CENTRAL VALLEY FALL-RUN CHINOOK SALMON
Oncorhynchus tshawytscha

High Concern. Status Score = 2.7 out of 5.0. The number of spawners typically exceeds 100,000 fish each year but the run is largely supported by hatchery production.

Description: Members of the Central Valley (CV) fall-run Chinook salmon Evolutionary Significant Unit (ESU), like other Chinook salmon, have numerous small black spots on the back, dorsal fin, and both lobes of the tail in both sexes. This spotting on the caudal fin and the black coloration of their lower jaw make them distinguishable from other sympatric salmonid species. They have 10-14 major dorsal fin rays, 14-19 anal fin rays, 14-19 pectoral fins rays, and 10-11 pelvic fin rays. There are 130-165 scales along the lateral line. Branchiostegal rays number 13-19. They possess more than 100 pyloric caeca and have rough and widely spaced gill rakers, 6-10 on the lower half of the first gill arch.

Spawning adults are the largest Pacific salmonid, typically 75-80 cm SL, but lengths may exceed 140 cm. In California, Chinook are usually smaller, typically 45-60 cm SL. The average weight is 9-10 kg, although the largest Chinook salmon taken in California was 38.6 kg. Spawning adults are olive brown to dark maroon without streaking or blotches on the side. Males are often darker than females and develop a hooked jaw and slightly humped back during spawning. Juveniles have 6-12 parr marks, which often extend below the lateral line, and the marks are typically equal to or wider than the spaces between them. Parr can also be distinguished from other salmon species by the adipose fin, which is pigmented on the upper edge, but clear at the base and center. Some parr begin to show spots on the dorsal fin, but most fins are clear. There are no morphological features to separate this ESU from other Chinook salmon ESUs, so separation is based on genetics and life history characteristics, especially adult freshwater entry timing.

Taxonomic Relationships: Central Valley fall-run Chinook salmon are part of the CV complex consisting of four Chinook salmon runs differentiated by genetic differences, timing of spawning migrations, maturity of fish entering freshwater, spawning location, incubation duration, and out-migration timing of juveniles (Moyle 2002). The seasonal runs of CV Chinook salmon (winter, spring, fall and late fall) are more closely related to each other than they are to populations outside the CV (Williams 2006).

Winter- and spring-run Chinook are recognized as distinct ESUs, while the National Marine Fisheries Service groups the fall-run and late fall-run in a single ESU. This report differs from that taxonomy in that we regard the late-fall run to be a distinct taxon with a unique life-history strategy and specific management concerns. While the four runs of CV Chinook salmon were historically genetically distinct from each other, decades of interbreeding between fall and spring run in the Feather River below Oroville Dam and in Feather River Hatchery has produced Chinook salmon that return to the Feather River and tributaries in spring but that are nearly genetically identical to fall-run. CV fall run are the principal salmon raised in CV hatcheries to support fisheries and are released in large numbers. Adults from different hatcheries have a long history of straying to non-natal streams, resulting in a genetically near-uniform population found throughout the CV.

Life History: Chinook salmon life history strategies differ in the timing of their spawning migration, a fact implicit in the naming of the different "runs" according to the season in which they enter rivers from the ocean. However, the season of adult spawning migration is only one of the multiple life history attributes that differ between the runs of CV Chinook salmon (Table 1). Procession from one salmon life stage to the next is often characterized by movement between habitat types. This account focuses on life history and migratory characteristics specific to the CV fall-run which have a life history that minimizes time spent in fresh water. Fry and smolts out-migrate in spring before water temperatures become too warm, allowing fall-run to exploit the extensive lower elevation reaches of Central Valley rivers and streams, where temperatures exceed thermal tolerances during late spring, summer and early fall. In contrast, the other three CV Chinook salmon runs require cool, riverine habitats year-round.

Adult CV fall-run Chinook salmon begin entering fresh water in late summer and early fall as mature individuals and move relatively quickly to spawning grounds. Spawning usually occurs within several weeks to two months of freshwater entry. Peak spawning time is typically in October-November, but can continue through December and into January. Juveniles typically emerge from the gravel in December through March and rear in fresh water for 1-7 months, usually moving downstream into large rivers within a few weeks (Moyle 2002). Smolts tend to initiate migration during storm events and flow is positively correlated with migration rate (McCormick et al. 1998, Michel et al. 2013). In the clear upper reaches of the Sacramento River, out-migrating smolts employ a nocturnal migration strategy, a behavior likely influenced by decreased predation under cover of darkness. Likewise, reduced water clarity has a strong positive relationship with increased survival during out-migration. Presumably this is the result of the strong association between high turbidity and large flow events, which in combination reduce predation efficiency (Michel et al. 2013) and move fish rapidly downstream to floodplains and other rearing areas.

