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RESEARCH

Farm to Fish: Lessons from a Multi-Year Study on Agricultural Floodplain Habitat

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ABSTRACT

Large areas of California's historic floodplain have been separated from adjacent river channels by levee construction, allowing the development of an extensive agricultural industry. Based on successful partnerships between agriculture and conservation groups to support migrating waterfowl, we examined whether seasonally flooded rice fields could be modified to provide off-channel rearing habitat for juvenile Chinook Salmon *Oncorhynchus tshawytscha*. During winter and spring of 2012-2017, we conducted a series of experiments in Yolo Bypass and other regions of California's Central Valley using hatchery Chinook Salmon as a surrogate for wild Chinook Salmon, the management target for our project. Overall, we found that seasonally flooded fields are highly productive, resulting in significantly higher levels of zooplankton and high Chinook Salmon growth rates as compared to the adjacent Sacramento River. We found similar results for multiple geographical areas in the Central Valley, and in different cover types, such as non-rice crops and fallow areas. Although field substrate type did not detectably affect fish growth and survival, connectivity with upstream and downstream areas appeared to drive fish occupancy, because rearing young salmon were generally attracted to inflow in the fields, and not all of the fish successfully emigrated off the fields without efficient drainage. In general, we faced numerous logistic and environmental challenges to complete our research. For example, periodic unmanaged floods in the Yolo Bypass made it difficult to schedule and complete experiments. During severe drought conditions, we found that managed agricultural habitats produced low and variable salmon survival results, likely because of periodically high temperatures and concentrated avian predation. In addition, our project required substantial landowner time and effort to install and maintain experimental fields. Recent and future infrastructure improvements in Yolo Bypass could substantially improve options for experimental work and broaden efforts to enhance salmon habitat.

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INTRODUCTION

Worldwide, the loss of floodplain habitat has resulted in considerable reduction in the productivity and diversity of large river ecosystems (Winemiller et al. 2016). California is no exception, as widespread levee construction separated historical riverine and estuarine floodplain habitats from adjacent river channels (Mount 1995; Opperman 2012; Whipple et al. 2012). At the same time, there have been corresponding declines in the distribution and abundance of a suite of native fishes (Moyle et al. 2011), an understandable outcome since a large body of research provides evidence that floodplains are high-quality habitat for multiple Central Valley fishes (Sommer et al. 2001a, 2001b; Feyrer et al. 2006a, 2006b; Jeffres et al. 2008; Sommer et al. 2014).

Construction of levees in the Central Valley has allowed the development of one of the most extensive and productive agricultural economies in the world (e.g., CDA 2018). Lands that formerly seasonally flooded can now be farmed in most years. Recently, there has been a growing interest in whether the vast acreage of farmland that now occupies formerly inundated floodplains adjacent to river systems could be managed to improve their value to fish and wildlife (Suddeth Grimm and Lund 2016; Katz et al. 2017). A case in point is the Central Valley Joint Venture Partnership, which promotes the use of flooded rice fields as a means to increase available wetlands to support shorebirds and waterfowl migrating, overwintering, and breeding along the Pacific Flyway (Shuford and Dybala 2017). Conservation biologists working in partnership with local farmers have developed a system by which fields are reflooded after rice harvest to create seasonal wetland habitat for water birds during fall and winter. These temporary agricultural wetlands are relatively productive habitats (Dybala et al. 2017), helping California meet some of its shorebird and waterfowl conservation objectives (Gardali et al. 2017; Strum et al. 2017).

The success of these avian-oriented programs raises the question of whether flooded fields can also be used as habitat for native fishes and whether management practices can affect habitat quality. One location where this question is relevant is Yolo Bypass (Figure 1), Sacramento River's primary remnant floodplain with large areas of agricultural lands (Sommer et al. 2001a, 2001b; Opperman 2012). Research over the past 2 decades has shown that seasonally flooded lands support a suite of native fishes and provide food web subsidies within and to downstream habitats (Sommer et al. 1997, 2001a, 2001b; 2004; Jeffres et al. 2008). At the same time, these studies have shown that the Yolo Bypass is far from optimal habitat because the landscape has been altered to drain relatively quickly, and is often disconnected from the Sacramento River by levees and weirs that create major passage problems for upstream migrating adult fishes, such as Chinook Salmon and sturgeon (Sommer et al. 2014; Herbold et al. 2018; Johnston et al. 2020). Several of these issues will be addressed in coming years by proposed structural changes to Fremont Weir at the upstream end of Yolo Bypass, and by the additional improvements to the floodplain's water distribution system (USBR and CDWR 2019). However, the question remains whether changes to agricultural land management and infrastructure can provide reliable fish habitat that can increase the growth and survival of juvenile native fishes, and thereby (1) contribute to reversing their overall decline, (2) aid in the recovery of native fishes listed under the U.S. and California Endangered Species acts, (3) and increase the availability of fishery resources.

