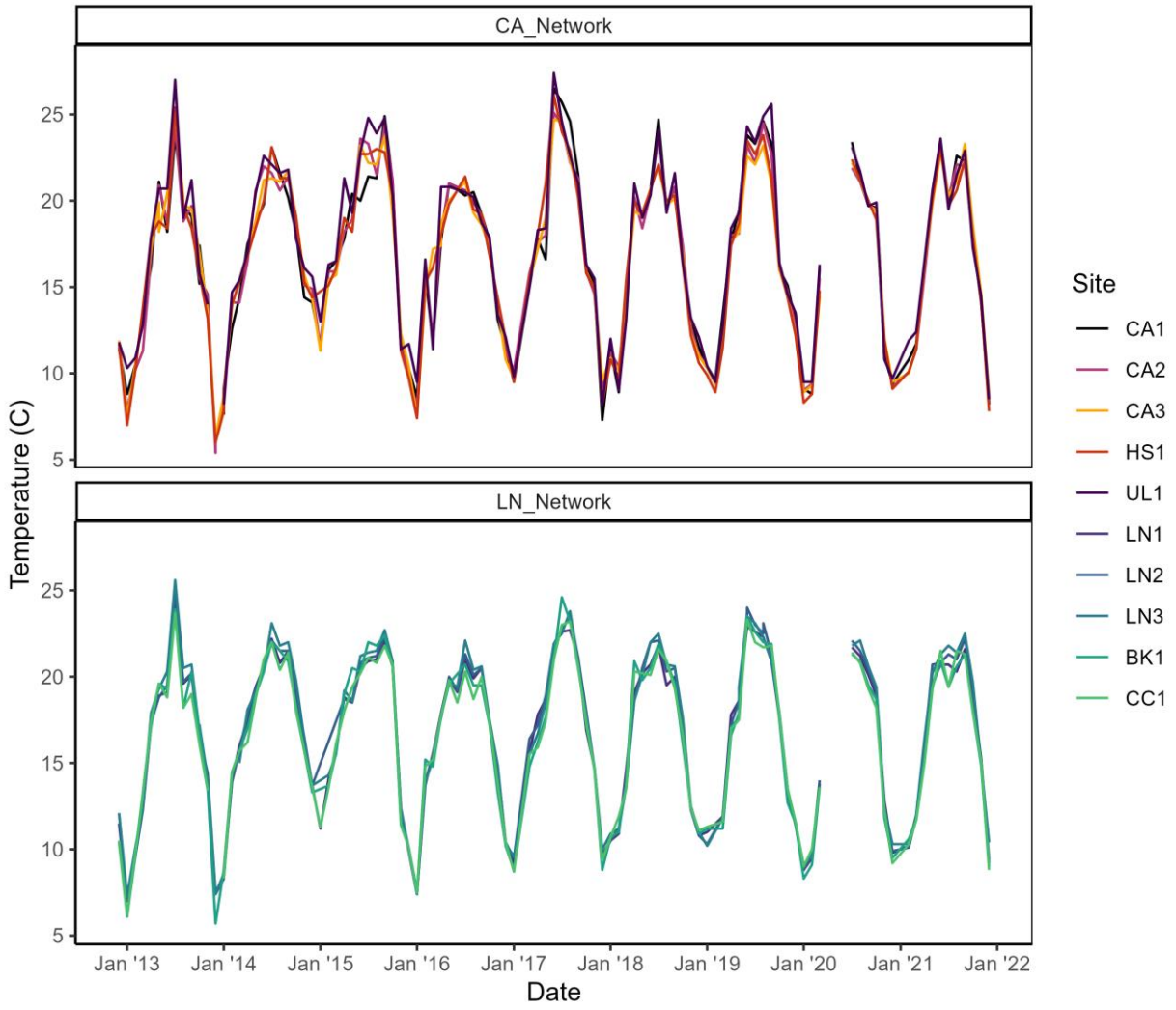

Figure 4. Monthly water temperature (°C) at otter-trawl sites.

Dissolved oxygen- Highest and lowest DO values occurred in upstream slough sites such as UL1, CA1, and CC1. Timing of minimum DO differed between the two slough complexes. In general, DO in the Cache Network was highest in winter and spring, and decreased throughout the summer and autumn. The Lindsey Network had highest values in autumn and winter, which then decreased and stabilized during spring and summer. DO was at sufficient concentrations (>3 mg/L) for most fishes at all sites (Figure 5). In 2021, DO was more extreme in the Cache Network during spring and almost identical between the complexes for the second half of the year.

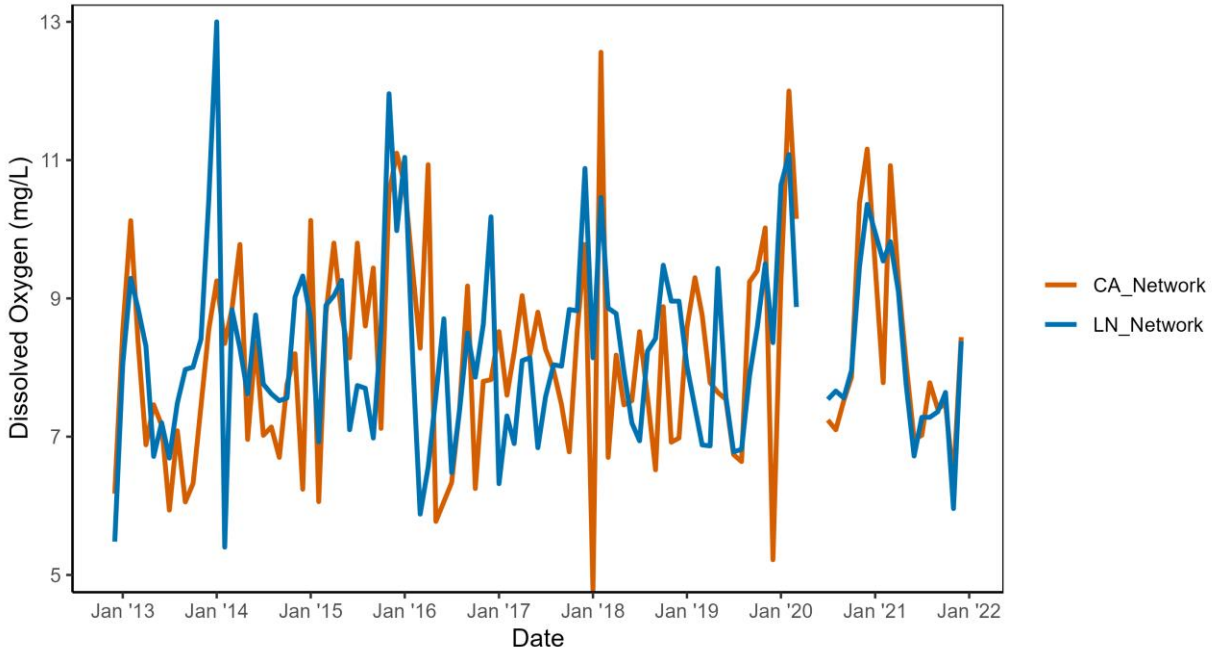

Figure 5. Monthly average DO (mg/L) for each network (CA_Network = Cache Network; LN_Network = Lindsey Network).

Specific conductivity- Specific conductivity was generally much higher in the Cache Network than in the Lindsey Network. Specific conductivity was highest at UL1 and decreased downstream toward CA3. Lindsey Slough was less variable from slough head to mouth, especially in summer. In winters, specific conductivity became elevated, increasing variation along slough length, with highest values in Barker Slough and lowest values at LN3 near the mouth (Figure 6). Seasonal variation occurred in both sloughs, with specific conductivity decreasing during summer when runoff was low. In 2021, upper slough sites in the Cache Network (UL1 and CA1) remained much higher than the most downstream site (CA3), while the Lindsey Network remained lower than pre-2020 levels the entire year.

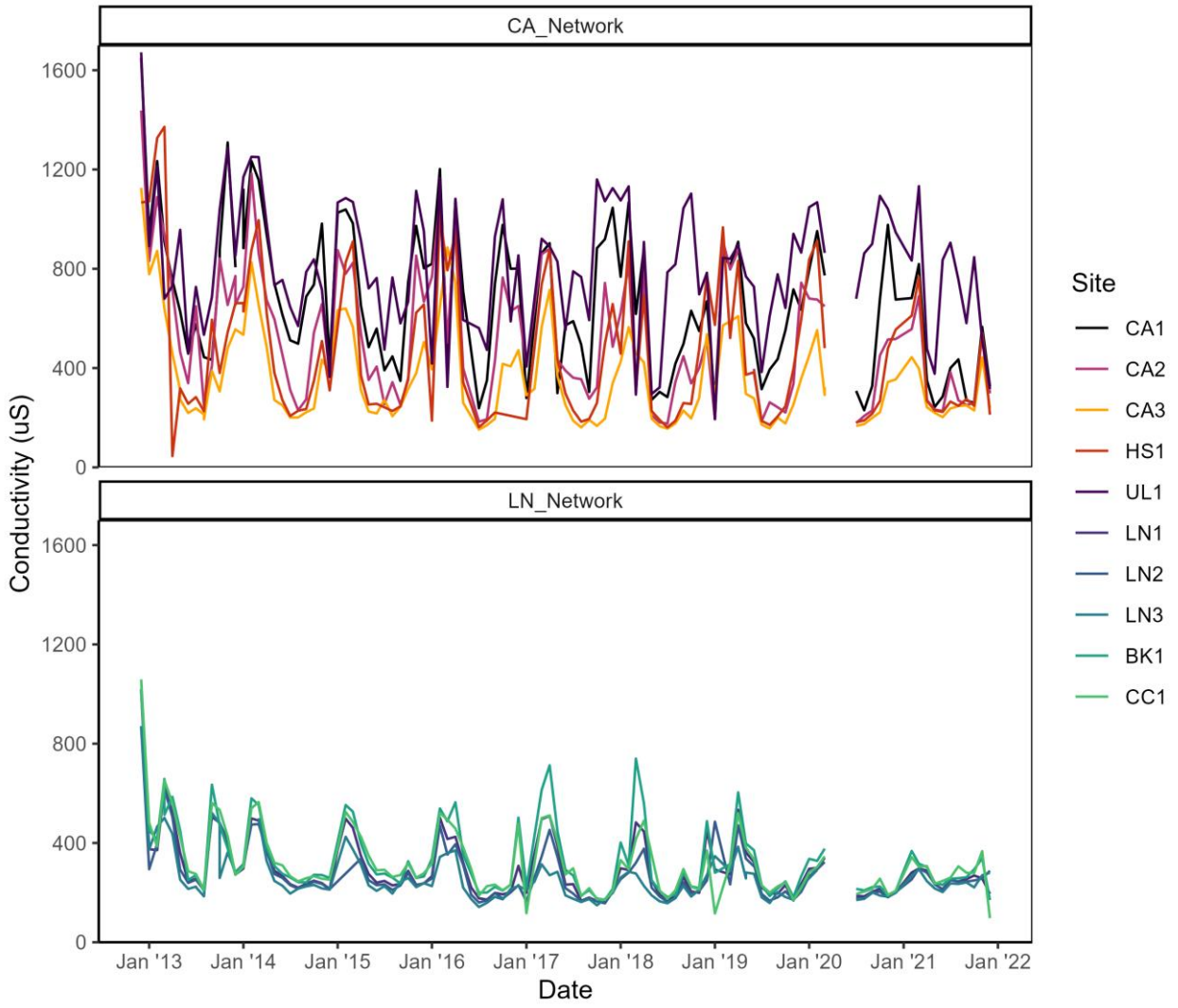

Figure 6. Monthly specific conductivity (µS) at otter-trawl sites. Top panel (CA_Network) includes Cache Network sites and bottom panel (LN_Network) includes Lindsey Network sites.

Secchi depth- Secchi depth increased throughout most of the study, especially in Lindsey Slough, Barker Slough, and lower Cache Slough (Figure 7). Sites with the slowest rate of increase in water clarity (i.e., Secchi depth) were UL1 and CA1. Each year saw a pattern of increasing clarity in late summer and autumn, followed by a decrease in the winter. Wet years, such as 2017 and 2019, decreased the water clarity. In 2021, although it was a dry year, Secchi depth decreased throughout the year.

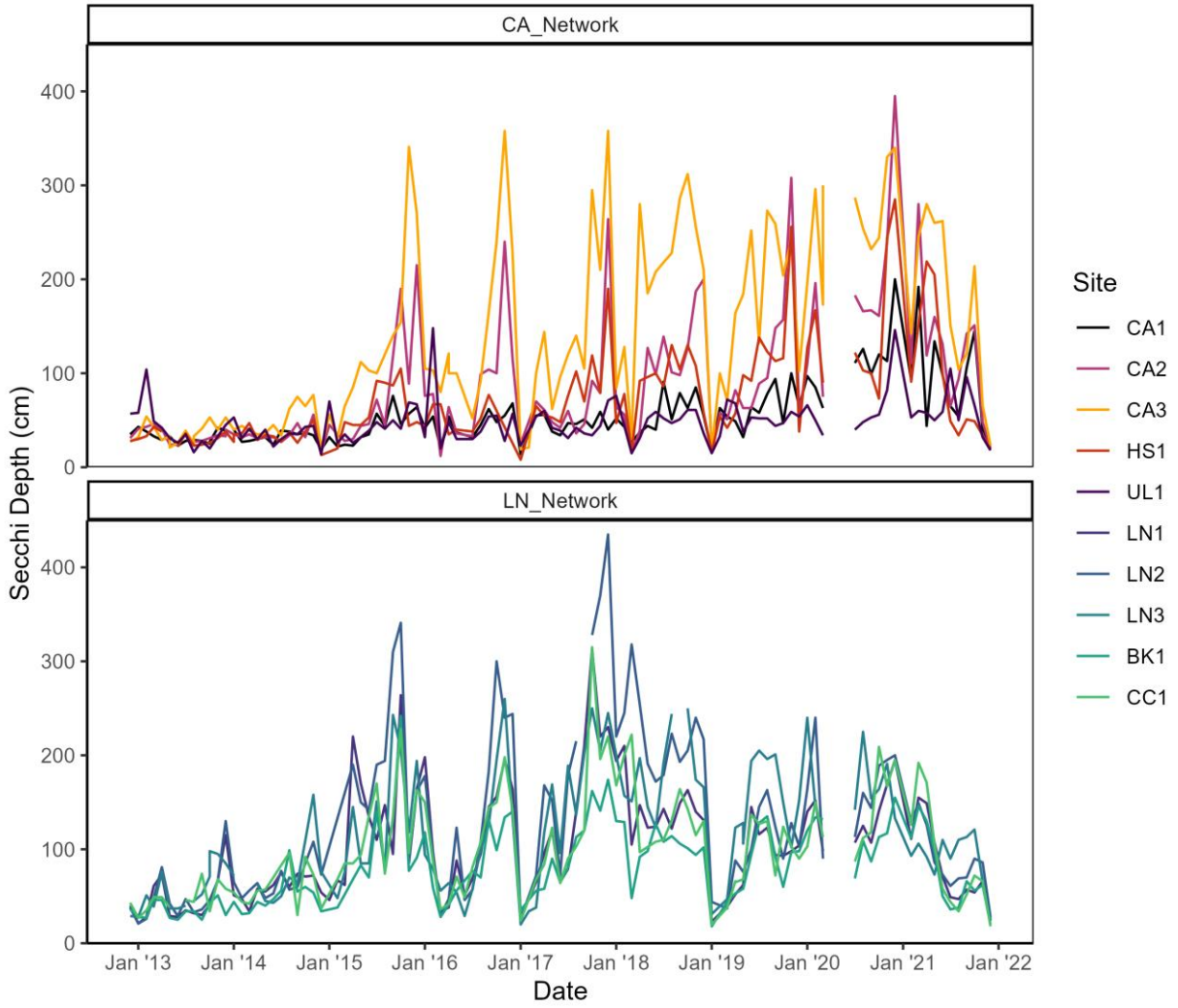

Figure 7. Monthly Secchi depth (cm) at otter-trawl sites. Top panel (CA_Network) includes Cache Network sites and bottom panel (LN_Network) includes Lindsey Network sites.

Water Quality Constituents (Water Grabs)

pH- pH has generally increased throughout the study, with peaks in spring of most years (Figure 8). UL1 consistently had the highest pH of all sites. The entire region has become more alkaline over time, possibly a result from increased primary production. pH was elevated at the beginning of 2021 and decreased during the summer.

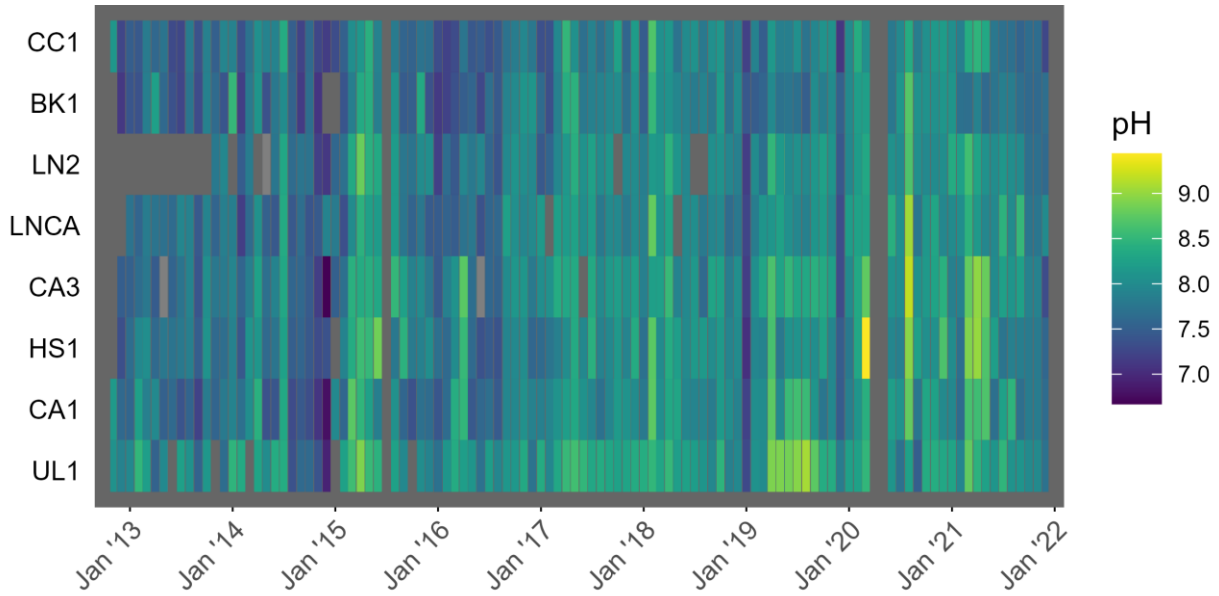

Figure 8. Monthly pH at water-quality/zooplankton sites.