In the past, CV fall-run juveniles likely reared on formerly extensive valley floor floodplains. Juvenile fish foraging in the few remaining highly productive floodplain habitats grow much more quickly than those in major river channels (Sommer et al. 2001, Jeffres et al. 2008). Historically, this rapid growth before ocean entry likely increased survival of fall-run juveniles, which enter the ocean at relatively small size and young age compared to juveniles of other CV Chinook runs.

The slowest movement rates are observed in the estuary (Michel et al. 2013). From the estuary, juveniles move through the Golden Gate into the Gulf of the Farallones, which in late spring and early summer is typically an extremely food-rich region because of wind-driven upwelling associated with the California Current. Immature fish spend 2-5 years at sea, where they feed on fish and shrimp before returning as adults. Most of the fish remain off the California coast between Point Sur and Point Arena during this period, but many move into coastal waters of Oregon as well. Their movements in the ocean during this rearing period are poorly understood. Inshore, offshore and along-shore movements are likely in response to changing temperatures and upwelling strength. The vast majority of fall-run adults returning to the Central Valley and harvested in commercial and sport fisheries are 3 years old (Palmer-Zwahlen and Kormos 2015).

There are many exceptions to this general life cycle, including juveniles that spend as long as one year in fresh water. This yearling life history is likely supported by the novel habitat conditions found in the tailwater stream reaches below Central Valley rim dams where fall-run experience year-round cool temperatures at relatively low elevations. Essentially, dams have brought the perennially cool water conditions found in mountain canyons down to the valley floor. In general, the attributes of fall-run Chinook salmon that have allowed them to adapt to low-elevation regulated rivers have also made them the preferred run for hatchery production. Mature fish can be spawned as they arrive and juveniles only need to rear for a short time before being released into the rivers.

	Migration period	*Peak migration*	*Spawning period*	*Peak spawning*	*Juvenile emergence period*	*Juvenile stream residency*
Sacramento River basin						
Late fall run	October–April	December	Early January–April	February–March	April–June	7–13 months
Winter run	December–July	March	Late April–early August	May–June	July–October	5–10 months
Spring run	March–September	May–June	Late August–October	Mid-September	November–March	3–15 months
Fall run	June–December	September–October	Late September–December	October–November	December–March	1–7 months

Table 1. Generalized life history timing of Central Valley Chinook salmon complex. Data from Yoshiyama et al. 1998.

Habitat Requirements: The general habitat requirements of CV fall-run are similar to those of other Chinook salmon that minimize their time in fresh water (Healey 1991, Moyle 2002).

Adult migration: Fall run enter fresh water as mature fish with ripe gonads; they tend to migrate fairly directly to spawning grounds without holding for appreciable amounts of time, although low water conditions may delay upstream migration.

Spawning and egg incubation: A female salmon makes a redd (an area containing a series of individual nests) by repeatedly turning on her side and flexing her body so she pushes water down against the river bed. This action forces gravel up into the water column where it is carried a short ways downstream by the current. In this manner, the female “digs” an oval depression into the streambed and the current mounds the excavated material immediately downstream (Crisp and Carling 1989). Often, several males will court and fertilize the eggs of a single female, which she deposits in the “pot” of the nest. She will then move upstream and repeat the digging maneuver, removing fine sediment and burying the eggs in clean substrate. Chinook salmon use the largest substrate of any California salmonid for spawning, a mixture of large gravel and small cobble with a median particle diameter up to about 10% of their body length (Kondolf and Wolman 1993). Such coarse material allows sufficient water flow through the substrate to provide oxygen for developing embryos, while simultaneously removing metabolic waste. Redd size is a function of female size and substrate mobility. Redds are typically over 2-15 m^2 in size (Healey 1991) and observed at depths from a few centimeters to several meters and at water velocities of 15-190 cm/sec. The selection of redd sites is often a function of gravel permeability and subsurface water flow. Preferred spawning habitat seems to be at depths of 30-100 cm and at water velocities of 40-60 cm/sec.

By filling interstitial spaces between gravels, fine sediment can reduce water flow through the redd, effectively “smothering” embryos by denying them sufficient dissolved oxygen, causing toxic build-up of metabolic wastes, or physically hindering emergence from the gravel. For maximum embryo survival, water temperatures must be between 5º and 13º C and oxygen levels close to saturation. Incubation time is highly dependent on water temperature, dissolved oxygen (DO), and substrate permeability (Merz et al. 2004). Under optimal conditions, embryos hatch after 40-60 days and remain in the gravel as alevins for another 4-6 weeks, usually until the yolk sac is fully absorbed.