To help the overarching objective of providing reliable fish habitat, our team

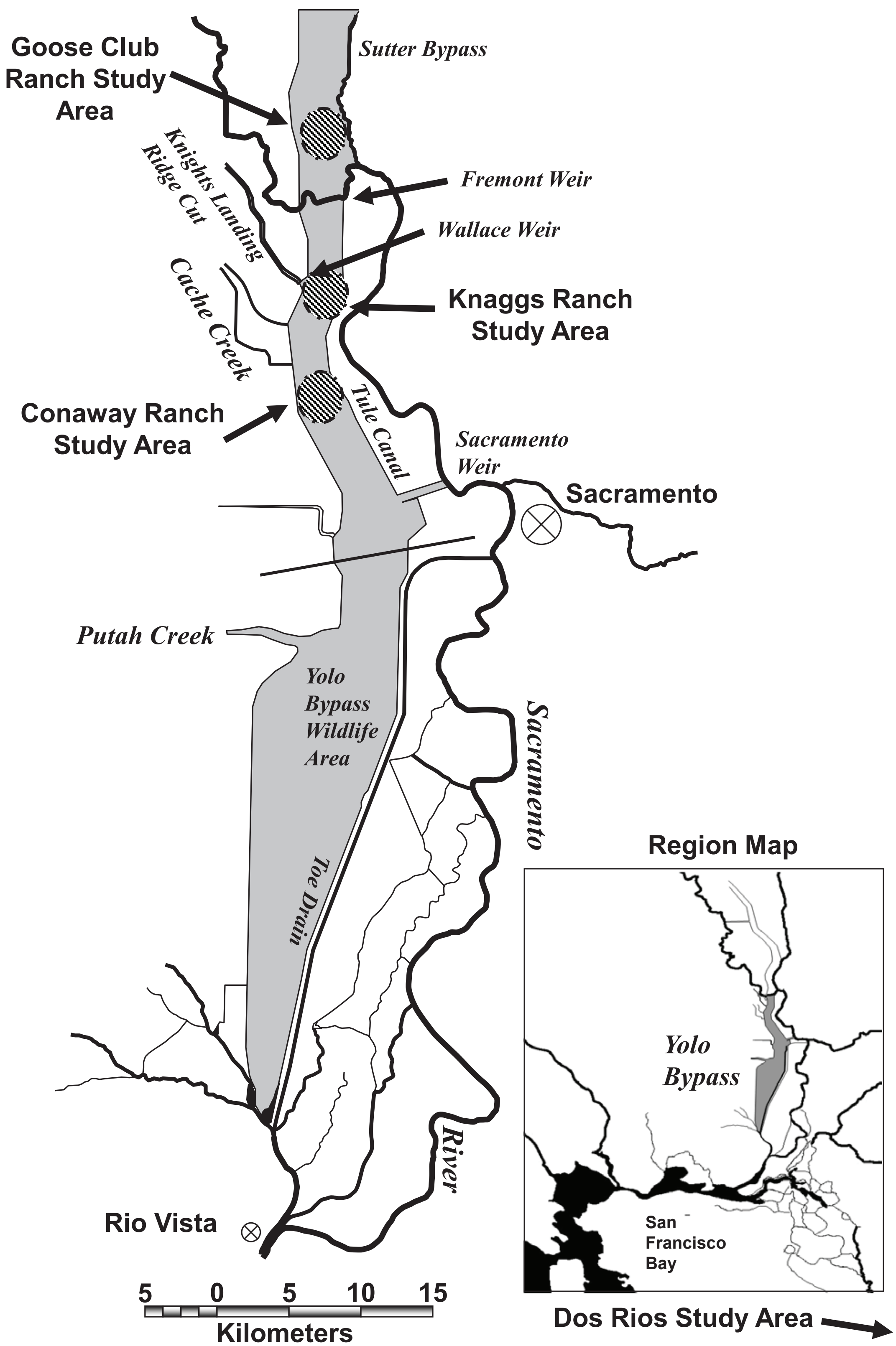

Figure 1 Location map for Yolo Bypass and related sampling areas. The Dos Rios study area is located along the San Joaquin River, south of the main area shown.

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conducted a series of field studies during 2012-2017. To test fish and food web responses within different land-management scenarios, we conducted our project on standard rice and winter wheat fields, adjacent fallow lands, and rice fields with different harvest practices or other experimental modifications. This work yielded several publications that provided insight into habitat conditions in flooded rice fields for fish and invertebrates (Conrad et al. 2016; Corline et al. 2017; Katz et al. 2017). The focus of our effort was on rearing habitat for young Chinook Salmon, but this work may also be relevant to other native fishes.

The goal of this paper is to summarize the key lessons learned from 6 years of research on the feasibility of using farm fields as rearing habitat for juvenile Chinook Salmon in the Yolo Bypass and other Central Valley locations. Our hope is that our summary will provide guidance to future researchers, as well as inform managers as they evaluate potential management approaches. An important caveat is that our studies were not intended as a proof of concept for any specific management actions. Rather, our research was intended to examine some of the attributes that could reduce limitations to rearing conditions identified in early research, and gain insight into some of the key considerations for potential future agricultural floodplain management. A second major caveat is that we had to rely on juvenile hatchery Chinook Salmon as a surrogate for wild Chinook Salmon, our ultimate target for habitat restoration. We recognize that there are several potential differences in the behavior of hatchery and wild Chinook Salmon (e.g., Davis et al. 2018). However, hatchery salmon were the only feasible alternative in this case since downstream migrating wild juvenile Chinook Salmon were mostly cut off from the Yolo Bypass because of extreme drought conditions. Nonetheless, hatchery salmon have been used successfully as a research tool in many types of ecological studies, so many of the lessons learned here should have at least some relevance to wild Sacramento River Chinook Salmon. Finally, our project was separate from a number of other fish management research projects in agricultural parcels, such as current efforts to investigate whether invertebrates grown on flooded rice fields can be used as a food subsidy for adjacent river channels (e.g., Cornwell and Katz 2017).

STUDY AREA

The Yolo Bypass is a 24,000-ha, partially leveed flood basin that is used to safely convey floodwaters away from Sacramento Valley communities (Figure 1). The Yolo Bypass contains a suite of habitats including agricultural lands, managed wetlands, upland habitat, and perennial ponds and channels, with broad open-water tidal wetlands at its downstream end where it joins the Sacramento–San Joaquin Delta (Sommer et al. 2005; Suddeth Grimm and Lund. 2016). The basin receives seasonal inflow from the Sacramento River, Colusa Basin (via Knights Landing Ridge Cut), Cache Creek, and Putah Creek, as well as substantial perennial tidal flow from the San Francisco Estuary via the lower Sacramento River at the downstream end of the floodplain (Figure 1). The Yolo Bypass floods to various degrees in approximately 80% of water years, but inundation events are often relatively short (< 2 weeks) and sometimes driven entirely by inflow from the west-side tributaries. The most substantial flow events come from the Sacramento River, which enters the Yolo Bypass via Fremont Weir and Sacramento Weir. However, in drought periods, such as during 2012–2015, there is little or no flooding.