Indicators of suspended detritus or sediment- Spatial patterns were observed for all four indicators, with highest values at UL1, CA1, and HS1. Samples from lower Cache Slough and from Lindsey Slough had lower values (Figure 9), including Calhoun Cut near the Lindsey Slough Restoration Project. All sites showed seasonal changes, with increasing values early in the year – especially during the very wet winters of 2017 and 2019.

Turbidity, VSS, and TSS decreased after 2014 in samples from Lindsey and lower Cache sloughs and generally remained low, even through wetter years following the drought. In 2021, turbidity, VSS, and TSS remained low until values spiked following a storm in December. In contrast, DOC values did not appear to change much over the study period. DOC was elevated in the Cache Network in 2021.

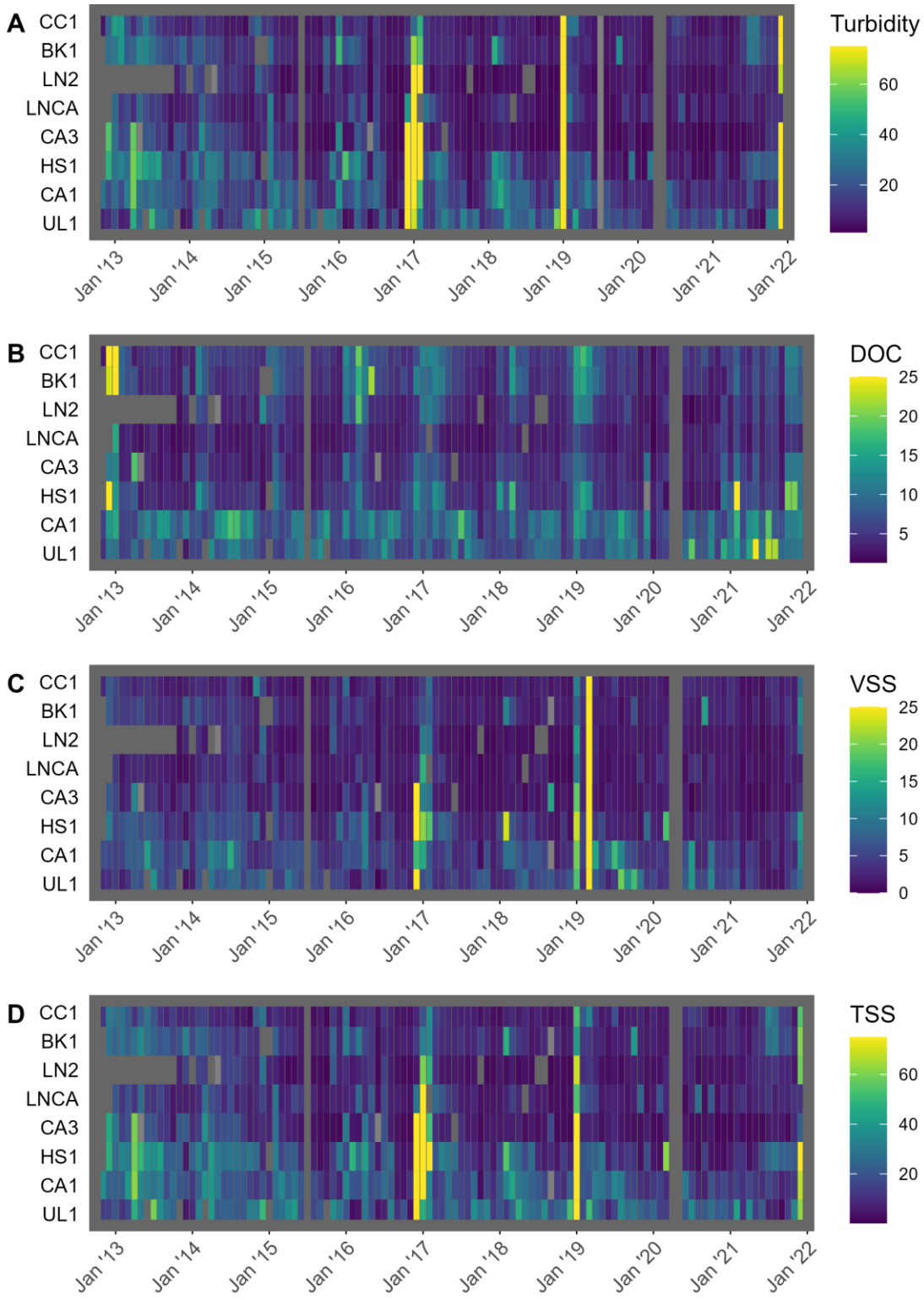

Figure 9. Indicators of suspended detritus or sediments. Monthly turbidity (NTU), dissolved organic carbon (DOC; mg/L), volatile suspended solids (VSS; mg/L), and total suspended solids (TSS; mg/L) at water-quality/zooplankton sites.

Phosphorus- All measurements showed similar seasonal and spatial patterns (Figure 10). Upstream Cache Network sites (UL1, CA1, and, to a lesser degree, HS1) had the highest phosphorus concentrations. Phosphorus was higher at Cache Network sites than Lindsey Network sites. Concentrations were highest during winter, following similar temporal patterns of suspended and dissolved materials. In 2021, phosphorous concentrations were very high at the beginning of the year at CA1 and UL1 and remained higher in the Cache Network than the Lindsey Network.

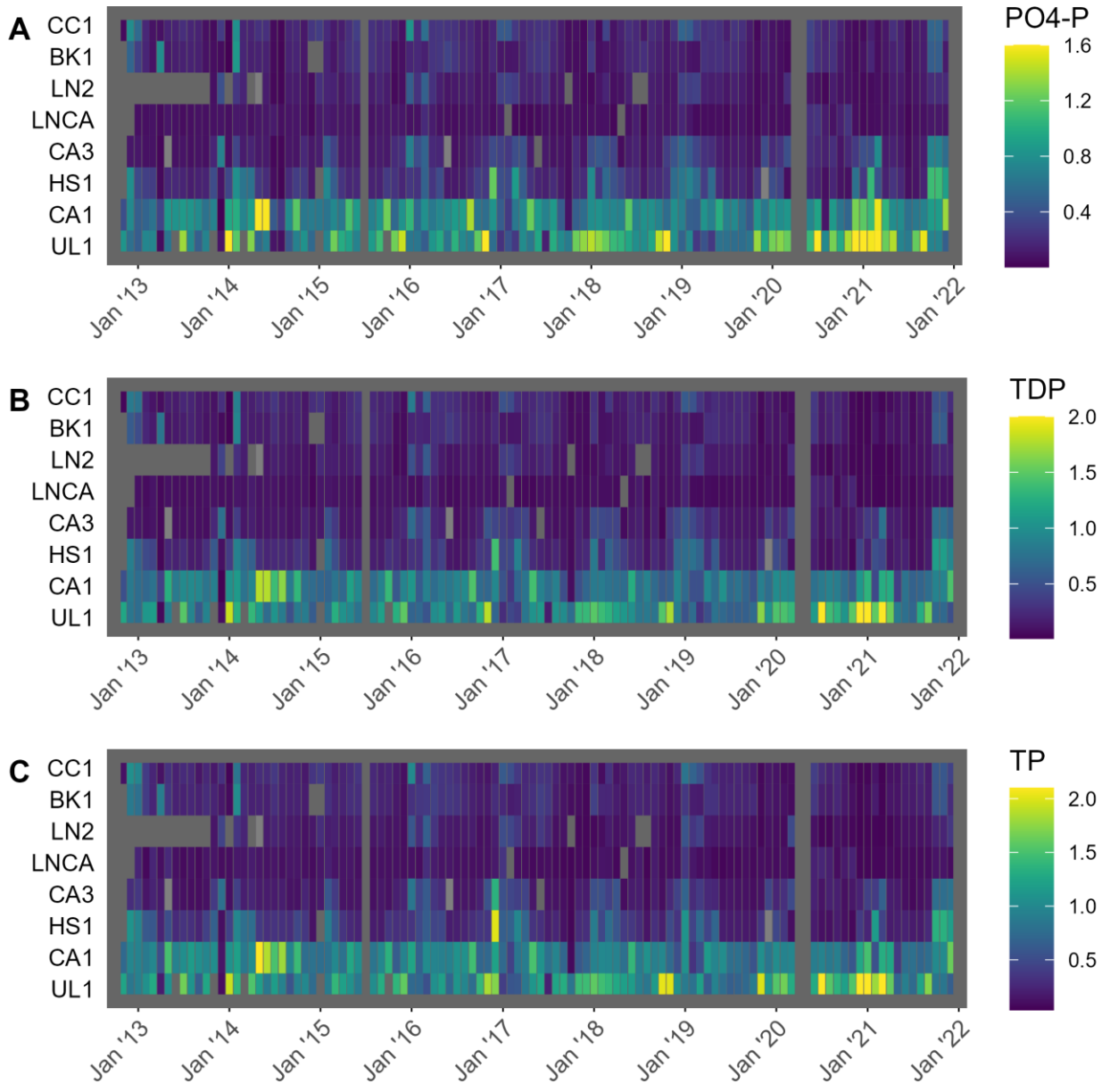

Figure 10. Monthly phosphorus as phosphate (PO_4), total dissolved phosphorous (TDP), and total phosphorous (TP), in mg/L, at water-quality/zooplankton sites.

Nitrogen- Relative patterns of nitrogen concentrations were similar for NO_3, TDN, and TN (Figure 11). Upstream sites in the Cache Network had the highest concentrations (UL1, CA1, and HS1, in descending order). Seasonal increases occurred during winter and spring across all sites. NH_4 did not follow as strong of seasonal patterns, and highest concentrations were found at the upstream CA1 site and the most downstream site, LNCA. The highest concentrations of nitrate, total dissolved nitrogen, and total nitrogen were measured from autumn through winter. The general trends were maintained in 2021, except for an anomalous spike in ammonium in the Cache Network at the end of the year and depressed concentrations at LNCA.

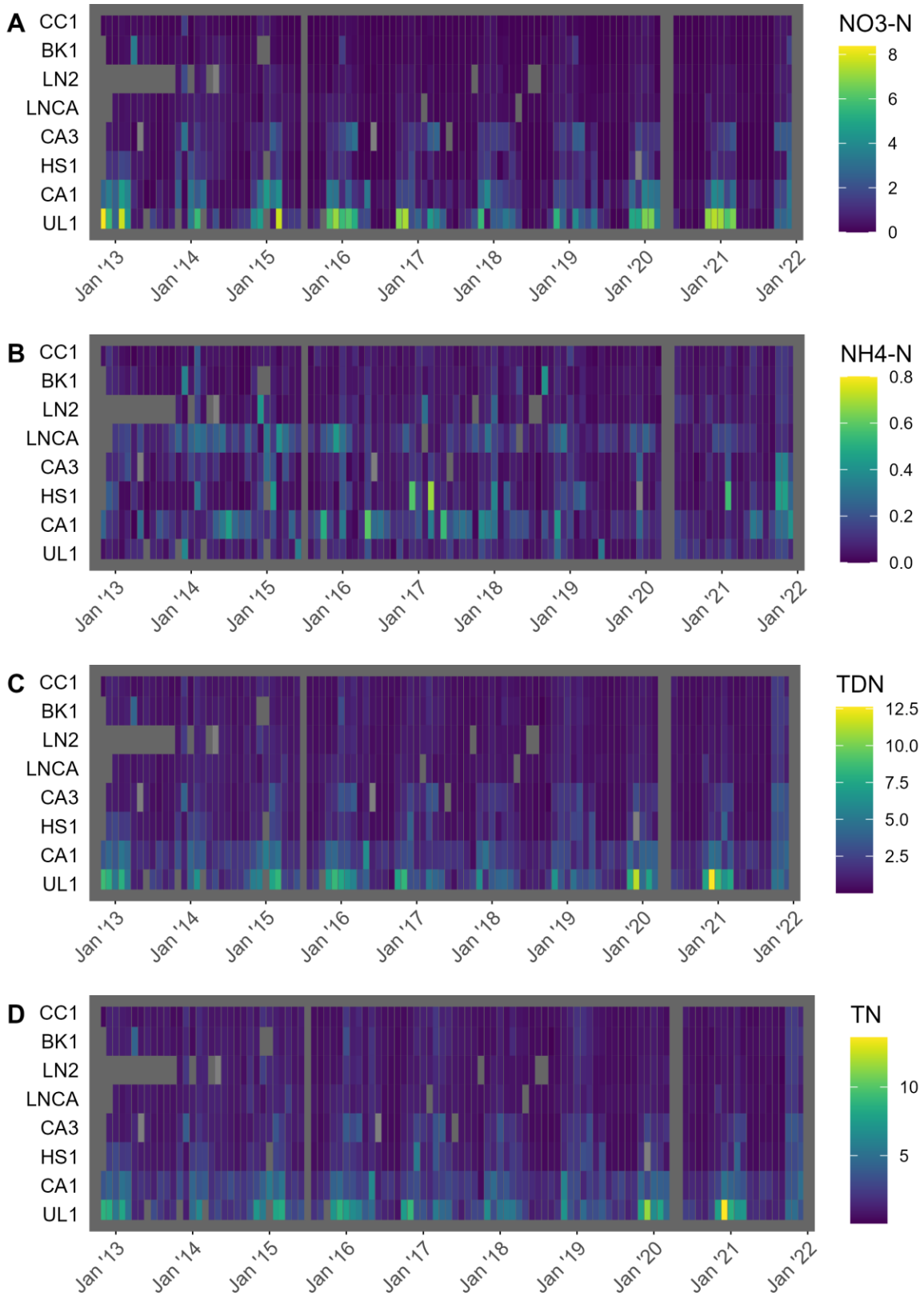

Figure 11. Monthly nitrogen as nitrate (NO_3), ammonium (NH_4), total dissolved nitrogen (TDN), and total nitrogen (TN), in mg/L, at water-quality/zooplankton sites.

Dissolved Inorganic Nitrogen to Phosphate Ratio (DIN:PO4)- All sites followed seasonal trends in the molar DIN to PO_4 ratio. In winter, primary producers at sites were generally phosphate-limited, as indicated by ratios above the Redfield ratio line. In summer, primary producers at sites were generally nitrogen-limited, as indicated by ratios below the Redfield ratio line (Figure 12). Locations of winter excess nitrogen levels varied among years. In 2021, all sites appeared nitrogen-limited with low DIN-to-PO_4 ratio and were generally below the Redfield ratio line.

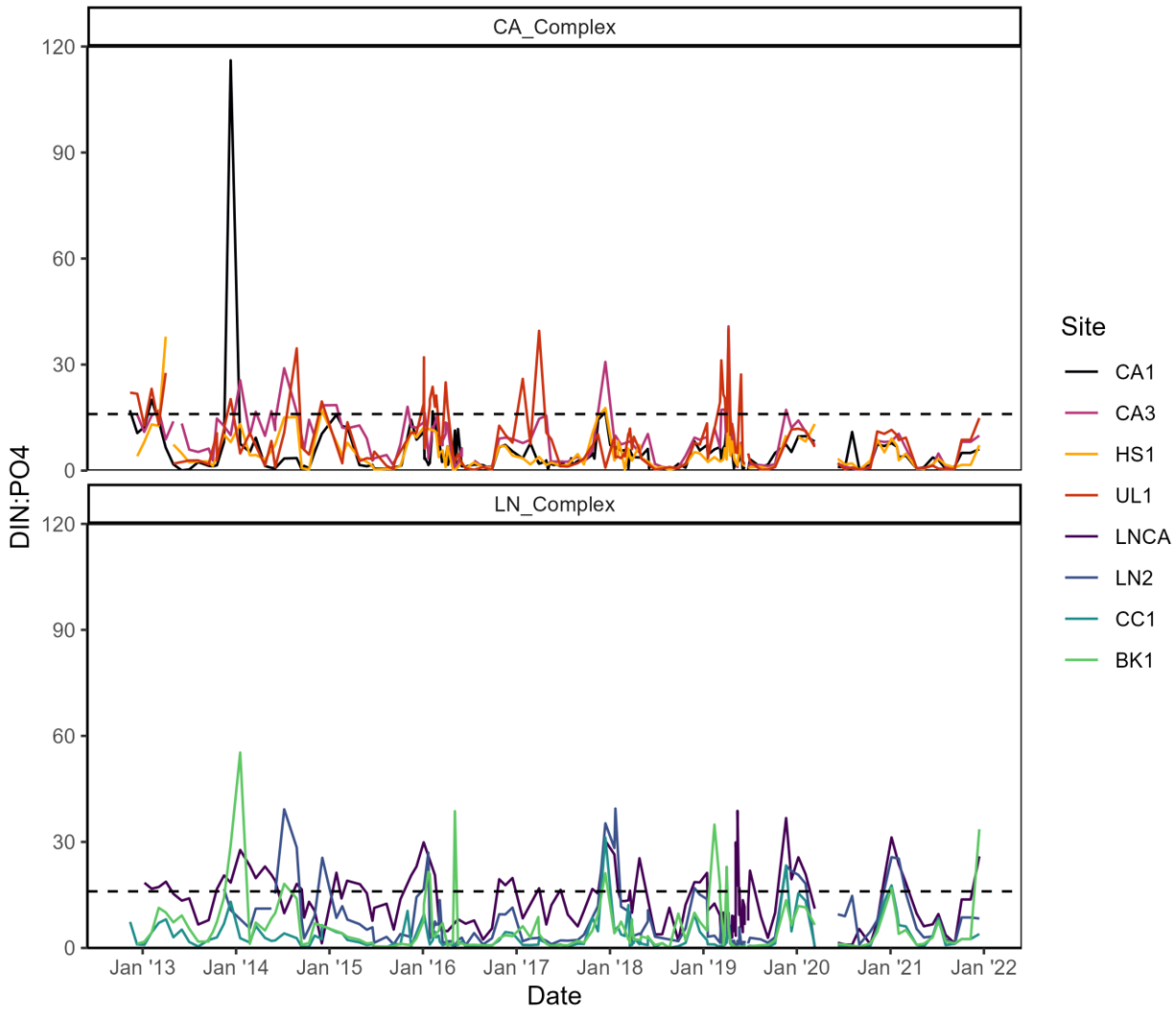

Figure 12. Ratio of dissolved inorganic nitrogen to phosphate (DIN:PO4) based upon monthly values at water-quality/zooplankton sites. The horizontal dashed line is the Redfield ratio (16:1), which is the ratio of nitrogen to phosphorus in phytoplankton – values above this line indicate phosphorus limitation and those below the line indicate nitrogen limitation for phytoplankton growth. Top panel (CA_Network) includes Cache Network sites and bottom panel (LN_Network) includes Lindsey Network sites.

Chlorophyll- Generally paralleling suspended-sediment and nutrient concentrations, both chlorophyll *a* and pheophytin *a* were highest in upstream sites of the Cache Network (CA1 and UL1, followed by HS1; Figure 13). Concentrations at the Cache-Lindsey confluence and in the Lindsey Network were consistently low, except for the occasional high value at BK1 and LN2. In 2021, we did not observe any very high chlorophyll-*a* (≥50 µg/L) or pheophytin-*a* (≥30 µg/L) concentrations.

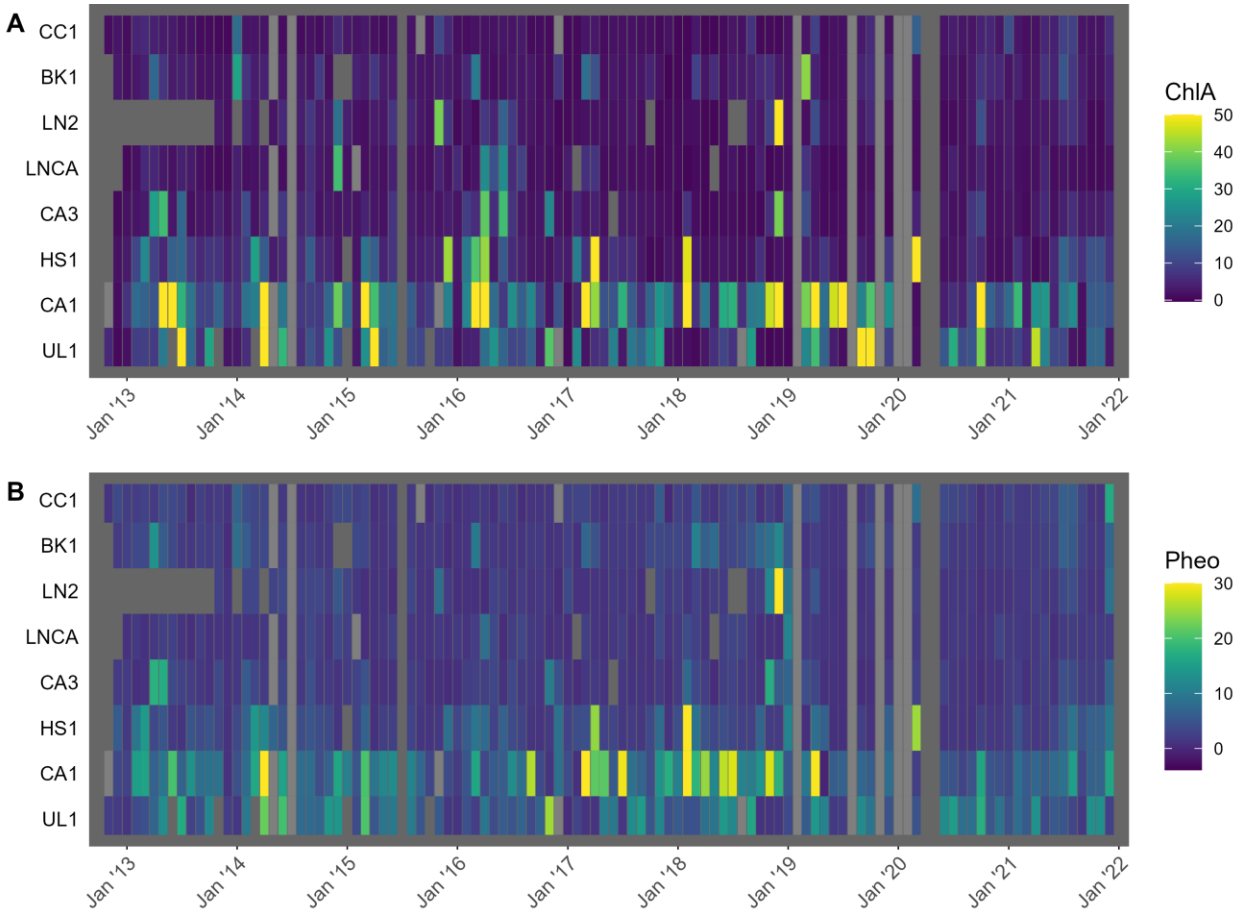

Figure 13. Monthly chlorophyll *a* (ChlA) and pheophytin *a* (Pheo), in micrograms per liter (µg/L), at water-quality/zooplankton sites.

Rates of Pelagic Metabolism – The greatest normalized rates of GPP and CR (more negative = higher CR) were measured from HS1 water – this shows that the planktonic community was most active in Hass Slough during several months. There was a notable increase in respiration at HS1 in April, indicating a large influx of carbon to that site from outside the system. In general, two of the Cache Network sites (UL1 and CA1) were net autotrophic, having a positive NCP, more often than the Lindsey Network sites (BK1 and CC1); however, early in the year all sites were net autotrophic (Figure 14). Hass Slough tended to be net heterotrophic, despite high levels of GPP, likely because of detrital material increasing respiration rates.

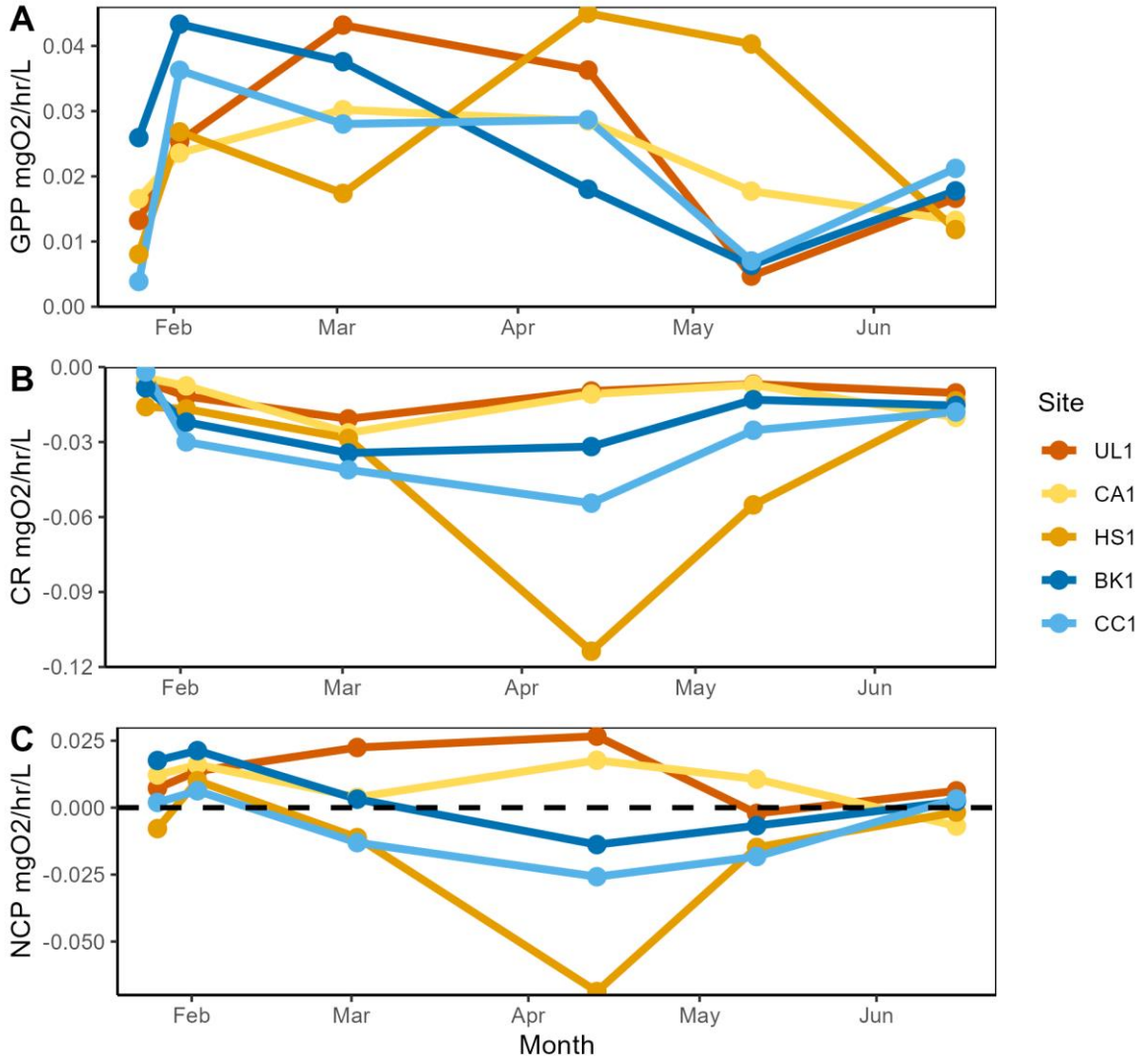

Figure 14. Ecosystem metabolism during spring 2019 and 2020. Chlorophyll-*a* normalized rate of change in DO concentrations from gross primary production (GPP; plot A), community respiration (CR; plot B), and net community production (NCP; plot C) calculated from six bottle incubations from January to June 2021. Values above the dashed line in plot C (NCP) indicate an autotrophic pelagic community and those below the line indicate a heterotrophic pelagic community.

Zooplankton

Temporal Trends

Overall, springtime zooplankton densities in dead-end slough sites declined throughout the nine years of study. Zooplankton densities were consistent from 2014-2016 and began to decline after 2017. Since then, densities have remained low (Figure 15).

Monthly trends had noticeable differences between years with low and high Delta outflow (Figure 16). Peak zooplankton densities tended to occur in April during drier years (2014, 2018, and 2021), while higher densities occurred in May during wetter years 2017 and 2019. One exception was 2016, a moderate flow year with high flows in March, resulting in similar trends to wet years, with lower densities in March and April, followed by higher densities in May.

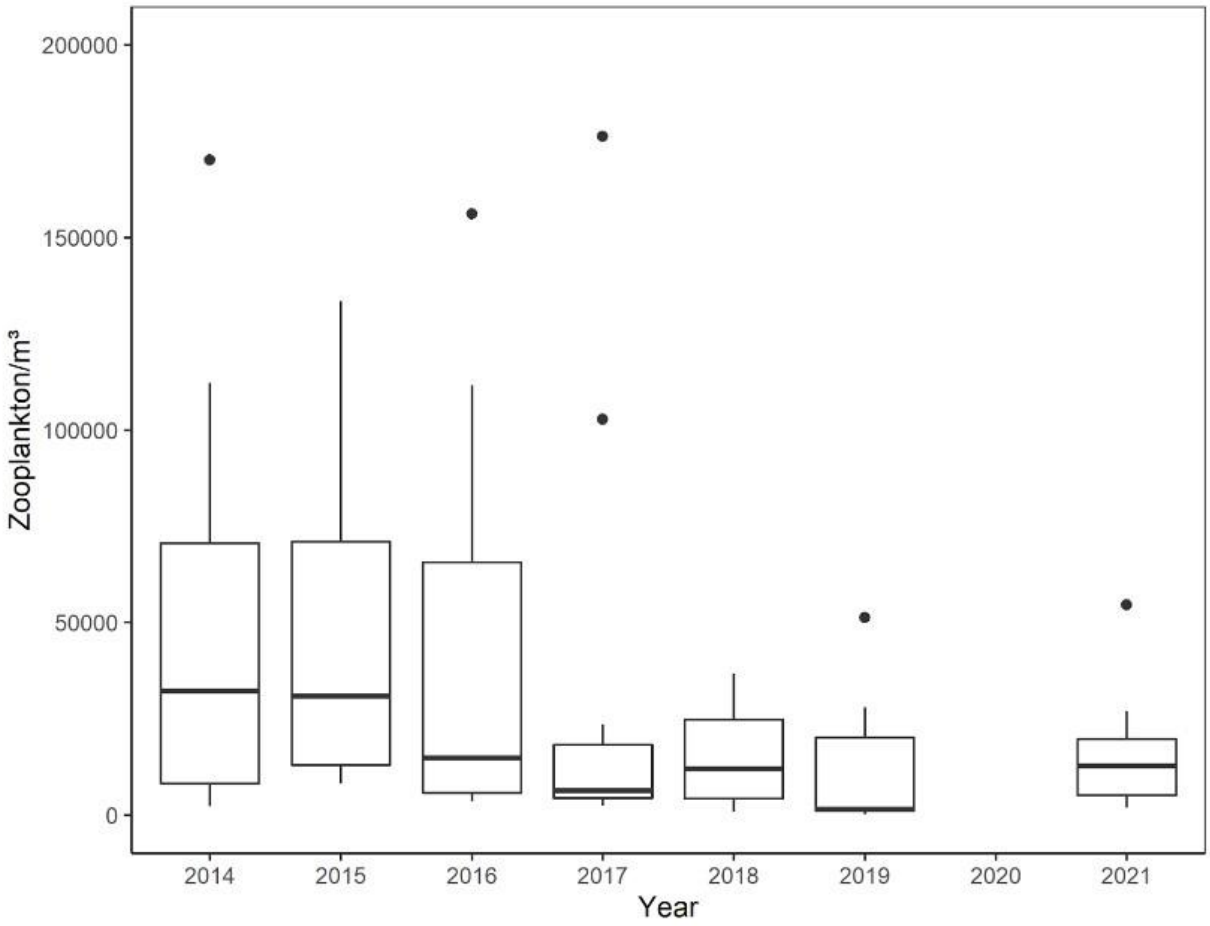

Figure 15. Mean springtime zooplankton densities from 2014 to 2021. Zooplankton densities consist of Calanoida, Cyclopoida, and Cladocera. Outlier omitted from 2016 with value of 522,783 individuals/m^3. Boxes represent the interquartile range with the bar as the median. Lines show the minimum and maximum values, and dots represent outliers.

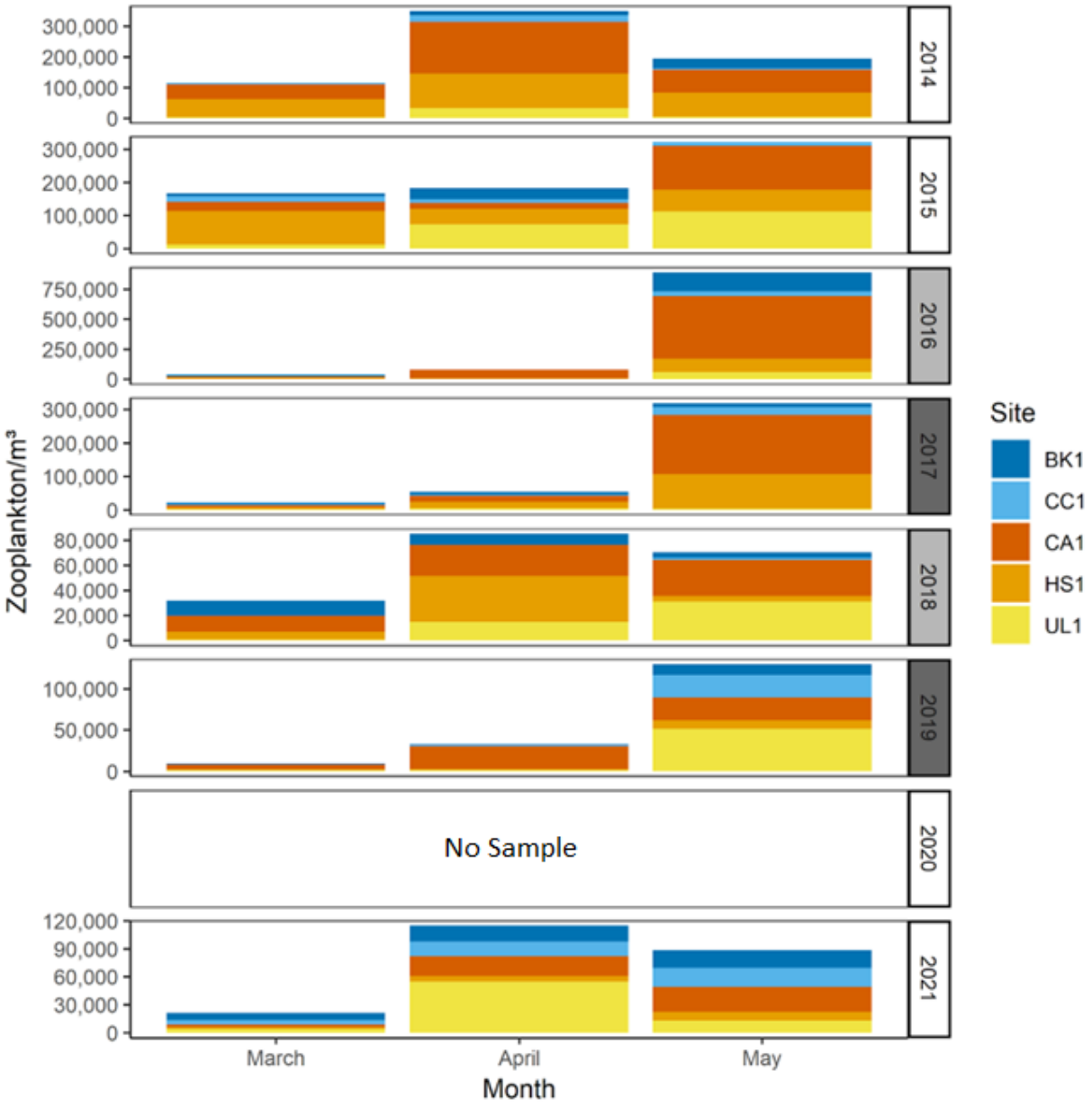

Figure 16. **Comparison of total spring zooplankton densities across sites.** Note the y-axis for each plot is different. Blue hues are a part of the Lindsey Network and orange/yellow hues are for the Cache Network. Color of year label indicates Delta outflow condition: white= dry, light gray=moderate, dark gray=wet.