METHODS

The general methods used for our field studies were described in detail by Katz et al. (2017), Conrad et al. (2016), and Corline et al. (2017). To improve the clarity of

Table 1 Summary of studies conducted during the multi-year investigation. *See text for details*.

Year	Water year type	Experiment	Start date	Duration	Location	Reporting
2012	Below normal	Pilot study	Jan 31	41 days	Yolo Bypass	Katz et al. 2017
2013	Dry	Substrate preference telemetry experiment	Mar 13	14 days	Yolo Bypass	Conrad et al. 2016
		Response to field substrate (replicated fields)	Feb 19	37 to 41 days	Yolo Bypass	Corline et al. 2017; Holmes et al. in prep
2014	Critically dry	Depth & inflow preference telemetry experiment	Feb 27	14 days	Yolo Bypass	California Trout et al. 2014
2015	Critically dry	Geographical location study	Feb 5	21 days	Yolo Bypass, Sutter Bypass, Dos Rios Ranch	California Trout et al. 2015
2016	Below normal	Flood extension	Mar 13	21[a] days	Yolo Bypass	California Trout et al. 2016
2017	Wet	Lower trophic sampling	Jan 19	122 days	Yolo Bypass	
		Flood extension	NA	NA[b]	Yolo Bypass	

a. Late flood event made full flood extension experiment protocol unfeasible. Limited lower trophic wild fish sampling was conducted at Knaggs Ranch.
b. Prolonged flooding precluded flood extension field containment. Limited lower trophic and wild fish sampling was conducted at Knaggs Ranch.

our multi-year synthesis, we summarize here the broad intent and general methods of each study year below and in Table 1. The general approach was to maintain shallow inundation (30–50 cm) in large (>2 ha: Figure 2) single or replicated rice fields (9 × 0.8 ha each) in northern Yolo Bypass using water from either Knights Landing Ridge Cut or the Tule Canal (Katz et al. 2017). Field drains employed a plastic mesh live-car trap that allowed for fish to be captured and measured as they volitionally left the field before moving downstream. Their downstream emigration pathway was via a drainage canal that discharged into the Tule Canal/Toe Drain, a perennial channel that connects to the lowermost Sacramento River. The Tule Canal/Toe Drain represents a primary migration corridor for fish in Yolo Bypass during winter and early spring (Johnston et al. 2018; Takata et al. 2018). In 2015, additional flooded fields were studied on Conaway Ranch in Yolo Bypass, in Sutter Bypass, and at Dos Rios, a San Joaquin River floodplain. Managed flooding generally

Figure 2 Photograph of example flooded field at Knaggs Ranch

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occurred in February and March with a duration of 3 to 6 weeks (Table 1), depending primarily on magnitude and duration of river and creek inflows to the bypasses, and opportunity for those waters to drain.

Sampling Approach

For each year, we evaluated water quality (temperature, dissolved oxygen [DO], turbidity, pH), food web responses (chlorophyll a, zooplankton), and fish growth and condition (Corline et al. 2017; Katz et al. 2017). Water temperature in fields was recorded continuously at 10- to 15-minute intervals with Onset HOBO® loggers, and a suite of other water-quality parameters (DO, pH, conductivity, and temperature) was measured and recorded using handheld and continuously installed multi-parameter sondes. We included plankton sampling with the broad goal of characterizing the communities and densities of phytoplankton and zooplankton in the study fields. Because long-term monitoring of the Yolo Bypass includes weekly plankton sampling in both the perennial Yolo Bypass channel of the Toe Drain and the Sacramento River, we could compare our experimental fields to productivity across habitats. Because the study fields were shallow compared to canal and riverine channel environments, sampling methods had to be slightly modified compared to the Toe Drain and Sacramento River. As a result, we used hand-tosses of a smaller 30-cm zooplankton net (153-μm mesh), recording the length of the toss, and the relative percent of the net mouth that was submerged during net retrieval. Detailed methods for zooplankton sampling are described in Corline et al. (2017).

Fish used in the experiments were primarily fall-run Chinook Salmon parr obtained from Feather River Fish Hatchery; however, small numbers of wild Sacramento River Chinook Salmon were also studied in 2013 (Feather River caught) and 2013, 2015, and 2016 (natural immigrants to flooded lands). The majority of the study fish were free-swimming throughout the flooded fields, but mesh cages were also used as a tool to compare hatchery salmon growth and survival across substrates in 2012 (Katz et al. 2017) or habitats (river, floodplain perennial channel, flooded fields) in 2016 and 2017.

2012: Pilot Study

The initial study year was a pilot effort to evaluate whether managed flooding of a rice field could provide suitable habitat for juvenile salmon rearing, and to assess associated growth and survival. A single 2-ha field contained a patchwork of four agricultural substrate types, including disced (plowed soil with all vegetation removed), short rice stubble (remains of rice plants left in the field after harvest, in this case 5 cm high), high rice stubble (35 cm high), and fallow (weedy) vegetation. Approximately 10,200 juvenile salmon were released in the field, with a subset implanted with passive integrated transponder (PIT) tags, so individuals could be identified, and individual growth rates could be measured. Twenty PIT-tagged fish were also released in each of eight enclosures placed over patches of the different substrate types, to determine if growth rates differed (Katz et al. 2017).

2013: Comparison of Agricultural Post-Harvest Substrates (Rice Stubble, Disced, or Fallow)

Substrates in flooded rice fields differ from those that juvenile salmon may encounter in natural floodplains or riverine systems. Thus, the goal of the second study year was to investigate whether juvenile salmon had differential growth and survival rates across agricultural substrates, and whether they would preferentially use a specific substrate type when given a choice. Our logic was that understanding these responses could provide insight into whether some agricultural practices provide more suitable salmon-rearing conditions than others.

To compare growth and survival rates across rice stubble, disced, and fallow substrates, we

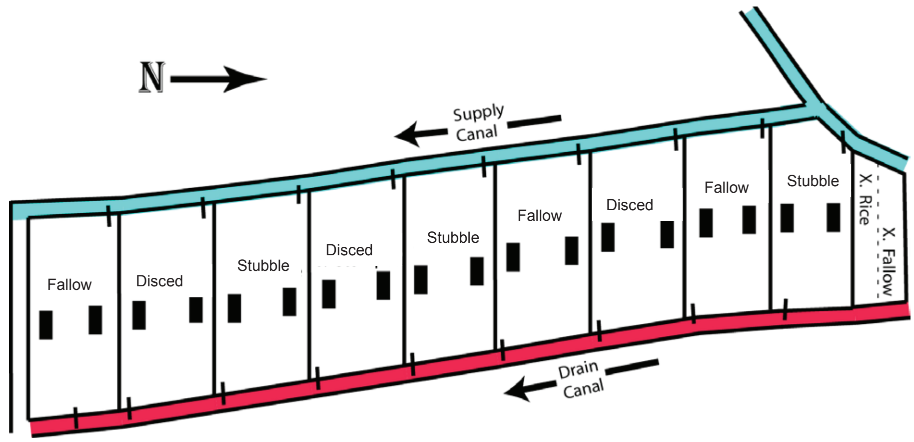

Figure 3 Schematic of nine replicated fields on Knaggs Ranch with substrate type and enclosure locations (*black boxes*)

created a series of nine 0.8-ha experimental fields with individual inlets and outlets, with three replicates of each substrate (Figure 3). We placed approximately 4,600 hatchery-origin juvenile Chinook Salmon in each field for 40 days and measured weekly during the study period to estimate average growth rates.

To examine substrate preference, we used PIT-tag technology to track individual fish in two large circular enclosures (15.25 m diameter). In addition to examining the potential for preference among agricultural substrates, this study also investigated whether newer and smaller PIT tags (8-mm tags compared to the traditional 12-mm tags) were viable for detecting juvenile salmon movements in these habitats. One enclosure included three habitat treatments (fallow, rice stubble, and disced), and the other served as a comparison with only the disced treatment. Each enclosure contained an array of six rectangular PIT antennas arranged in the same orientation. Fish remained in the enclosures for 14 days, during which occupancy data were collected. Detailed methods can be found in Conrad et al. (2016).

2014: Testing of Water Depth and Flow Characteristics of Fields

Observations during earlier study years indicated that juvenile salmon tended to congregate in areas near inflow and in deeper portions of fields. In 2014, we tested experimentally whether depth, proximity to inflow, or a combination of both affected juvenile Chinook Salmon occupancy patterns. Similar to 2013, we employed PIT-tag technology in combination with large field enclosures to track juvenile salmon movement. Specifically, we divided the study field into three 18-m × 15-m enclosures. Within each enclosure, three 6-m × 15-m panels were excavated into the substrate to achieve three water depths: 0.45 m, 0.75 m, and 1.0 m. Panels were arranged so each depth was represented at each of three flow positions (upstream, midstream, downstream) in a 3 × 3 factorial design. PIT antennae were placed in each depth panel, and PIT-tagged juvenile salmon were released into each enclosure, where they resided for 2 weeks.

2015: Comparison Across Different Geographical Areas (Sutter Bypass, Yolo Bypass, San Joaquin River)

Until 2015, our studies had been restricted to the Knaggs Ranch property in the northern Yolo Bypass. We extended our geographic scope during the fourth study year, investigating the food webs, juvenile salmon survival, and juvenile salmon growth on other agricultural properties, and in other Central Valley floodplain-river systems. These additional properties were

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Conaway Ranch adjacent to Cache Creek in the Yolo Bypass and south of the Knaggs Ranch property, Goose Club Ranch adjacent to the Feather River in the Sutter Bypass, and Dos Rios Ranch Preserve, located at the confluence of the Tuolumne and San Joaquin rivers (Figure 1). At each site we installed three 6-m × 12-m enclosures. We measured, weighed, and placed 40 juvenile salmon in each enclosure. After 3 weeks, we extracted, re-measured, and re-weighed fish, and analyzed gut contents to compare diets across sites. We collected zooplankton and drift invertebrate samples at each location to characterize the overall food web response to field inundation.

2016: Test of Feasibility of Using Agricultural Fields to Extend Natural Flood Events, Comparison of Different Habitats (flooded Yolo Bypass, Tule Canal, Sacramento River), Difference in Methodologies of Draining Fields

As an engineered floodplain, the Yolo Bypass is designed to drain efficiently. During moderate inundation events, availability of floodplain habitat can be brief—persisting for a week or less. In 2016, our focus was to test the feasibility of using agricultural infrastructure to extend the duration of a small to moderate flood event, increasing the length of time flooded habitat was available to fish. We called this idea "flood extension." We planned similar studies in other study years, but extreme weather events prevented implementation (*see below*). Landowner partners in the Yolo Bypass at Knaggs Ranch, Conaway Ranch, and Swanston Ranch agreed to maintain shallow inundation for 3 to 4 weeks in a designated experimental field after a natural flood event. At Knaggs Ranch, the landowner made modest to extensive modifications to the drainage infrastructure to allow more control (using a screw-type valve) over the drainage rate from the inundated field to the Toe Drain. At Swanston and Conaway ranches, inundation was maintained with flashboards, which could be removed once it was time to drain the field. During the first week of flood extension, we held stocked hatchery salmon and any entrained natural-origin salmon, allowing us to estimate growth and survival rates upon drainage. Thereafter, we allowed salmon to leave fields if they chose to do so. We outfitted field drains with a plastic mesh live-car trap, where we captured and measured emigrating individuals before they proceeded downstream.

2017: Lower Trophic Monitoring During Extensive Flooding

In 2016, the attempt to test a "flood extension" concept was unsuccessful because inundation occurred late in the season, resulting in unsuitably warm water temperatures for juvenile salmon in our experimental fields. We therefore made a second attempt to conduct a flood extension pilot in 2017 at Knaggs Ranch, Conaway Ranch, and Swanston Ranch, and at a new site in the Yolo Bypass Wildlife Area (YBWA) located south of Interstate 80 between the cities of Davis and Sacramento (Figure 1). Field infrastructure was identical to 2016, with the YBWA utilizing flashboards to hold water in similar fashion to Conaway and Swanston ranches. As we describe below, high flows made it infeasible to complete the flood extension work, although we were still able to conduct water-quality and food-web sampling, along with the use of experimental cages to evaluate salmon growth comparatively across experimental sites.