Spatial Trends

The Cache Network supported higher overall zooplankton densities than Lindsey in almost every year and month (Figure 16 and 17). The Cache Network contributed over 50% of zooplankton density for each sample date across 2013-2021 (Figure 18). The only years the Lindsey Network contributed more to density were 2013 and 2021. In 2013, data were missing from UL1 and HS1, skewing the percentages (Table 1). CA1 and HS1 typically contributed the most to zooplankton densities; however, in recent years, UL1 has contributed more than HS1. CC1 contributed the least across all sites within both

complexes. Within the Lindsey Network sites, BK1 typically contributed more to densities than CC1, except for the latter part of spring in 2019.

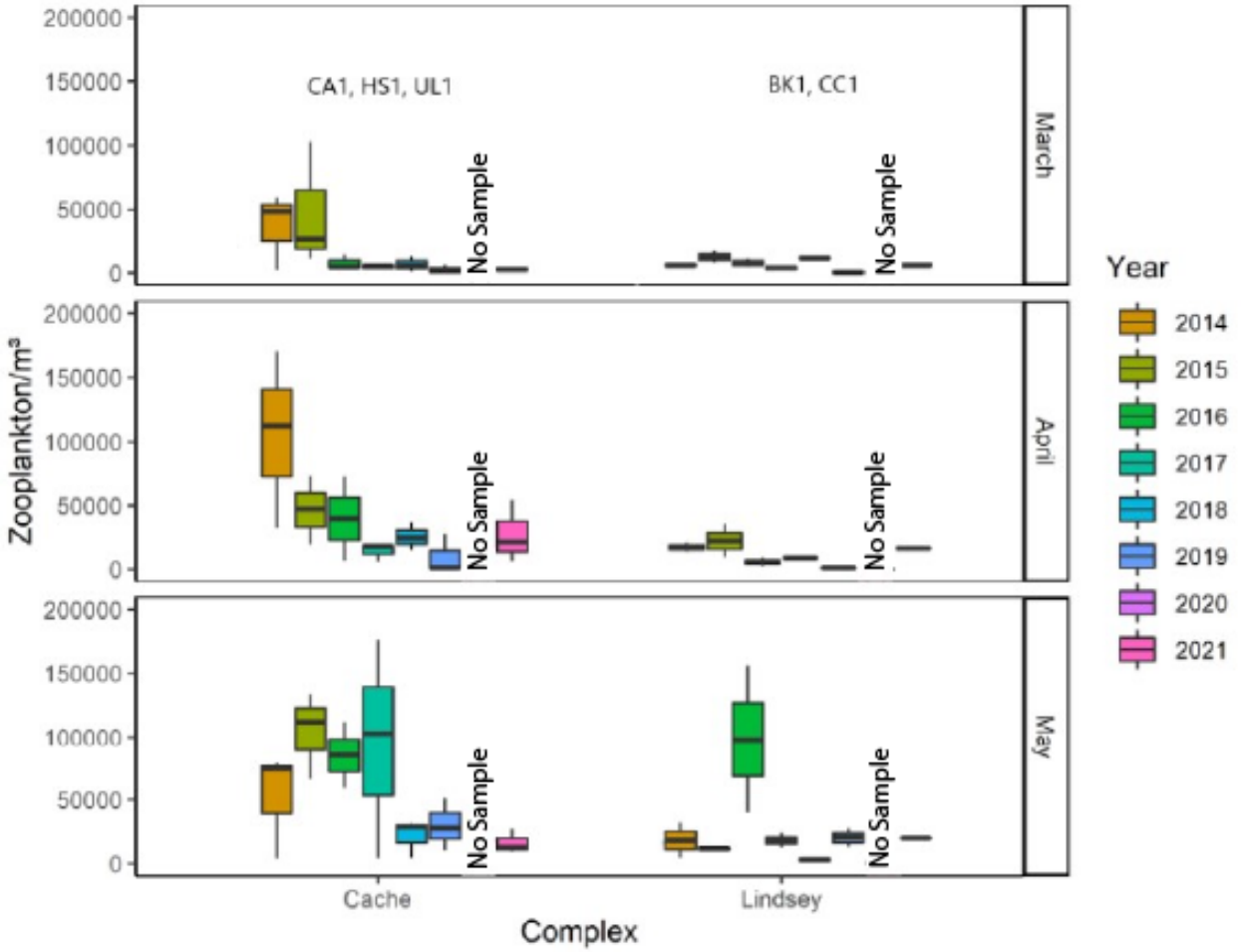

Figure 17. Comparison of mean total zooplankton densities across complexes during spring from 2014-2021. Cache complex includes HS1, UL1, CA1. Lindsey complex includes CC1 and BK1. Boxes represent the interquartile range with the bar as the median. Whiskers show the minimum and maximum values.

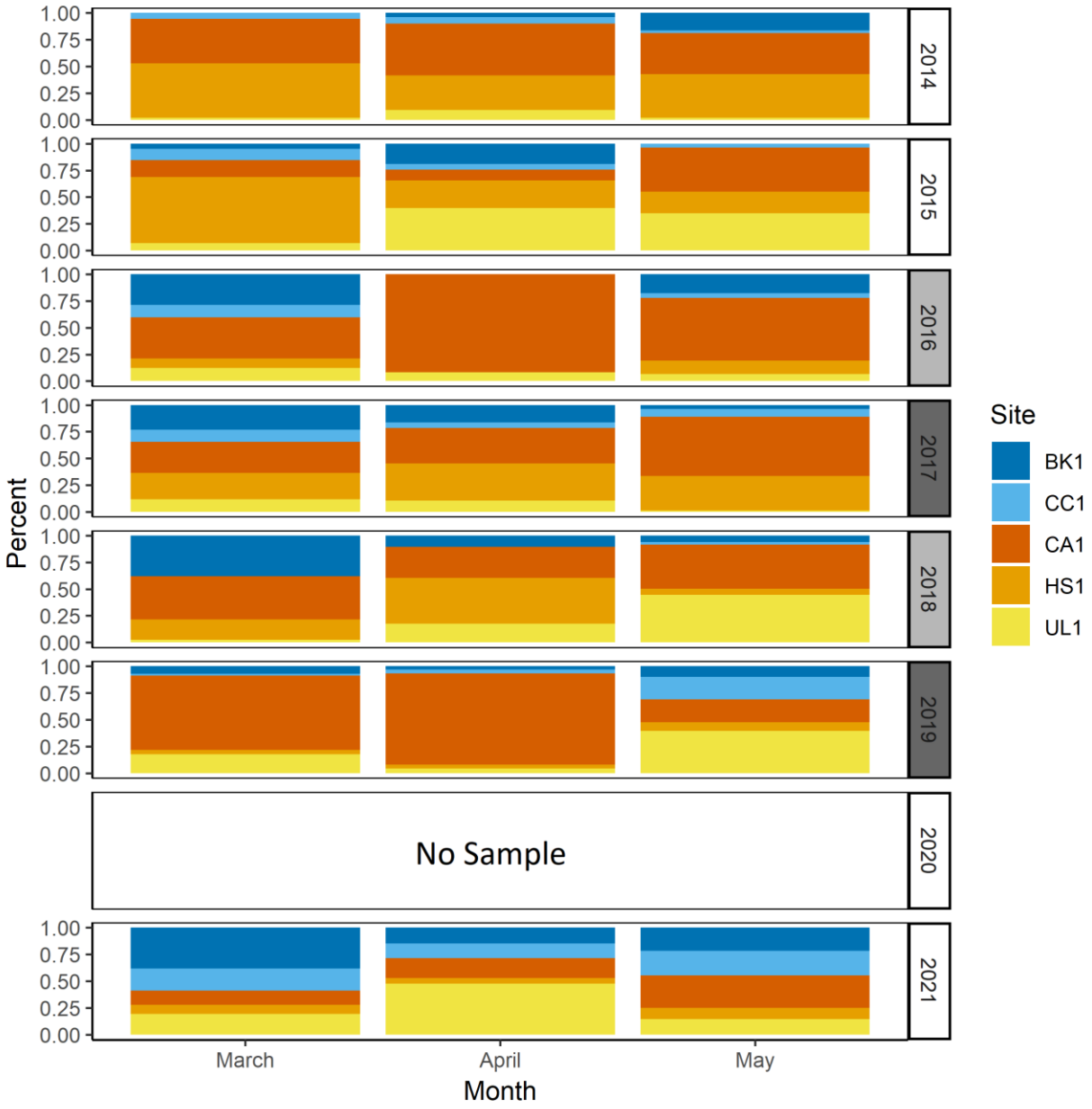

Figure 18. Percent contributions of spring zooplankton density from each site. Blue hues are a part of the Lindsey Network and orange/yellow hues are for the Cache Network. Color of year label indicates Delta outflow condition: red=white, yellow=light gray, blue=dark gray.

Fish and Aquatic Vegetation

Aquatic Vegetation

Aquatic vegetation captured in otter trawls increased throughout the study until 2021 (Figure 19). Most samples were dominated by the invasive Brazilian waterweed (*Egeria densa*). The largest volumes previously occurred at CC1 until 2018 when BK1 and CA3 were heavily colonized, then another shift occurred in 2020 when dense beds of Brazilian waterweed formed at HS1. Substantial increases occurred at BK1, CA1, CA2, CA3, and HS1 over the study period. Several sites had little to no aquatic vegetation at the onset of the study, including all of the Cache Network, but all contained some by 2018. In 2021, vegetation decreased at nearly every site – the most precipitous decline occurred in August, and the amount of vegetation in the trawls remained low through December.

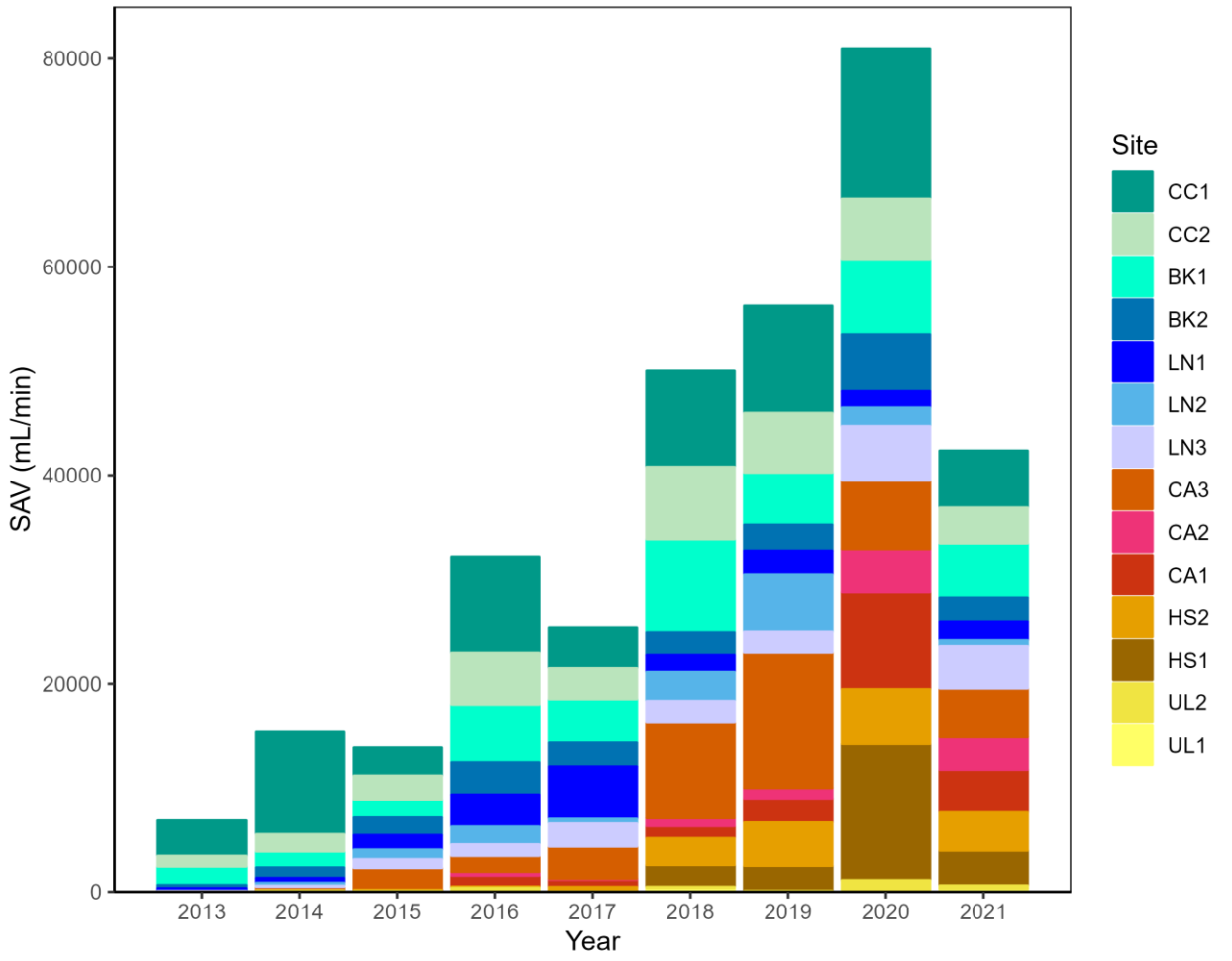

Figure 19. Annual CPUE of submersed aquatic vegetation (SAV) (mL/minute) retrieved in otter trawls at different sites from 2013-2021.

Fish Assemblage

Temporal patterns

Native fishes were typically most abundant during spring in both otter-trawl and electrofishing catches, but diminished in abundance overall since the start of the study. Non-native fish proportion increased in otter trawls from 2012 to 2014, plateauing until 2019 (Figure 20). Non-native fish proportion was variable in electrofishing catch, with a peak in 2016 and 2017. In 2021, a relatively high proportion of native fishes persisted through most the year (Figure 20 and 21). Three native species – hitch, prickly sculpin, and tule perch – made a resurgence in 2021, with the highest otter-trawl CPUE for a given month for each species (hitch and prickly sculpin in July, tule perch in November; Figure 22), and high catches of hitch and prickly sculpin in both spring and autumn electrofishing in 2021 (Figure 23).

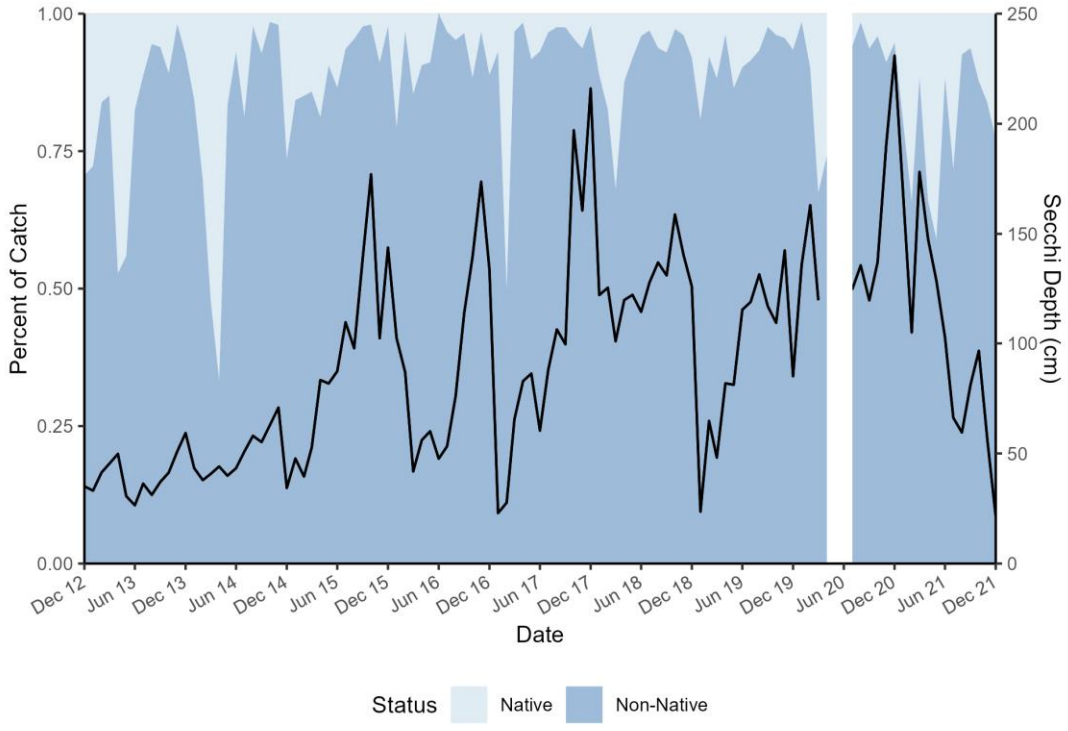

Figure 20. Percent of CPUE of fishes by native or non-native status from otter trawls. Secchi depth, a measure of water clarity, is represented by the black line.

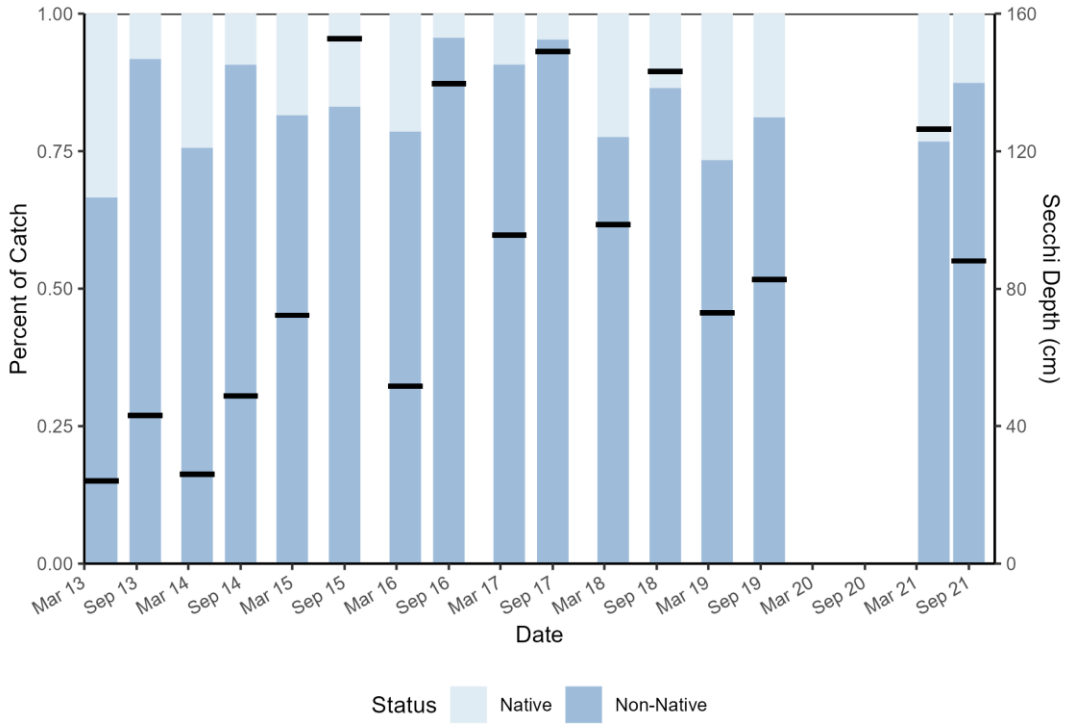

Figure 21. Percent of CPUE of fishes by native or non-native status from electrofishing. Mean Secchi depth, a measure of water clarity, is represented by the horizontal black lines.

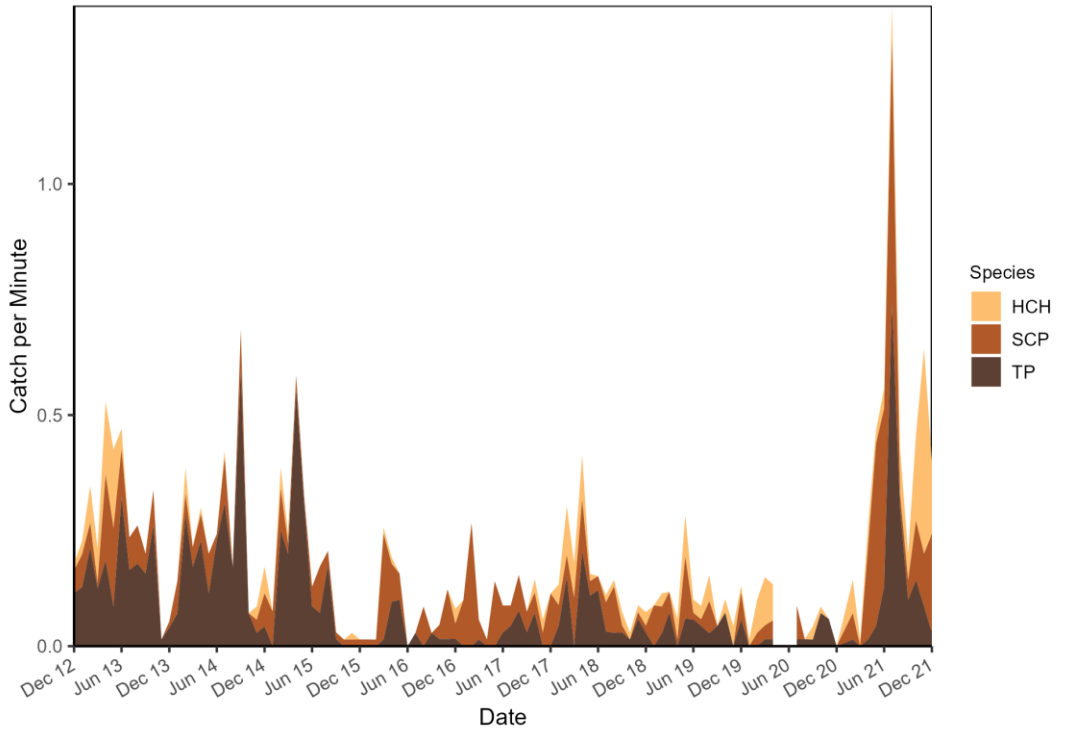

Figure 22. Monthly catch per minute of hitch (HCH), prickly sculpin (SCP), and tule perch (TP) from otter-trawling.

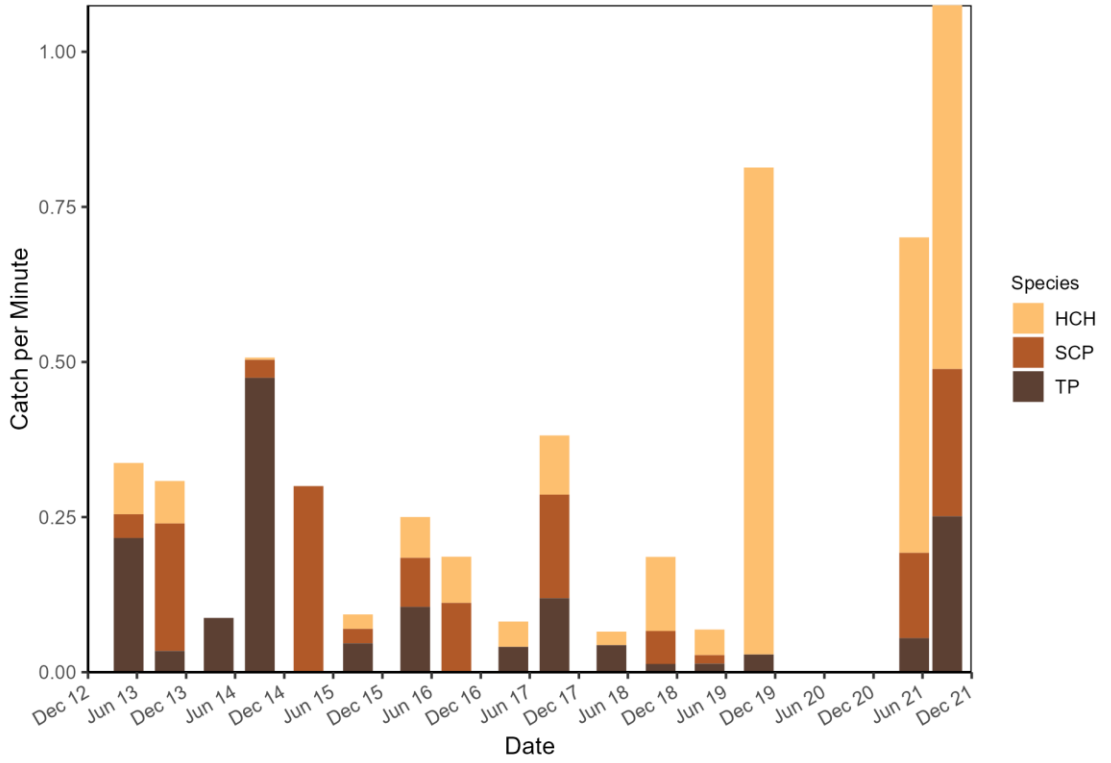

Figure 23. Monthly catch per minute of hitch (HCH), prickly sculpin (SCP), and tule perch (TP) from electrofishing.

Both otter-trawl and electrofishing CPUE in the CLC was dominated by pelagic and littoral fishes (Figure 24 and 25), with the littoral group generally having increased over the study period. Otter-trawl CPUE underwent seasonal shifts, with fish generally being least abundant during winter. Abundances of the habitat-associated groups were somewhat seasonal, with littoral fishes typically dominating otter-trawl catches in spring and pelagic fishes dominating otherwise (Figure 26). Littoral-associated species seasonally dominated otter-trawl CPUE for the duration of the study, with year-round elevated CPUE in 2018 and 2019, and dominated all electrofishing samples (Figure 26 and 27).

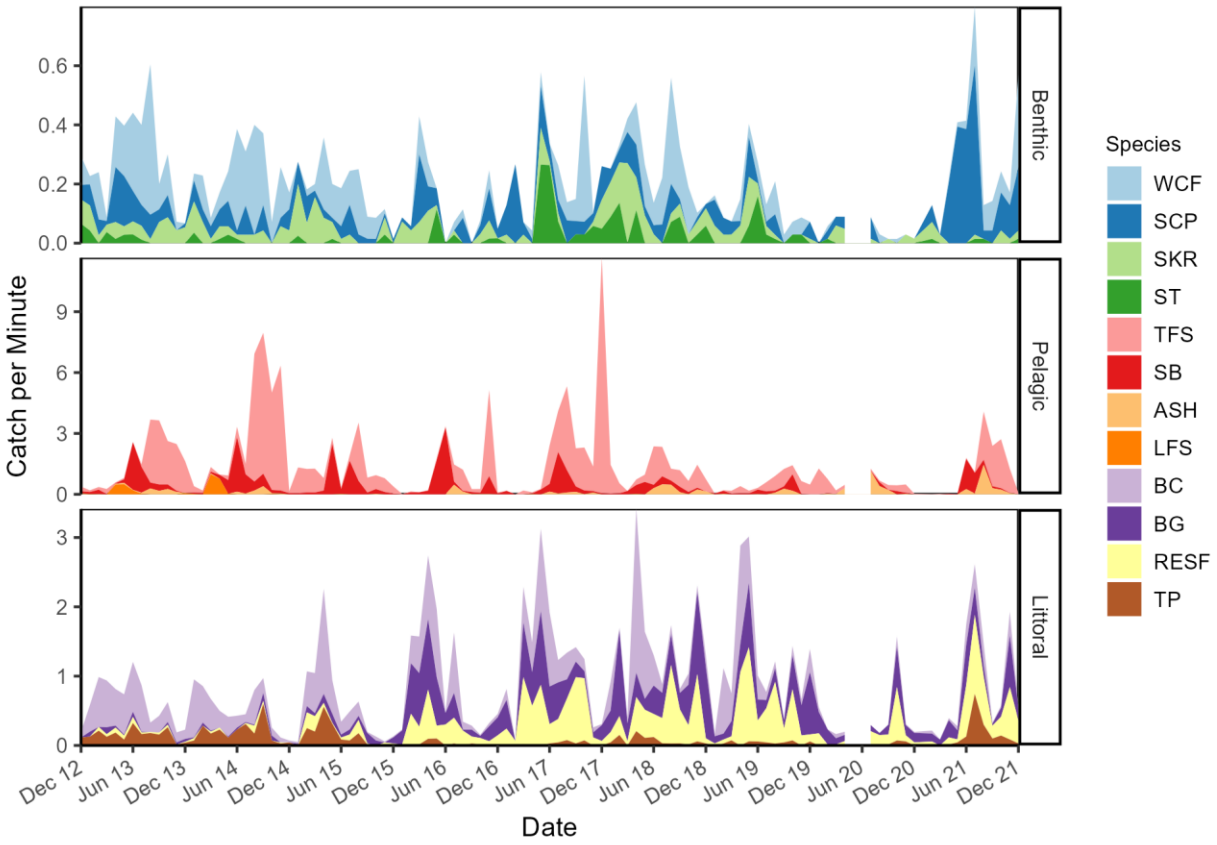

Figure 24. Monthly catch per minute of fishes from otter trawls separated by habitat association (benthic, pelagic, and littoral species). Included are the four most abundant species in otter trawl catch for each habitat-association grouping over the survey period (2013-2021). No data were collected between April and June of 2020 due to shutdowns as a result of the COVID-19 pandemic. Note differences in scale along the Y-axes.

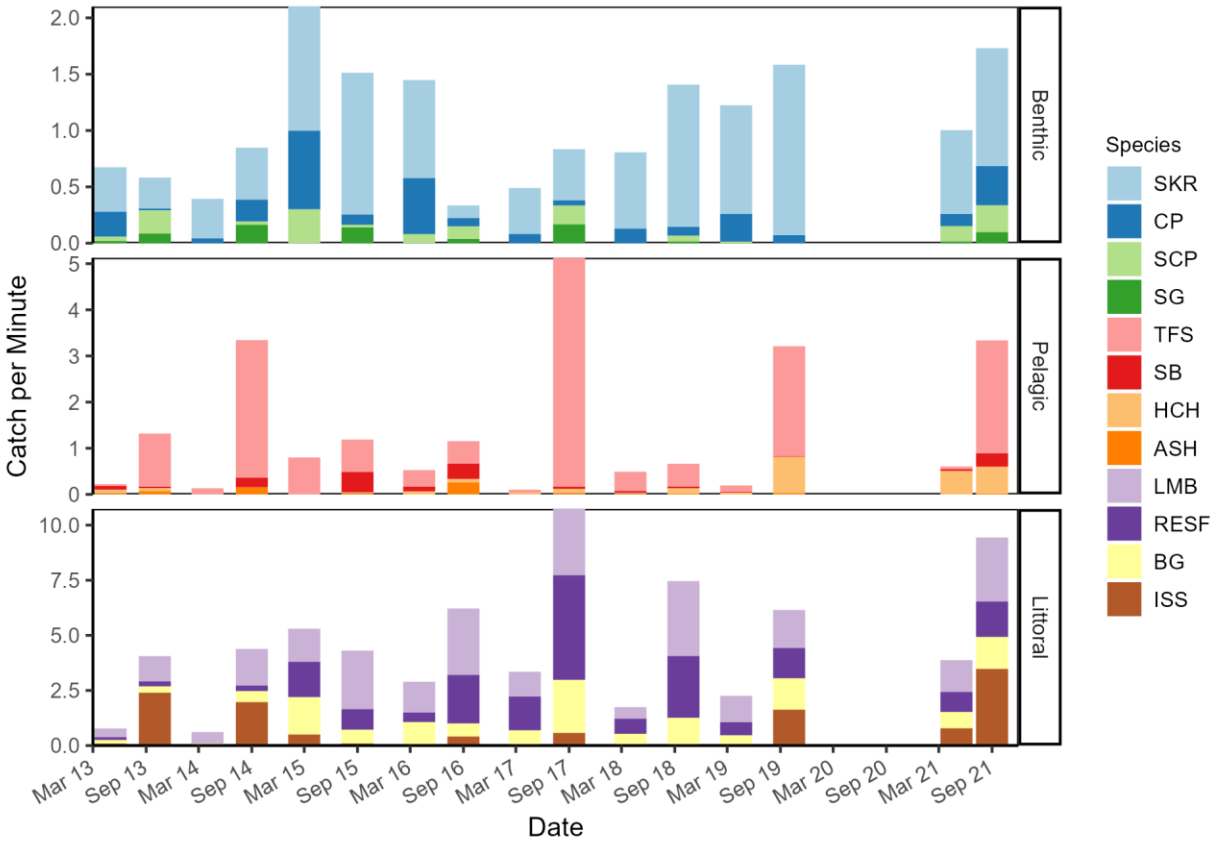

Figure 25. Monthly catch per minute of fishes from spring and autumn electrofishing separated by habitat association (benthic, pelagic, and littoral species). Included are the four most abundant species in electrofishing catch for each habitat association grouping over the survey period (2013-2021). Note differences in scale along the y-axes.

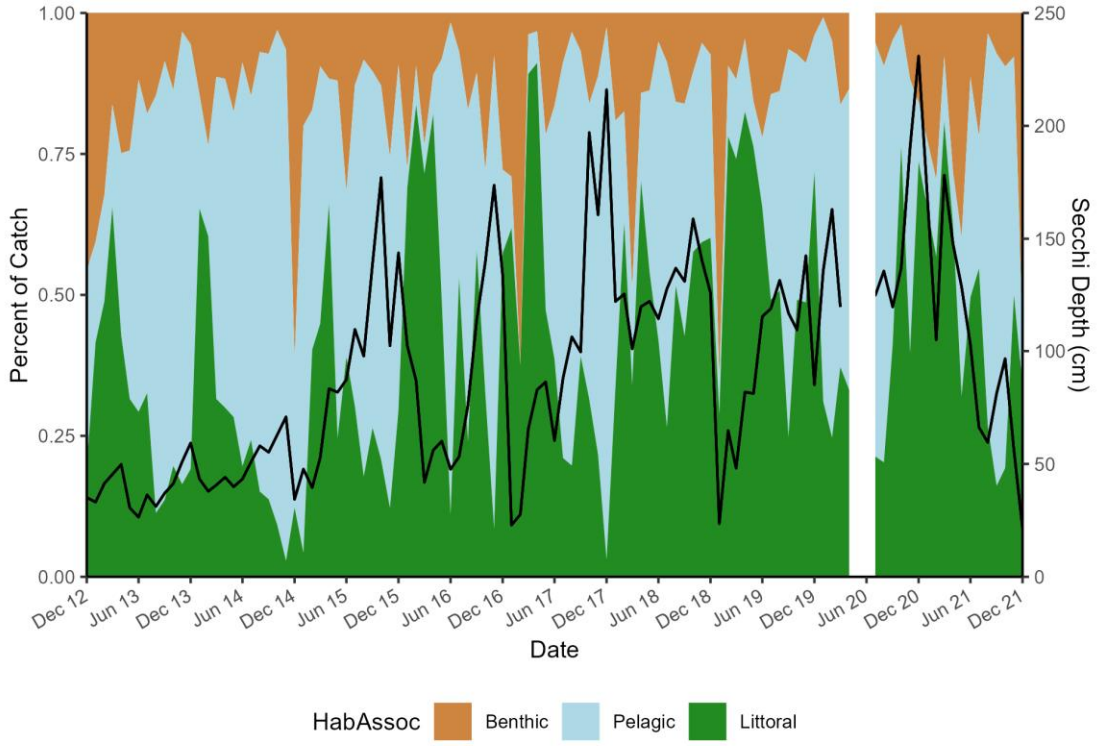

Figure 26. Percent of CPUE of fishes by habitat association from otter trawls. Secchi depth, a measure of water clarity, is represented by the black line.