Lessons Learned

Flooded Farm Fields Support High Biological Productivity

Previous research has shown that inundated Yolo Bypass floodplain habitat typically has substantially higher densities of phytoplankton, zooplankton, and drift invertebrates than the adjacent Sacramento River across a suite of water year types (Sommer et al. 2001a, 2001b; 2004; Goertler et al. 2018). Our studies consistently showed that managed inundation of agricultural fields supported statistically higher levels of phytoplankton and invertebrates than the Sacramento River (Corline et al. 2017). Also notable was that phytoplankton and zooplankton densities in our flooded experimental fields in Yolo Bypass were higher than those measured during river-inundated flood events and in the Toe Drain, a perennial tidal channel (Corline et al. 2017; Katz et al. 2017). In addition, the invertebrate community in flooded rice fields was completely dominated by zooplankton (Corline et al. 2017), particularly Cladocera, whereas drift invertebrates such as Diptera were found in higher concentrations in study sites at Conaway Ranch and Dos Rios. Drift invertebrates are often a more substantial part of the food web in natural flood events in Yolo Bypass (Sommer et al. 2001a, 2001b, 2004; Benigno and Sommer 2009). Nonetheless, zooplankton densities can be relatively high in Yolo Bypass (as compared to the Sacramento River) during dry seasons and drought years (Frantzich et al. 2018; Goertler et al. 2018). The specific reasons for these differences include longer residence time and shallower depths in the Yolo Bypass than in adjacent perennial river channels (Sommer et al. 2004). Water source also may have been important for quantity and composition of invertebrates, including zooplankton, since all the managed flooding work was conducted using water from Knights Landing Ridge Cut, not the Sacramento River.

Resulting Fish Growth Was Rapid

Given the high densities of prey in the flooded fields, along with the low metabolic costs of maintaining position in a relatively low-velocity environment, it is not surprising that growth rates of juvenile salmon were comparatively high (e.g., Katz et al. 2017). This result was consistent across approaches used: cages, enclosures open to the substrate, and free-swimming fish.

When cages were used, salmon were PIT-tagged to track individual fish growth rates within a specific habitat. We consistently found that salmon growth rates in cages placed in flooded in rice fields were higher than growth rates for juvenile Chinook Salmon of comparative life stage in any of the adjacent riverine habitats and in other regions (Katz et al. 2017; Holmes et al., preprint under review).

Growth rates were also comparatively high when free-swimming salmon were introduced into larger-scale, 0.8-ha flooded agricultural fields. These studies were more representative than those using cages of how migrating salmon might use these habitats under natural flow events. For the multiple years that free-swimming salmon were used (Table 1), they averaged a mean daily growth rate of 0.98 mm d^{-1}. Throughout all study years, caged salmon and free-swimming salmon showed very similar growth rates within the same experimental study units, despite the fact that they likely experienced different micro-habitat conditions (e.g., velocity, prey, cover). This observation suggests that our salmon growth results were not influenced by cage effects, a well-known issue in enclosure studies (Kellison et al. 2003).

To better understand managed floodplain processes across the region, in 2015, salmon were introduced in fields at a variety of locations in the Central Valley with various vegetative substrates: Sutter Bypass (rice), three locations on the Yolo Bypass (rice wetland), and Dos Rios Ranch at the confluence of the Tuolumne and San Joaquin rivers (winter wheat). At all of the locations, juvenile Chinook Salmon grew at rates (range: 0.76–0.89 mm d^{-1}) similar to those observed in experiments conducted at Knaggs Ranch in the Yolo Bypass during previous study years. These results suggest that multiple geographical regions and substrate types can support high growth rates of juvenile Chinook Salmon.

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Substrate Type Was Less Important for Growth than Expected

A key objective of our work in flooded fields was to determine whether substrate type has a measurable influence on growth and survival of juvenile Chinook Salmon. Substrate and vegetation can be an important micro-habitat feature for young Chinook Salmon (Tabor et al. 2011), so we posited that there could potentially be some difference in salmon performance across treatments. In 2013, we examined this question across different substrate types in two ways: (1) telemetry studies using PIT tags; and (2) replicated fields. Both approaches indicated that juvenile salmon did not have a clear preference for different substrates, and grew at similar rates across substrates.

Telemetry

We monitored the movements and use of PIT-tagged, hatchery-origin juvenile Chinook Salmon for approximately 1 month over fallowed, disced, and rice stubble substrates in two circular enclosures to determine if there was any preferential use. One enclosure included all three substrates, and one contained only disced substrate (see Conrad et al. 2016 for further detail). Juvenile salmon did not exhibit a habitat preference among these three choices. Although growth rates were slightly higher in the enclosure that contained all three substrate types, juvenile salmon grew at very high rates, averaging 1.1 mm/d regardless of enclosure. These growth rates were higher than other published growth rates for juvenile Chinook Salmon in the Yolo Bypass, and the region generally (Sommer et al. 2001b).

Replicated Fields

We also observed comparably high juvenile Chinook Salmon growth rates across treatments in large replicated field experiments. The 2013 study involved placing juvenile Chinook Salmon in nine fields, which contained three replicates of each substrate type (fallow, disced, and rice-stubble; Figure 3), all receiving water from Knights Landing Ridge Cut. Our hypotheses for the replicated field study were that there would be no differences in water quality, invertebrate diversity, juvenile salmon growth, or juvenile salmon survival among substrate types.

Zooplankton levels increased over time, but did not show a consistent effect of substrate type on density or community structure (Corline et al. 2017). However, the disced treatment had lower average *Daphnia pulex* abundance in comparison to the fallow and stubble treatments, during the fifth week of the experiment. Densities over all substrate treatments were much higher compared to open water or river habitats (Sommer et al. 2004).