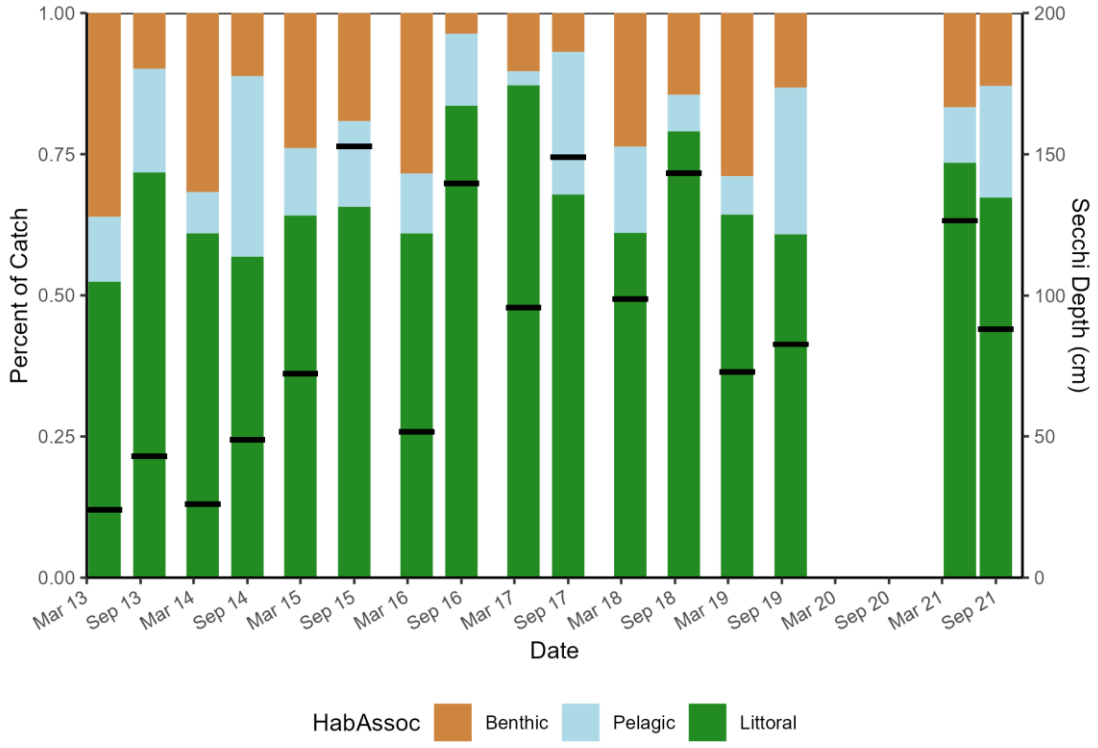

Figure 27. Percent of CPUE of fishes by habitat association from spring and autumn electrofishing. Secchi depth, a measure of water clarity, is represented by the horizontal black lines.

The benthic-associated group was comprised mostly of Sacramento sucker (SKR), which has varied in abundance and remained relatively high since 2018 in electrofishing catch; white catfish (WCF), which has generally declined in abundance; and prickly sculpin (SCP), which has varied in abundance in otter trawls (Figures 24 and 25). Native Sacramento splittail abundance peaked in 2017, remained relatively high for several years, and virtually disappeared from otter trawls since 2019. Benthic species often accounted for the highest proportion of total catch in winter and their relative proportion has remained fairly stable throughout the study (Figures 26 and 27).

The pelagic-associated group was dominated by threadfin shad (Figures 24 and 25), with peak numbers occurring in late summer and early autumn. Also seasonally abundant were striped bass, which appeared mostly in early summer as juveniles. Both striped bass and threadfin shad remained seasonally abundant throughout the study but declined in catch after 2017. Listed Delta smelt and longfin smelt numbers, while never high, were negligible after 2014. 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 spring 2014 and none after April 2018.

Non-native sunfishes increased across the study period (Figures 24 and 25). Representing a relatively small fraction of the CPUE in 2012-13, they came to dominate catches by 2015 and continued increasing in abundance thereafter. Comparing the otter-trawl CPUE of the most abundant sunfishes, bluegill (BG) and redear sunfish (RESF), with the ecologically similar native tule perch (Figures 24 and 25), 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 sunfishes. Electrofishing showed similar trends but captured many more largemouth bass as a proportion of the overall CPUE.

Wet years and decreased water clarity often correspond to increased fish numbers in the estuary, particularly for natives (O'Rear *et al.* 2021). Although high flows and slightly decreased water clarity both occurred in 2019, fish abundance in the CLC did not increase notably. Also, the proportion of native to non-native species remained low in otter-trawl catch through the wet year of 2019, with an increase in the dry year of 2021. Changes in habitat association in the CLC have not changed as expected with water-year type.

Spatial Differences

Spatial differences in catch were pronounced between the Cache and Lindsey networks (Figures 28 and 29). Natives made up a higher proportion of the otter-trawl CPUE at CA3, CC1, and CC2 (Figure 30), and a higher proportion of the electrofishing CPUE in all Cache Network sites than in the Lindsey Network sites (Figure 31). Sacramento sucker and tule perch were the two most-abundant native species in both otter-trawl and electrofishing samples. Sacramento suckers were more commonly caught in Cache Network sites, while tule perch tended to be well-distributed across all sites. Hitch were most abundant in Cache Network sites in otter-trawl sampling but most abundant in Lindsey Network sites with electrofishing. Threadfin shad were the most abundant non-native species in the Cache complex, while sunfish species were most abundant in the Lindsey Network.

Benthic species did not vary much between the networks in otter trawls but were much more abundant in the Cache Network in electrofishing catch (Figures 32 and 33). Sacramento suckers, white catfish, common carp (CP), and Sacramento splittail were more abundant in the Cache Network, while prickly sculpins were the more abundant benthic fish in the Lindsey Network (Figures 28 and 29).

Pelagic species were more abundant in the Cache Network than in the Lindsey Network (Figures 30 and 31). For both networks threadfin shad and striped bass were the most abundant pelagic species in both otter-trawl and electrofishing catches.

Sunfishes made up a majority of the littoral CPUE in otter-trawl and electrofishing samples (Figures 28 and 29). Black crappie were the most abundant littoral fish caught with otter trawls in the Cache Network and Barker Slough, with redear sunfish or bluegill being the dominant littoral species in other Lindsey Network sites. Largemouth bass were the dominant littoral species in electrofishing catch, and largemouth bass and redear sunfish were more abundant in Lindsey Slough sites. Bluegill appeared to be somewhat evenly distributed across all sites and both gear types.

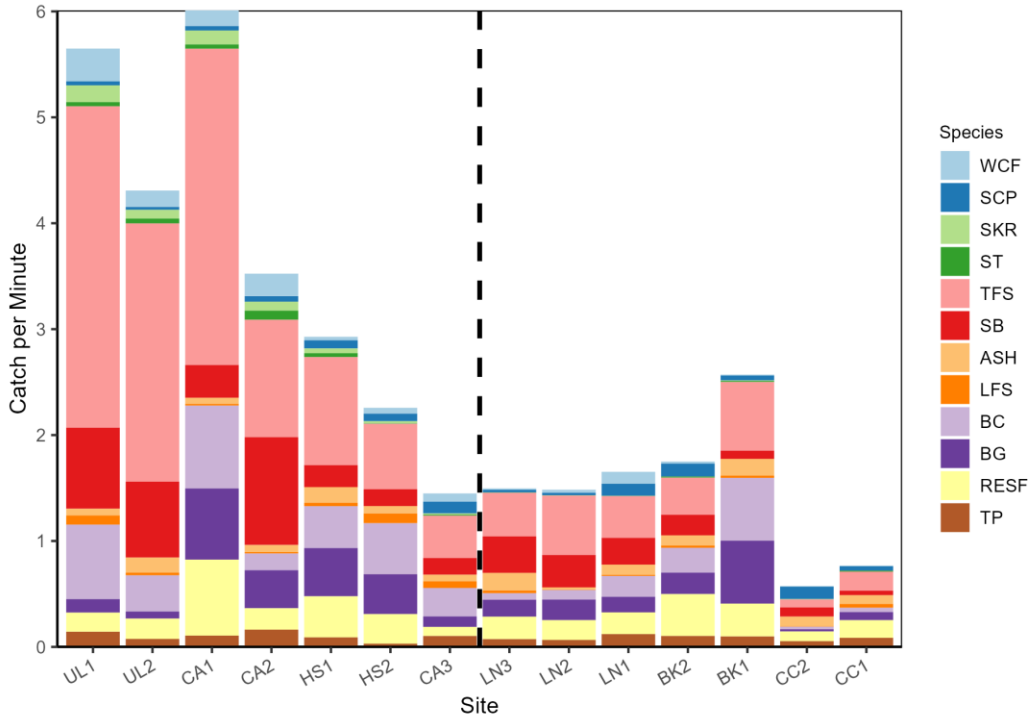

Figure 28. Catch per minute of fish species by site from otter trawls. Included are the four most abundant species in otter trawl catch for each habitat association grouping (benthic, pelagic, littoral) over the survey period (2013-2021). Dashed vertical line separates Cache and Lindsey networks.

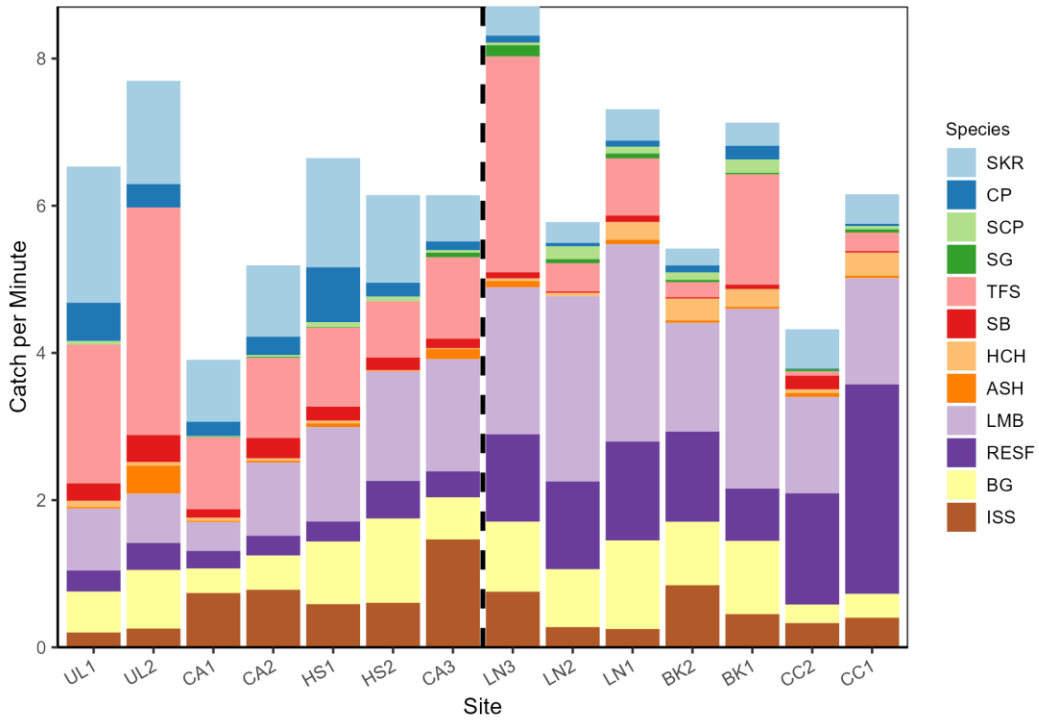

Figure 29. Catch per minute of fish species by site from electrofishing. Included are the four most abundant species in electrofishing catch for each habitat association grouping (benthic, pelagic, littoral) over the survey period (2013-2021). Dashed vertical line separates Cache and Lindsey networks.

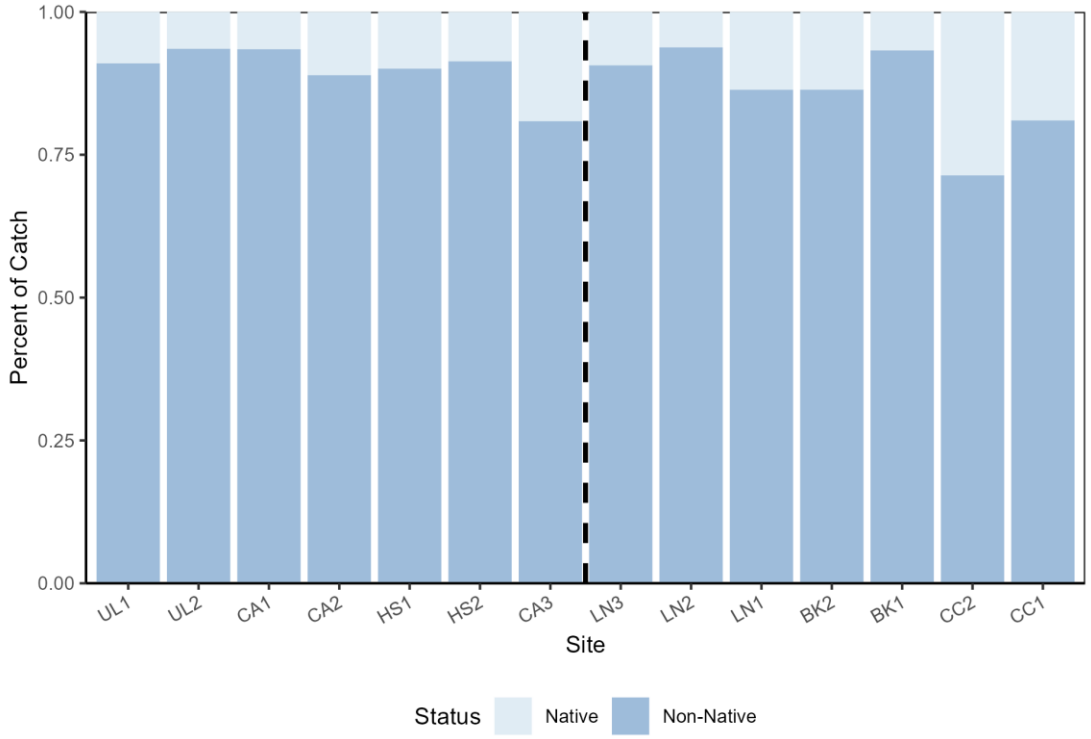

Figure 30. Percent of CPUE of fish species by native/non-native status across sites from otter trawl.

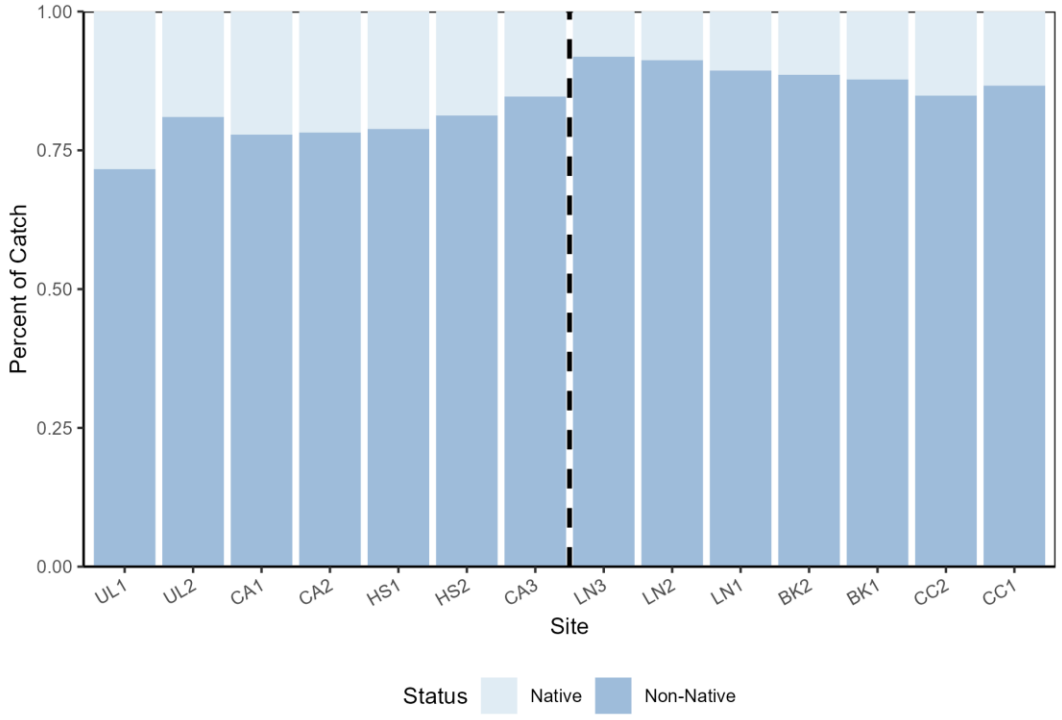

Figure 31. Percent of CPUE of fish species by native/non-native status across sites from electrofishing.

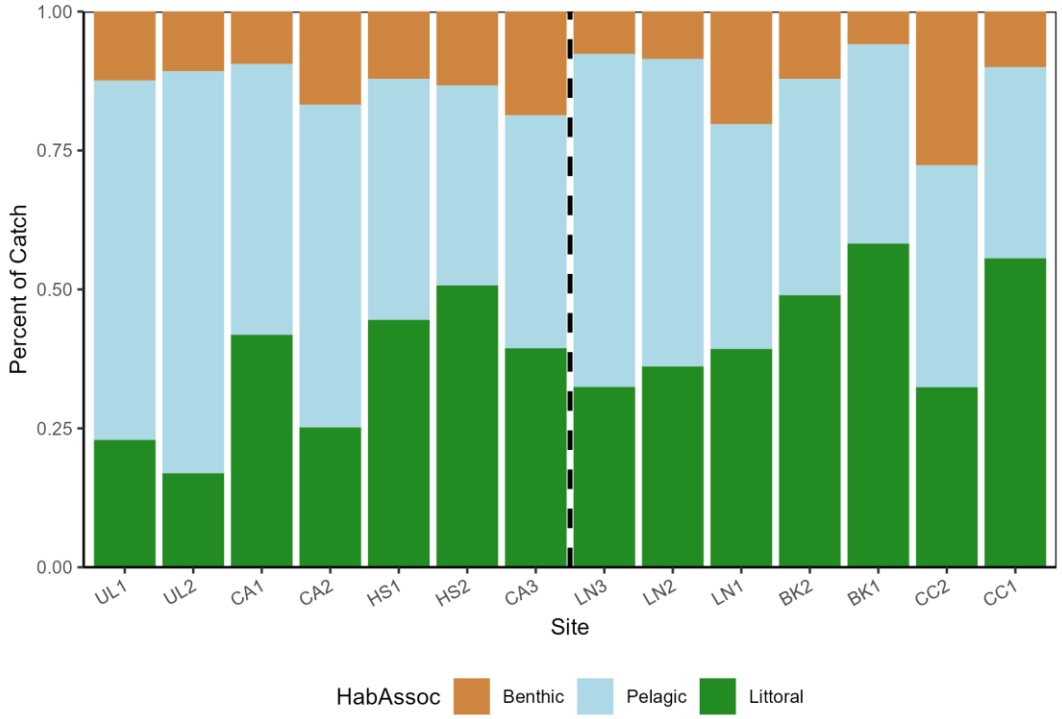

Figure 32. Percent of CPUE of fish species by habitat association (benthic, pelagic, littoral) across sites from otter trawls.