Fish from the fallow fields grew a little more slowly than fish from disced and stubble fields, but the differences were not statistically significant (Figure 4). Fish from all treatments grew at very high rates.

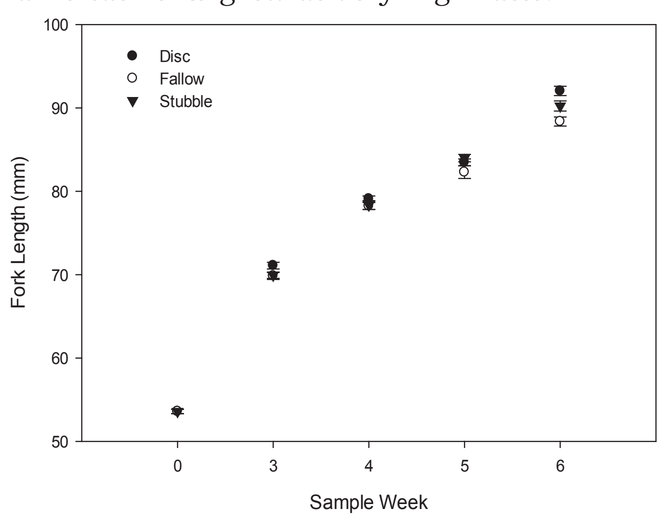

Figure 4 Mean fork length (± standard error) of free-swimming juvenile Chinook Salmon across substrate types over time.

Across all fields, the average growth rate was 0.93 mm/d, which is high compared to other published estimates from river channel habitats (e.g., Sommer et al. 2001b; Katz et al. 2017).

Flow and Connectivity are Critical Features of Juvenile Salmon Habitat on Flooded Agricultural Fields

Behavior

Throughout the 2012–2016 study period, we consistently observed that juvenile Chinook Salmon were attracted to sources of inflow, and that this sometimes became the dominant factor in the distribution of salmon on experimental fields or in enclosures. In the previously described PIT-tag observations in 2013, salmon in both enclosures positioned themselves nearest the inflow, regardless of surrounding habitat structure (Conrad et al. 2016). This result is not surprising, given that juvenile stream salmonids commonly adopt and defend flow-oriented positions in stream environments (e.g., Fausch 1984) for acquisition of drifting food resources. On flooded agricultural fields, this orientation toward flow may not only be related to feeding behavior but may also serve to keep juvenile salmon in habitat areas that are hydrologically connected and have higher velocities. In fact, analyses of the environmental factors that predict movement of large groups of tagged juvenile Chinook Salmon in the Yolo Bypass found that drainage of flooded areas was a reliable predictor of fish emigration at downstream trapping stations (Takata et al. 2017).

Survival

Although juvenile Chinook Salmon growth rates were consistently high across substrates and study years, we observed highly variable survival of salmon, and available evidence from the studies suggests that this was related, at least in part, to differences among years in drainage rates of the study fields and habitat availability on the floodplain at large. For example, survival in 2013 ranged from 0.0% to 29.3% (7.4% average) in the replicated fields containing different agricultural substrates. This variability was likely unrelated to substrate type; instead, these low survival rates were most likely a result of very dry conditions across Yolo Bypass and the Central Valley, generally, when record drought conditions prevailed during 2012–2015, which affected water quantity and quality. In 2013, our replicated field study likely presented one of the only wetted floodplain areas for miles around, and thus presented a prime feeding opportunity for avian predators such as cormorants, herons, and egrets. However, when the same set of fields was used in 2016, survival was much higher (ranging from 53.8% to 71.1%). This was generally a wetter period, avian predation pressure was reduced, and we more efficiently opened the flash boards (simple rice field drainage structures) to facilitate faster drainage and fish emigration. Note, however, there were some differences in methodology among years, which may have contributed to survival variability. Taken together, these observations of free-swimming salmon survival suggest that field drainage rate, and overall floodplain habitat availability, are important factors for improving survival in managed agricultural floodplain habitats.

Our observations of juvenile salmon orientation to flow, and the importance of efficient drainage on survival, reinforce observations from natural floodplains that connectivity between perennial channel habitat and seasonal floodplain habitat is an essential attribute of river-floodplain systems (Heiler et al. 1995). Connectivity of managed floodplain habitats to unmanaged habitats in the river and floodplain is therefore a foundational condition needed to allow volitional migration of juvenile salmon. Further research is needed to identify how to provide sufficient connectivity to maximize rearing and migration opportunities for wild Chinook Salmon.

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These Types of Studies Generate Numerous Challenges

Natural and managed floodplain habitat is subject to a variety of flow and environmental conditions. Variation in flow and temperature dictates when and where managed agricultural habitats may be accessible and suitable for rearing salmonids, with challenges during both wet and dry years, as well as during warm periods. As noted previously, survival in the replicated fields was variable but generally low. We associate these results with the effects of extreme drought conditions that prevailed during the core of our study from 2012 through 2015. Although our field studies were conducted during a time of year when wild salmon have historically used the Yolo Bypass floodplain (Takata et al. 2017; Goertler et al. 2018), the extreme drought made for warm water temperatures, and resulted in our study site being one of the few inundated wetland locations in the region. As such, avian predators were attracted to the experimental fields, exacerbating salmon mortality during drainage. We observed high concentrations of cormorants, herons, and egrets on the experimental fields, and this concentration increased over the study period. As many as 51 wading birds (great blue heron, snowy and great egrets) and 23 cormorants were noted during a single survey. The small scale of our project could have further exacerbated predation issues. This situation highlights the importance of the weather-dependent, regional context of environmental conditions, which govern how and when managed floodplains can be beneficial rearing habitats for juvenile salmon. Under certain circumstances, flooded fields can generate high salmon growth but in other scenarios, these habitats can provide poor environmental conditions (e.g., exceed thermal tolerances) for salmonids and/or become predation hot spots.

Even during wetter conditions, we found that management of agricultural floodplain habitat was challenging. For example, we had hoped to test the idea of using rice field infrastructure to extend the duration of Yolo Bypass inundation events in an attempt to approximate the longer-duration events of more natural floodplains; that is, through flood extension. As noted by Takata et al. (2017), use of the Yolo Bypass by wild Chinook Salmon is strongly tied to hydrology, and salmon quickly leave river-inundated floodplains once drainage begins. We therefore reasoned that flooded rice fields might provide an opportunity to extend the duration of flooding beyond the typical Yolo Bypass hydrograph. In 2015, a flood extension study was planned but not conducted because drought conditions precluded Sacramento River inflow via Fremont Weir. To test the flood extension concept in 2016, we needed substantial landowner cooperation and assistance to install draining structures that allowed maintenance of local flooding after high flow events. Even then, we found it difficult to maintain water levels and field integrity during the tests. In our case, we were fortunate to have the cooperation of willing landowners. Partnership with landowners was key, and would be critical with any future efforts to test the concept of flood extension. We also planned a similar test in 2017, but high and long-duration flood flows prevented the study from occurring. Over the 6 years of study, except perhaps for 2013 when we focused on other study priorities, we never experienced ideal conditions to adequately test the flood extension concept. We were either in a severe drought, during which the Yolo Bypass did not flood from the river, or we experienced severe and sustained flooding, which made it impossible to contain flood waters within study fields.

Based on these experiences, studying the concept of flood extension appears to depend on the occurrence of moderate flood events at the right time of year (December through March or April), provided fields are appropriately designed to hold water and allow efficient immigration and emigration of potentially large numbers of juvenile salmon. However, significant outreach and communication is necessary with landowners to maintain floodwaters on their fields during the natural drainage period. Because these events cannot be predicted well ahead of time, these communications—and availability of robust infrastructure—need to be constantly maintained even outside the flood extension period. As suggested in the previous section, such potential actions would need to be taken in a way that maintains hydrologic connectivity and salmon access, so that salmon can successfully locate potential managed habitats, use them for rearing, and then successfully emigrate from them at the appropriate time. Timing of such potential manipulations is critical because previous sampling has shown that salmon quickly emigrate from the floodplain during large-scale drainage events (Sommer et al. 2005), leaving relatively low densities of salmon in remaining ponded areas to potentially benefit from flood extension.

Although our use of hatchery salmon gave us more experimental options during drought conditions, the use of these fish resulted in additional challenges. Our approach relied on a non-traditional use of hatchery salmon, which required a suite of permits and approvals to execute the project. As noted above, the project coincided with a major drought, so access to hatchery salmon was limited as a result of low salmon population levels. In addition, use of hatchery salmon affected the time-period when we could conduct experimental work. We were unable to test salmon response to early season flooding (e.g., January), because the hatchery salmon were too small to receive coded-wire tags (CWTs) as required under our permit conditions. Similarly, the timing of our work was affected by the availability of holding tanks at our partner hatchery (Feather River Fish Hatchery), and by the availability of transport staff and vehicles to move salmon to our study site.

While we were able to assess many important biological metrics in our study, direct measurement of the population-level effect of floodplain rearing on agricultural habitats proved elusive. A traditional approach to addressing this question involves inserting CWTs into very large numbers (e.g., 100,000s) of experimental salmon and estimating the population response from expanded CWT recaptures in the ocean fisheries. Recoveries of CWTs in adult salmon from experimental releases made in the Yolo Bypass have generally been very low (Takata et al. 2017), making it difficult to get a high level of resolution with which to reliably compare survival rates, including with values in the literature. Although CWT recoveries could potentially be improved by increasing the number of tagged salmon, the effort required even to collect a single data point would be substantial and is limited by the availability of surplus hatchery salmon. A related issue is that it is difficult to design a survival experiment that provides a useful comparison to other management strategies or migration corridors. For example, it is challenging to assess the incremental survival value of flooded agricultural habitat versus adjacent perennial channels (i.e., Sacramento River, Yolo Bypass Tule Canal). Telemetry can partially address this issue, but current acoustic tagging technology does not allow estimates of survival once smolts emigrate from the estuary, and is also limited in the size of salmon that can be tagged. Ultimately, addressing the question of population-level effects will likely depend on a combination of measured field data, incorporating new methodologies for assessing survival to adulthood (e.g., isotopic and genetic tracers), and fish population models.

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Infrastructure Improvements Could Substantially Increase Research and Management Options

Our observations must be considered within the constraints of the infrastructure in the Yolo Bypass during the time of our field work. In the intervening years since our field studies, there has been a substantial amount of progress in improving Yolo Bypass infrastructure to support native fishes. During 2017-2018, an inflatable dam fish barrier and collection facility was constructed at Wallace Weir at Knights Landing Ridge Cut (Figure 1). This facility can enhance potential water distribution options for managed flooding studies under relatively low flow conditions when only Yolo Bypass tributary flows are available, including sources from Colusa Basin, which may not always have suitable water quality for juvenile salmonids. It is important to note, however, that these local water sources are not useful unless there is improved connectivity with the Sacramento River, allowing wild juvenile salmon to access seasonal habitat throughout the Yolo Bypass. To that end, the joint Environmental Impact Statement/Report was finalized in 2019 for a project that will improve connectivity between the Sacramento River and Yolo Bypass with a proposed notch in Fremont Weir (USBR and CDWR 2019). This proposed facility would allow managed flows at lower Sacramento River stages than the current weir structure, thereby increasing the frequency and duration of seasonal inundation, and providing improved access to the floodplain from the Sacramento River fish migration corridor. This upgrade is required as a condition of the 2009 Biological Opinion for Salmonids for long-term operation of the federal and state water projects (NMFS 2009).

Our study did not specifically address these new facilities or their operations, and how the concept of managed agricultural floodplain habitat can be integrated into the primary purposes of these improvements. Hence, potential use of flooded agricultural fields as juvenile salmon rearing habitat should be evaluated in light of both a modified hydrology and local land use and infrastructure changes. Additional research is needed to address the efficacy and suitability of different potential water sources, hydrology timing, connectivity with the Sacramento River, and related issues, such as the effects of operations on land use and other species or life stages (e.g., upstream migrating adult salmon).