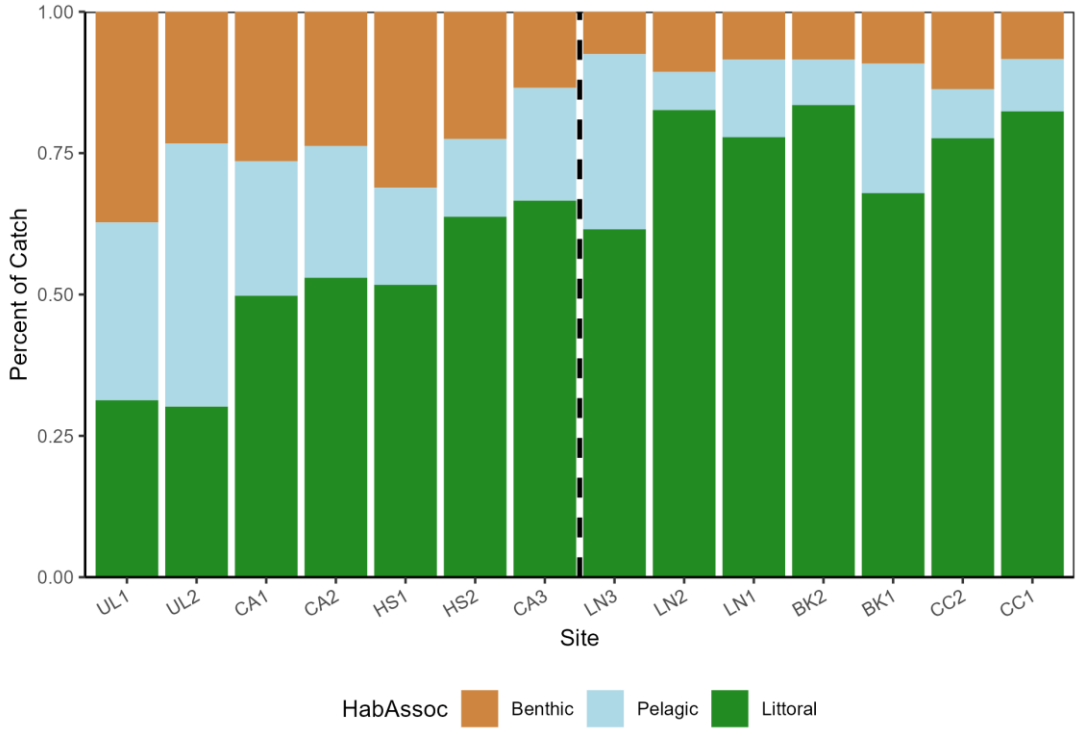

Figure 33. Percent of CPUE of fish species by habitat association (benthic, pelagic, littoral) across sites from electrofishing.

Restoration Comparison

The North Liberty Island Mitigation Bank restoration site had steadily increasing autumn electrofishing CPUE until 2019, while spring CPUE increased to a peak in 2018 then steadily declined – this pattern was similar to surrounding sites, except adjacent sites had more pronounced peaks in autumn in wet years (2017 and 2019; Figure 34). September 2021 had the highest proportion of native fishes in NLIMB, which was driven by hitch abundance. The Lindsey restoration generally had lower catches than surrounding waterways, but a similar proportion of native fishes. In 2021, the Lindsey restoration had a higher-than-average electrofishing CPUE.

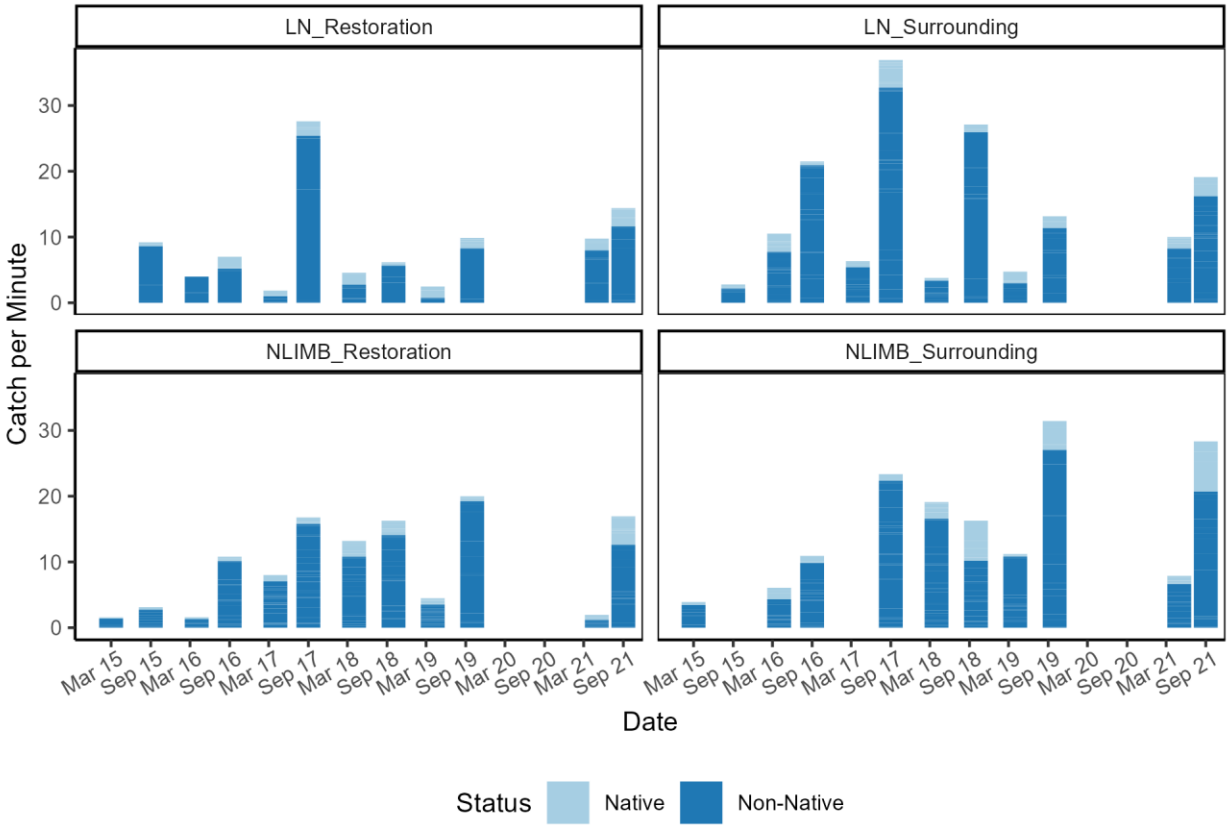

Figure 34. Percent of CPUE of fish species by native/non-native status across sites from electrofishing in restoration and restoration-adjacent sites (CC1 and CC2 for Lindsey Restoration; SS1 and PR1 for NLIMB).

Discussion

From 2012 - 2021, the CLC was subject to drought, record floods, experimental water releases from the Yolo Bypass, and tidal restoration. Our study captured a suite of responses to these dynamic

conditions, with the most profound being the proliferation of aquatic weeds. During the 2012-16 drought, aquatic weeds expanded concurrently with much clearer water, decreased zooplankton abundance, and increased abundance of non-native sunfishes. Persistence of the weeds and sunfishes even during the wet years of 2017 and 2019, and expansion throughout the complex, indicated a shift to a littoral-dominated ecosystem. Upstream ends of small sloughs with freshwater inflows appeared resilient to the ecosystem shift, remaining turbid and supporting relatively high numbers of plankton and native fishes, but by 2020, except for Ulatis Creek, all waterways were weed-choked and dominated by non-native species. However, in 2021, aquatic weeds declined substantially, and determining the mechanism of decline is important for managing weeds and maintaining pelagic productivity.

Temporal Changes

Over the study period, water quality changed substantially in the Lindsey Network and near the confluence, with decreasing measures of suspended material in the water column (i.e., turbidity, VSS, and TSS). These water-quality changes were likely driven by the expansion of aquatic weeds in the area. Submersed vegetation, such as Brazilian waterweed, has been shown to slow water and capture sediment in the southern Delta (Santos et al. 2011; Hestir et al. 2016) . While proximity of the CLC to Yolo Bypass and Ulatis Creek (both of which provide detritus, sediment, and scouring flows) may have delayed the spread of aquatic weeds, the duration and intensity of the 2012-16 drought, which limited flooding on the bypass and reduced flows, appeared to offer an opportunity for invasion. This pattern may have changed by June 2021, when we observed rooted aquatic weeds coated in filamentous algae; by the following month, the weeds had died back, remaining low for the rest of the year. We hypothesize that the algae blocked sunlight from reaching the rooted weeds and caused them to senesce. Water quality did not vary notably before the die back, so the mechanism that caused the flourishing of the filamentous algae remains unknown.

Springtime zooplankton densities declined over the study period at upstream sites, with a major drop in overall abundance occurring after 2017 – the same year that aquatic weeds became common in the Cache Network. Timing of zooplankton peaks appeared partly tied to precipitation, with peaks more commonly occurring later in spring when flows were high.

The rapid expansion of aquatic weeds during the drought co-occurred with changes in the fish assemblage. Historically, the Delta was much more turbid than it is today, and native fishes are adapted to these conditions. Increasing water clarity tends to decrease habitat for native species while improving conditions for many non-native fishes, especially sunfishes, such as bluegill, redear sunfish, and

largemouth bass. Consistent with shifting conditions, native smelt species nearly disappeared while abundance of sunfishes dramatically increased. Tule perch, a normally ubiquitous species endemic to lowland rivers and estuaries in California, declined dramatically during the study, but increased in 2021 with decreasing volume of aquatic weeds. Catch of other species – notably native prickly sculpin and hitch, and non-native threadfin shad, American shad, striped bass, and Mississippi silverside – increased during 2021, when weeds died back, to abundances not observed since 2017.

Spatial Differences

Spatial differences between the two slough networks were exacerbated by the drought. Early in the study, the upper Cache Network remained more resilient to changes than the Lindsey Network and the confluence: alkalinity, turbidity, VSS, TSS, phosphorus, nitrogen, and chlorophyll *a* all remained considerably high. However, 2018-2020 saw major shifts in all but the uppermost Cache Slough site and Ulatis Creek. Concomitantly, zooplankton densities were often higher in the Cache Network, in particular CA1 and UL1. The resiliency of the Cache Network was surprising because it lacks the complex physical structure and habitat (emergent wetlands and a restoration site) of the Lindsey Network. But Ulatis Creek and agricultural runoff provided Cache Slough with fresh water, detritus, and nutrients, and may have slowed the encroachment of aquatic weeds into the network's upper reaches.

Differences in water quality and plankton production between the Cache and Lindsey networks were paralleled by fish catch and assemblage. POD species, which need zooplankton for at least part of their life cycle, were most abundant in the upper Cache Network while being rarer in most of the Lindsey Network. The most abundant POD species in the region was threadfin shad, which moved seasonally into the upper reaches of the Cache Network where zooplankton concentrations were higher (Montgomery et al. 2016, Montgomery 2017). The second most-abundant POD species was juvenile striped bass, which was also seasonally more abundant in the Cache Network. Catch of sunfishes by electrofishing tended to be highest in the Lindsey Network, especially for redear sunfish and largemouth bass, likely because it was weedier, although bluegill were also common in the Cache Network. Black crappie tended to be more prevalent in Cache Slough and Ulatis Creek, probably because they are more well-suited for open-water, turbid conditions and are well-adapted for eating zooplankton. The somewhat higher otter-trawl catch of sunfishes in the Cache Network was likely due to higher turbidities coupled with less submersed vegetation, resulting in movement of sunfishes away from edges and into the channel thalweg where the trawl sampled (Todd and Rabeni 1989, Abrahams and Kattenfeld 1997, Ahrenstorff *et al.* 2009).

Special Study: Pelagic Metabolism

In 2014, we determined that fishes were getting a higher contribution of carbon from phytoplankton in the upper Cache Network than in other regions of the CLC (Young *et al.* 2021). We hypothesized that higher nutrient loads from agricultural runoff and wastewater effluent flowing into the upper Cache Network were driving phytoplankton production and causing a pelagic food web to be dominant. A metabolism study in 2019 indicated that the highest nutrient loads were not tied to the highest rates of primary production and that HS1 had the overall highest rates of GPP and CR, which was corroborated in 2021.

Net community production rates revealed that in 2021, at HS1, BK1, and CC1, more carbon was being respired than fixed more often than at UL1 and CA1. Inputs of carbon from outside of the system will cause higher rates of respiration than primary production. Lower NCP was not surprising in Barker Slough and Calhoun Cut, sloughs that are bordered by emergent wetlands and receive carbon inputs from marsh detritus. HS1 is connected to a large area of agricultural land and a large subsidy of carbon could have pulsed into the system in April when very high respiration was observed. Incubations in 2021, a dry year, contrast with our study in 2019, a wet year – we observed autotrophy nearly every month at UL1 in 2021, likely because little carbon was flushed into the site from the Ulatis Creek drainage. Preliminary analysis suggest that nutrient concentrations are not the primary driving force of pelagic primary production – the assemblage of phytoplankton might be more important and could be linked to management of upland waterways.

With declining chlorophyll *a,* zooplankton, and pelagic fishes in the Cache-Lindsey Slough complex, it is important to determine what is driving phytoplankton-production rates so that management can increase them. Also, phytoplankton produced at BK1 were likely entrained into the Barker Slough Pumping Plant (Jasper 2020), so modifications to the pumping schedule could also benefit phytoplankton production. An analysis of the taxa of phytoplankton is underway and further investigation of upland waterways could shed light on how to maximize phytoplankton production.

Conclusions

The CLC ecosystem has rapidly changed, a change facilitated by the drought. Whereas the region was once a stronghold for native species, that resiliency has shown signs of weakening. In particular, the spread and persistence of non-native, invasive organisms are indicative of an ecological shift that may be difficult to reverse without substantial and dramatic intervention. However, a decrease in aquatic

weeds in 2021 was coupled with an increase of several native fish species – the mechanism of the weed die off must be explored further. Tidal restorations, while providing habitat for some native species, may also support invaders, especially aquatic weeds, depending on where the restorations are in the landscape. Likewise, if conditions are unfavorable in adjacent channels, then connectivity to other parts of the Delta will be limited, inhibiting the movement of desirable fishes in and out of restoration sites. Local inflows from farmlands and small waterways often occur with conditions favored by many native and pelagic species, and they hold promise for integrating agriculture with restoration efforts.

Our study highlights some useful lessons and future directions:

1. Differences in physical structure between the two networks, as well as effects of tidal restoration, are superseded by the effects of hydrodynamic differences. In particular, the Cache Network benefits from periodic freshwater flows entering from Ulatis Creek and, to a lesser extent, from Hass Slough. Lindsey Slough has a small freshwater source entering from Campbell Lake into Barker Slough, but the effect of the lake's outflows and occasional high rates of primary production are muted by water withdrawals. Relocating the North Bay Aqueduct and increasing connectivity with upslope flows from Jepson and Maine Prairie may improve plankton productivity in the Lindsey Network while limiting distribution of aquatic weeds.

2. Flow pulses from upstream sources appear to support high local productivity in upper slough networks. Pulses may deliver important subsidies of nutrients to upstream reaches where phytoplankton-production potential is high, creating important regional blooms which may become rarer in the Delta with the elimination of ammonium coming from the Sacramento Wastewater Treatment Plant. Many fishes are able utilize food webs based upon local sources of primary and secondary production, as seen by relatively high catches of native and POD fishes in upper Cache Slough, upper Hass Slough, and Ulatis Creek.

3. Any changes to flows or landscapes must account for aquatic weeds. Herbicides are currently used but are probably insufficiently effective over the long term and may harm the ecosystem in unknown ways. Directional flow pulses increase turbidity and help control weeds locally, presenting a management opportunity to maintain small areas of weed-free habitat. Also, promotion of filamentous algae growth to smother weed beds must be explored. The use of temporary or intermittently used gates at restoration sites would provide a tool to drain sites and remove invasive organisms, allowing an ecosystem a fresh start. Creation of channels in restoration sites that are deep enough to inhibit colonization by aquatic weeds will favor pelagic and benthic habitat that is increasingly rare in the CLC.

4. Restorations that are designed to look like historic natural landscapes may fail to meet goals of aquatic restoration. Pervasive and permanent changes in the landscape favor the persistence of non-native species. Directing flows across tidal landscapes from upstream sources may be the most effective way of supporting restoration goals. Such directional flows increase local nutrient availability, mobilize sediment, and limit colonization by non-native weeds. New restoration projects should incorporate inflows from upland drainages that can direct sediment and nutrients into the area. An optimal hydrograph would include flow pulses in early spring to benefit food-web production for recruiting native fishes, followed by a late spring/early summer flow pulse to move them out and to help them avoid high summer temperatures. In winter, allowing increased flow could help reduce aquatic vegetation.

Literature cited

Abrahams, M., and M. Kattenfeld. 1997. The role of turbidity as a constraint on predator-prey interactions in aquatic environments. Behavioral Ecology and Sociobiology 40: 169-174.

Ahrenstorff, T. D., G. G. Sass, and M. R. Helmus. 2009. The influence of littoral zone coarse woody habitat on home range size, spatial distribution, and feeding ecology of largemouth bass (*Micropterus salmoides*). Hydrobiologia 623: 223-233.

Delhez E, Campin J-M, Hirst AC, Deleersnijder E. 1999. Toward a General Theory of the Age in Ocean Modelling. Ocean Modelling 1(1):17-27.

DWR. 2022. Interagency Ecological Program. Available: www.iep.water.ca.gov (March 2022).

Durand J, Fleenor W, McElreath R, Santos MJ, Moyle P. 2016. Physical controls on the distribution of the submersed aquatic weed *Egeria densa* in the Sacramento-San Joaquin Delta, California and implications for habitat restoration. San Franc Estuary Watershed Sci. 14(1). doi:10.15447/sfews.2016v14iss1art4. [accessed 2016 Apr 14]. http://escholarship.org/uc/item/85c9h479.

Durand, J. R., Jasper C., Williamson B., Kruger A., O'Rear T., & Holleman R. (2020). North Delta Arc Study 2019 annual report: Cache and Lindsey Slough water quality, productivity, and fisheries. https://watershed.ucdavis.edu/files/biblio/2019%20North%20Delta%20Arc%20Annual%20Report%20Final.pdf

Durand JR. 2017. Evaluating the aquatic habitat potential of flooded polders in the Sacramento-San Joaquin Delta. San Franc Estuary Watershed Sci. 15(4). [accessed 2018 Jul 20]. https://escholarship.org/uc/item/6xg3s6v0.