CONCLUSIONS

Based on over 2 decades of research, California now has some of the best-studied temperate floodplains in the world. Work conducted in the lowland floodplains of California's Central Valley complements a growing body of literature from western North America that off-channel seasonal areas are important rearing habitat for several species of salmonids (e.g., Swales and Levings 1989; Ogston et al. 2015). The programs of study in the Yolo Bypass and the Cosumnes River (e.g., Sommer et al. 2001a, 2001b; Jeffres et al. 2008) have demonstrated the ecological value of floodplain habitat to Central Valley Chinook Salmon, and have contributed to California policies focused on multi-purpose projects that integrate flood-risk management objectives with the restoration of seasonal floodplain habitat (CDWR 2017). The Yolo Bypass is a particularly interesting example because it shows how flood management potentially can be integrated with agriculture, wildlife, recreation, and fisheries, thereby balancing the interests of multiple stake-holder groups (Sommer et al. 2001a; Opperman 2012; Suddeth et al. 2016). Previous research on the Yolo Bypass during river inundation events has consistently documented how access to seasonal floodplain increases rearing habitat and food availability, leading to enhanced growth and life-history diversity of juvenile Chinook Salmon. The same research has shown that the duration of floodplain inundation is constrained by the system's design, so young salmon can be forced off the floodplain before they accrue maximum benefits, which is now being addressed by the Fremont Weir Salmonid Habitat Restoration and Fish Passage Project (USBR and CDWR 2019). Hence, survival of young salmon in the Yolo Bypass can be relatively high (Sommer et al. 2001a, 2001b; Takata et al. 2017; Johnston et al. 2018), but anthropogenic features limit rearing benefits and create some stranding risks (Sommer et al. 2005; USBR and CDWR 2019).

In this context, our work on agricultural fields examined whether there were ways that agricultural habitats—one of the key anthropogenic features in the Yolo Bypass and in other developed large-river floodplains globally—could be improved for use by juvenile Chinook Salmon. As noted in the Introduction, our research effort was not intended as a proof of concept. Instead, we sought to better understand several critical habitat features in seasonally inundated agricultural fields, and to identify some of the challenges that would need to be addressed in future research and pilot implementation projects. Furthermore, our project should not be considered as advocacy for managed agricultural habitats as a substitute for more natural, unmanaged floodplain restoration projects. One of our goals was to identify ways in which managed flooding on agricultural fields in floodplains could potentially help mitigate for typically short inundation periods by extending natural flood events, allowing juvenile salmon to realize floodplain habitat benefits. We therefore still consider targeted inundation of agricultural fields to be an experimental approach that may in the future be complementary to demonstrated salmon restoration tools, such as creation of natural habitats (e.g., floodplain, tidal wetlands, and riparian habitat), gravel rehabilitation, removal of migration barriers, flow supplementation, and water temperature management.

As described in previous sections, flooded agricultural fields generate abundant food resources that support high juvenile salmon growth rates, but there were multiple challenges (e.g., high water temperatures, variable hydrology, predation, connectivity, infrastructure, and fish entrainment) that limited salmon survival and study execution. These observations suggest several targeted strategies aimed at improving the suitability of managed agricultural habitat for salmon rearing.

1. Temperature problems may be reduced by avoiding managed inundation of agricultural fields during warm spring periods. This does not mean that spring inundation is always undesirable, because some years have cool March and April periods, when habitat conditions could be highly suitable for juvenile salmon rearing.

2. Targeted inundation is questionable in drought situations when flooded fields appear more likely to draw avian predators, since shallow water foraging habitat is limited elsewhere. Maintaining deeper areas (e.g., 1 m or more) may help to provide juvenile salmon with predator refugia during any water year type.

3. Fields designed as fish habitat need to have sufficient structural integrity to support deeper water and flow. Our observations suggest that typical production rice fields do not meet these criteria.

4. Finally, and most important, managed fields would need to have high connectivity with adjacent channels for juvenile salmon to easily move on and off the seasonal habitat under their own volition. Simply put, the flooded fields are not viable rearing habitat unless wild juvenile Chinook Salmon have some way to find these locations, are able to find predator and temperature refugia as

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necessary, and then safely emigrate by the time water draw-down occurs.

As noted previously, fish entry into these managed agricultural floodplain habitats in the Yolo Bypass could be facilitated through natural flood events or perhaps new infrastructure (e.g., Fremont Weir notch; USBR and CDWR 2019). However, extension of natural flood events remains an unproven concept; moderate flood events timed in the middle of the winter-spring rainy season were uncommon during our study, and structural modifications to address needs for enhanced flow connectivity and depth were not in place when these moderate flood events did occur. Continued research on the potential value of extended natural flood events on agricultural habitat will need these structural modifications (e.g., Fremont Weir notch) in place to adequately test this concept. A related issue is that managed fields need to be located close to channels that are viable migration corridors. Long drainage ditch networks may not be viable emigration corridors since they could have high densities of predators and low water quality. Contributing to the development of "predator hot spots" as juvenile salmon emigrate from flooded agricultural fields would potentially negate the growth advantage that salmon can gain from these habitats. Future research should include modeling that weighs the growth advantages that flooded agricultural fields can confer against the focused predation risk that may develop when large numbers of juvenile salmon leave the fields synchronously during drawdown.

As a next step, we advocate continued research and pilot projects to address the key issues and remaining scientific uncertainties we identified in our studies. Continued research will require active partnership with local landowners to achieve structural modifications on fields with prime locations near major migration corridors, before additional experimental work. If the concept of managed extension of natural flood events on agricultural fields is supported with evidence of not only high growth rates but also high rates of wild salmon entrainment, suitable thermal conditions, and high survival rates of juvenile salmon, the next step would then be to move past the research and pilot stage to large-scale implementation, which would be a major effort. Developing a program in which extension of natural flood events is one of the tools available to managers to provide quality rearing habitat to juvenile salmon will require significant investment in resources for coordination between agencies and landowners, scientific support to provide for continued adaptive management, and monetary investments in infrastructure in flood bypasses and easements.

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