Feyrer F, Cloern JE, Brown LR, Fish MA, Hieb KA, Baxter RD. 2015. Estuarine fish communities respond to climate variability over both river and ocean basins. Global Change Biology 21: 3608-3619.

Feyrer F, Nobriga ML, Sommer TR. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Can J Fish Aquat Sci. 64(4):723–734.

Grimaldo LF, Miller RE, Peregrin CM, Hymanson ZP. 2004. Spatial and temporal distribution of native and alien ichthyoplankton in three habitat types of the Sacramento-San Joaquin Delta. Am Fish Soc Symp. 39:81–96.

Gross E, Andrews S, Bergamaschi B, Downing B, Holleman R, Burdick S, Durand J. 2019. The Use of Stable-Isotope-Based Water Age to Evaluate a Hydrodynamic Model. Water 11(11):2207

Hammock BG, Moose SP, Solis SS, Goharian E, The SJ. 2019. Hydrodynamic modeling coupled with long-term field data provide evidence for suppression of phytoplankton by invasive clams and freshwater exports in the San Francisco Estuary. Env Mgmt 63:703-717.

ICF International. 2013. Bay Delta Conservation Plan. Sacramento, CA: California Department of Water Resources; US Bureau of Reclamation; US Fish and Wildlife Service; National Marine Fisheries Service.

Jasper, CR. 2020. Watershed management drives ecological dynamics in California estuarine wetlands. MS Thesis. University of California, Davis. 83p.

Ketefian GS, Gross ES, Stelling GS. 2015. Accurate and consistent particle tracking on unstructured grids. Int J Num Meth Fluids 80:648-665. doi:10.1002/fld.4168.

Kimmerer WJ. 1996. Changes in the zooplankton of the San Francisco Bay estuary since the introduction of the clam *Potamocorbula amurensis*. In: Hollibaugh JT, editor. San Francisco Bay: The Ecosystem. San Francisco, CA: American Association for the Advancement of Science. p. 403–425.

Kimmerer WJ. 2004. Open water processes of the San Francisco Estuary: from physical forcing to biological responses. San Francisco Estuary and Watershed Science 2(1).

Lund J, Medellin-Azuara J, Durand J, Stone K. 2018. Lessons from California's 2012–2016 drought. J Water Resour Plan Manag. 144(10):04018067.

Lund JR, Hanak E, Fleenor W, Howitt R, Mount J, Moyle P. 2007. Envisioning Futures for the Sacramento-San Joaquin Delta. San Francisco, CA: Public Policy Institute of California.

Montgomery, J. 2017. Foodweb dynamics in shallow tidal sloughs of the San Francisco Estuary. MS Thesis. University of California, Davis. 110p.

Montgomery J, Durand JR, Moyle P. 2016. Zooplankton biomass and chlorophyll-*a* trends in the North Delta Arc: two consecutive drought years. IEP Newsletter 28(3):14-23.

Mount J, Twiss R. 2005. Subsidence, sea level rise, and seismicity in the Sacramento-San Joaquin Delta. San Franc Estuary Watershed Sci. 3(1):5.

Moyle, P.B., 2002. Inland fishes of California: revised and expanded. Univ of California Press.

Moyle PB, Brown LR, Durand JR, Hobbs JA. 2016. Delta Smelt: Life history and decline of a once abundant species in the San Francisco Estuary. San Franc Estuary Watershed Sci. 14(2). https://escholarship.org/uc/item/09k9f76s.

Moyle P, Durand J, Jeffres C. 2018. Making the Delta a Better Place for Native Fishes. Davis, CA. https://www.coastkeeper.org/white-paper/

O'Rear, T. A., J. Montgomery, P. B. Moyle, and J. R. Durand. 2021. Suisun Marsh Fish Study: trends in fish and invertebrate populations of Suisun Marsh January 2020 - December 2020. Davis, CA. Department of Water Resources.

O'Rear, T. A., P. B. Moyle, and J. R. Durand. 2019. Suisun Marsh Fish Study: trends in fish and invertebrate populations of Suisun Marsh January 2017 - December 2017. Davis, CA. Department of Water Resources.

Simenstad C, Toft J, Higgins H, Cordell J, Orr M, Williams P, Grimaldo L, Hymanson Z, Reed D. 2000. Sacramento/San Joaquin Delta Breached Levee Wetland Study (BREACH). Seattle: University of Washington.

Syrett, P.J., 1981. Nitrogen metabolism of microalgae. Can. Bull. Fish. Aquat. Sci. 210: 182-210.

Todd B.L., and C. F. Rabeni. 1989. Movement and habitat use by stream-dwelling smallmouth bass. Transactions of the American Fisheries Society 118(3): 229-242.

Thompson J. 1957. The settlement geography of the Sacramento-San Joaquin Delta, California. [Palo Alto, California]: Stanford University.

Wang, J.C., 1986. Fishes of the Sacramento-San Joaquin estuary and adjacent waters, California: A guide to the early life histories. Interagency Ecological Program Technical Report, 9: 1-690.

Young MJ, Howe E, O'Rear TA., Berridge K, and Moyle PB, 2021. Food web fuel differs across habitats and seasons of a tidal freshwater estuary. Estuaries and Coasts, 44(1): 286-301.

Appendix I: Site data

Table A1. Site names and locations.

Site Code	Site Description	Subregion	Waterway	Latitide & Longitide	Channel Width (m)	Avg. Depth (m)
BK1	Barker Slough upstream	Upper Lindsey	Barker Slough	38°16'20.0"N 121°47'40.3"W	29.5	3
BK2	Barker Slough downstream	Upper Lindsey	Barker Slough	38°15'47.1"N 121°46'48.5"W	25.5	3.5
BM1	Liberty Isl Mitigation Bank upstream	Liberty Island	Stairsteps	38°19'44.0"N 121°40'23.8"W	10.6	2.4
BM2	Liberty Isl Mitigation Bank downstream	Liberty Island	Stairsteps	38°20'02.0"N 121°40'15.8"W	16.4	2.7
BP1	Beaver Pond 1	Liberty Island	Beaver Pond	38°19'29.5"N 121°40'60.0"W	32.9	NA
BP2	Beaver Pond 2	Liberty Island	Barker Slough	38°19'29.5"N 121°40'60.0"W	32.9	NA
CA1	Cache Slough upstream of conf with Ulatis	Upper Cache	Cache Slough	38°18'05.3"N 121°45'20.9"W	33.7	1.9
CA2	Cache Slough upstream of conf with Haas	Upper Cache	Cache Slough	38°17'45.1"N 121°44'41.4"W	55.1	2.8
CA3	Cache Slough downstream of conf with Haas	Lower Cache	Cache Slough	38°17'05.3"N 121°43'04.6"W	298.3	3.7
CC1	Calhoun Cut upstream	Upper Lindsey	Calhoun Cut	38°15'34.9"N 121°47'49.8"W	50.8	2.1
CC2	Calhoun Cut downstream	Upper Lindsey	Calhoun Cut	38°15'36.6"N 121°47'09.1"W	29.3	2.4
HS1	Haas Slough upstream	Upper Cache	Haas Slough	38°18'37.7"N 121°44'08.7"W	40.2*	2.3
HS2	Haas Slough downstream	Upper Cache	Haas Slough	38°18'06.2"N 121°43'47.0"W	159.3*	4
LN1	Lindsey Slough upstream	Upper Lindsey	Lindsey Slough	38°15'31.4"N 121°45'57.4"W	73.7	4.9
LN2	Lindsey Slough upstream of telephone line	Upper Lindsey	Lindsey Slough	38°15'31.4"N 121°44'41.5"W	90.9	5.7
LN3	Lindsey Slough upstream of bridge	Lower Lindsey	Lindsey Slough	38°15'00.8"N 121°42'50.1"W	140.1	5.2
LNCA	Conf of Cache/Lindsey	Lower Cache	Cache/Lindsey Confluence	38°14'39.9"N 121°41'19.6"W	229.2	NA
PR1	Downstream of USGS sonde	Liberty Island	Prospect Slough	38°19'44.2"N 121°40'02.2"W	62.5	5.6
PR2	Prospect Slough downstream trawl and lower prospect seining beach	Liberty Island	Prospect Slough	38°17'52.5"N 121°40'02.2"W	50.9	6.4
SG1	Upstream from side channel to Cache	Liberty Island	Shag Slough	38°18'10.7"N 121°41'34.3"W	88.9	7.7
SG2	Downstream from side channel to Cache	Liberty Island	Shag Slough	38°16'58.8"N 121°41'34.3"W	95.1	7.8
UL1	Ulatis Slough upstream	Upper Cache	Ulatis Slough	38°17'33.2"N 121°45'51.4"W	38.4	2.4
UL2	Ulatis Slough downstream	Upper Cache	Ulatis Slough	38°17'46.1"N 121°45'11.1"W	49.6	2.4

Appendix II: Fish data and catch totals

Table A2. Total fish catch from 2012-2021.

Species Code	*Common Name*	*Scientific Name*	*Habitat Association*	*Status*	*Otter Trawl*	*Electro-fishing*
ASH	American Shad	*Alosa sapidissima*	Pelagic	Non-Native	670	129
BB	Brown Bullhead	*Ameiurus nebulosus*	Benthic	Non-Native	61	24
BC	Black Crappie	*Pomoxis nigromaculatus*	Littoral	Non-Native	2214	405
BF	Sacramento Blackfish	*Orthodon microlepidotus*	Benthic	Native	4	21
BFG	American Bullfrog	*Lithobates catesbeianus*	Littoral	Non-Native	40	2
BG	Bluegill	*Lepomis macrochirus*	Littoral	Non-Native	1785	1570
BGRE	Bluegill/Redear Hybrid	*Lepomis spp.*	Littoral	Non-Native	20	6
BLB	Black Bullhead	*Ameiurus melas*	Benthic	Non-Native	100	18
BLP	Bigscale Logperch	*Percina macrolepida*	Littoral	Non-Native	594	163
CCF	Channel Catfish	*Ictalurus punctatus*	Benthic	Non-Native	30	11
CENTRARCH	Unknown Centrarchid	*Centrarchid spp.*	Littoral	Non-Native	7	0
CFU	Unknown Catfish	*NA*	Benthic	Non-Native	1	0
CLUPEIDAE	Unknown Clupeid	*NA*	NA	NA	55	2
CP	Common Carp	*Cyprinus carpio*	Benthic	Non-Native	119	433
CS	Chinook Salmon	*Oncorhynchus tshawytscha*	Pelagic	Native	2	40
DS	Delta Smelt	*Hypomesus transpacificus*	Pelagic	Native	16	1
FHM	Fathead Minnow	*Pimephales promelas*	Littoral	Non-Native	11	6
GF	Goldfish	*Carassius auratus*	Benthic	Non-Native	11	66
GS	Green Sturgeon	*Acipenser medirostris*	Benthic	Native	1	11
GSF	Green Sunfish	*Lepomis cyanellus*	Littoral	Non-Native	2	3
GSH	Golden Shiner	*Notemigonus crysoleucas*	Littoral	Non-Native	188	1129
HCH	Sacramento Hitch	*Lavinia exilicauda exilicauda*	Pelagic	Native	220	219
ISS	Mississippi Silverside	*Menidia audens*	Littoral	Non-Native	275	1520
LFS	Longfin Smelt	*Spirinchus thaleichthys*	Pelagic	Native	221	2

LMB	Largemouth Bass	*Micropterus salmoides*	Littoral	Non-Native	172	3303
MINU	Unknown Minnow	*Cyprinid spp.*	NA	NA	0	0
MQF	Western Mosquitofish	*Gambusia affinis*	Littoral	Non-Native	5	29
MSF	Unknown Sunfish	*Lepomis spp.*	Littoral	Non-Native	288	342
RESF	Redear Sunfish	*Lepomis microlophus*	Littoral	Non-Native	1811	1739
RSNR	Red Shiner	*Cyprinella lutrensis*	Littoral	Non-Native	1	0
RT	Rainbow/Steelhead Trout	*Oncorhynchus mykiss*	Pelagic	Native	0	3
RWK	Rainwater Killifish	*Lucania parva*	Littoral	Non-Native	11	7
SB	Striped Bass	*Morone saxatilis*	Pelagic	Non-Native	2356	289
SCP	Prickly Sculpin	*Cottus asper*	Benthic	Native	461	132
SF	Starry Flounder	*Platichthys stellatus*	Benthic	Native	2	0
SG	Shimofuri Goby	*Tridentiger bifasciatus*	Benthic	Non-Native	145	94
SKR	Sacramento Sucker	*Catostomus occidentalis*	Benthic	Native	283	1606
SPM	Sacramento Pikeminnow	*Ptychocheilus grandis*	Pelagic	Native	39	112
ST	Sacramento Splittail	*Pogonichthys macrolepidotus*	Benthic	Native	156	9
STBK	Threespine Stickleback	*Gasterosteus aculeatus*	Littoral	Native	2	2
TFS	Threadfin Shad	*Dorosoma petenense*	Pelagic	Non-Native	7218	2668
TP	Tule Perch	*Hysterocarpus traski*	Littoral	Native	665	413
WAKASAGI	Wakasagi	*Hypomesus nipponensis*	Pelagic	Non-Native	226	0
WC	White Crappie	*Pomoxis annularis*	Littoral	Non-Native	272	38
WCF	White Catfish	*Ameiurus catus*	Benthic	Non-Native	601	51
WM	Warmouth	*Lepomis gulosus*	Littoral	Non-Native	21	70
YFG	Yellowfin Goby	*Acanthogobius flavimanus*	Benthic	Non-Native	29	49

Table A3. Fish catch in 2021.

Species Code	*Common Name*	*Scientific Name*	*Habitat Association*	*Status*	*Otter Trawl*	*Electro-fishing*
ASH	American Shad	*Alosa sapidissima*	Pelagic	Non-Native	164	1
BB	Brown Bullhead	*Ameiurus nebulosus*	Benthic	Non-Native	11	2
BC	Black Crappie	*Pomoxis nigromaculatus*	Littoral	Non-Native	104	24
BF	Sacramento Blackfish	*Orthodon microlepidotus*	Benthic	Native	0	0
BFG	American Bullfrog	*Lithobates catesbeianus*	Littoral	Non-Native	1	0
BG	Bluegill	*Lepomis macrochirus*	Littoral	Non-Native	193	158
BGRE	Bluegill/Redear Hybrid	*Lepomis spp.*	Littoral	Non-Native	1	2
BLB	Black Bullhead	*Ameiurus melas*	Benthic	Non-Native	4	1
BLP	Bigscale Logperch	*Percina macrolepida*	Littoral	Non-Native	40	4
CCF	Channel Catfish	*Ictalurus punctatus*	Benthic	Non-Native	2	0
CENTRARCH	Unknown Centrarchid	*Centrarchid spp.*	Littoral	Non-Native	0	0
CFU	Unknown Catfish	*NA*	Benthic	Non-Native	0	0
CLUPEIDAE	Unknown Clupeid	*NA*	NA	NA	18	0
CP	Common Carp	*Cyprinus carpio*	Benthic	Non-Native	10	33
CS	Chinook Salmon	*Oncorhynchus tshawytscha*	Pelagic	Native	0	0
DS	Delta Smelt	*Hypomesus transpacificus*	Pelagic	Native	0	0
FHM	Fathead Minnow	*Pimephales promelas*	Littoral	Non-Native	1	0
GF	Goldfish	*Carassius auratus*	Benthic	Non-Native	0	0
GS	Green Sturgeon	*Acipenser medirostris*	Benthic	Native	0	0
GSF	Green Sunfish	*Lepomis cyanellus*	Littoral	Non-Native	2	0
GSH	Golden Shiner	*Notemigonus crysoleucas*	Littoral	Non-Native	32	124
HCH	Sacramento Hitch	*Lavinia exilicauda exilicauda*	Littoral	Native	85	79
ISS	Mississippi Silverside	*Menidia audens*	Littoral	Non-Native	42	306
LFS	Longfin Smelt	*Spirinchus thaleichthys*	Pelagic	Native	0	0
LMB	Largemouth Bass	*Micropterus salmoides*	Littoral	Non-Native	43	313

MINU	Unknown Minnow	*NA*	NA	NA	0	0
MQF	Western Mosquitofish	*Gambusia affinis*	Littoral	Non-Native	3	9
MSF	Unknown Sunfish	*Lepomis spp.*	Littoral	Non-Native	14	5
RESF	Redear Sunfish	*Lepomis microlophus*	Littoral	Non-Native	302	181
RSNR	Red Shiner	*Cyprinella lutrensis*	Littoral	Non-Native	0	0
RT	Rainbow/Steelhead Trout	*Oncorhynchus mykiss*	Pelagic	Native	0	1
RWK	Rainwater Killifish	*Lucania parva*	Littoral	Non-Native	11	6
SB	Striped Bass	*Morone saxatilis*	Pelagic	Non-Native	208	24
SCP	Prickly Sculpin	*Cottus asper*	Benthic	Native	149	27
SG	Shimofuri Goby	*Tridentiger bifasciatus*	Benthic	Non-Native	19	8
SKR	Sacramento Sucker	*Catostomus occidentalis*	Benthic	Native	13	129
SPM	Sacramento Pikeminnow	*Ptychocheilus grandis*	Pelagic	Native	0	0
ST	Sacramento Splittail	*Pogonichthys macrolepidotus*	Benthic	Native	4	0
STBK	Threespine Stickleback	*Gasterosteus aculeatus*	Littoral	Native	1	0
TFS	Threadfin Shad	*Dorosoma petenense*	Pelagic	Non-Native	572	179
TP	Tule Perch	*Hysterocarpus traski*	Littoral	Native	112	22
WAKASAGI	Wakasagi	*Hypomesus nipponensis*	Pelagic	Non-Native	22	0
WC	White Crappie	*Pomoxis annularis*	Littoral	Non-Native	0	0
WCF	White Catfish	*Ameiurus catus*	Benthic	Non-Native	61	0
WM	Warmouth	*Lepomis gulosus*	Littoral	Non-Native	4	4
YFG	Yellowfin Goby	*Acanthogobius flavimanus*	Benthic	Non-Native	20	28