Chinook salmon are semelparous meaning that they spawn once and die, although individuals may survive for weeks after spawning. Especially where available spawning area is limited, late-arriving spawners may dig directly on top of previously constructed redds. Superimposition of redds can be a major mortality factor for incubating embryos and may result in a density-dependent relationship between the abundance of spawners and egg-to-fry survival.

Juvenile rearing and outmigration: Once alevins emerge and become fry, they tend to aggregate along stream edges, seeking cover in vegetation, swirling water, and dark backgrounds. As they grow larger and become increasingly vulnerable to avian predators, especially herons and kingfishers, they move into deeper (> 50 cm) water. Larger juveniles may often use the tails of pools or other moderately fast-flowing habitats, where food is abundant and there is some protection from predators. As juveniles move downstream, they use more open water during night while seeking protected pools during the day. Pools that are cooler than the main river, either from upwelling or tributary inflow, may be preferred by migrating juveniles as daytime refuges. The route by which Sacramento River smolts pass through the Sacramento-San Joaquin rivers Delta (Delta) has a significant effect on survival. Those that migrate through the interior Delta have higher mortality rates than fish remaining in the mainstem Sacramento River (Perry et al. 2010).

Fall-run tend to spend the least amount of time of any of the CV runs in fresh water largely because they must migrate to the ocean before their low elevation habitats get too hot during late spring and early summer. Juvenile use of off-channel habitat for rearing, including floodplains, improves growth prior to ocean entry (Sommer et al. 2001, Limm and Marchetti 2006, Jeffres et al. 2008). Off-channel habitat can also be important in the San Francisco Estuary (e.g., tidal marshes), but these habitats are now largely unavailable because they are cut off by levees. Today, less than 10% of historical CV wetland habitats remain accessible to CV salmon (Frayer et al. 1989, Hanak et al. 2011). The rich aquatic food webs found in off-channel wetland habitats along the valley reaches of rivers and in the Delta and estuary were a major driver of historical abundance.

Ocean habitats used for the first few months are poorly documented, but it is assumed that fish stay in coastal waters where the cold California Current, through upwelling, creates rich food supplies, particularly small shrimp. During the day, juveniles and subadults seem to avoid surface waters. Sub-adult Chinook salmon consume Pacific anchovies (*Engraulis mordax*), juvenile rockfish (*Sebastes spp.*), Pacific herring (*Clupea pallasii*), and other small fishes, typically at depths of 20-40 m and move offshore into deeper waters in response to temperature, food availability, and avoidance of predators.

Distribution: Central Valley fall-run Chinook salmon historically spawned in all major rivers of the CV, migrating as far as the Kings River to the south and the Upper Sacramento, McCloud, and Pit rivers to the north. Today, in the Sacramento and San Joaquin River watersheds, they spawn upstream as far as the first impassible dams. Passage into the mainstem San Joaquin River, above the confluence with the Merced River, is intentionally blocked at the CDFW-operated weir at Hills Ferry. Overall, it is estimated that approximately 60% of fall-run spawning habitat has been blocked by dams (Yoshiyama et al. 2001), although coldwater releases from dams now allow spawning in some places where it did not formerly exist (Yoshiyama et al. 1998). Fall-run Chinook salmon have been impacted less by dam construction than winter and spring-run Chinook salmon, because fall-run historically spawned in lower elevation stream reaches, up to 152-304 m (500–1,000 feet) above sea level (Yoshiyama et al. 2001). Levees block juveniles from accessing most historical floodplain and tidal marsh rearing habitats in the Central Valley and Bay-Delta.

Trends in Abundance: The historical abundance of fall-run Chinook salmon is difficult to estimate because populations declined before extensive monitoring and good record keeping. Yoshiyama et al. (1998) estimates that fall-run Chinook were historically one of the largest runs in the CV, with about a million spawners returning each year (Yoshiyama et al. 1998). Wild populations, however, were affected by a multitude of effects. Hydraulic mining operations during the Gold Rush Era buried spawning and rearing areas under mining debris before the first estimates of salmon population numbers. Likewise, Chinook salmon were extensively harvested in-river during the 19th century and, accurate, detailed records of run and river source were not documented. The exploitation by fisheries and alteration of California rivers during the Gold Rush likely reduced Chinook salmon abundance to about 10% of historical numbers by the early 1900s (Yoshiyama et al. 1998). Construction of large dams throughout the CV in the 1940s-60s further reduced wild Chinook populations. The extent of the impacts on CV Chinook populations is uncertain because artificial propagation also began during this era and no effort was made to differentiate wild Chinook from those produced by hatcheries. Until recent years, escapement estimates for CV fall-run salmon included both hatchery and natural-origin fish, with unknown relative proportions.

	Sub-Optimal	Optimal	Sub-Optimal	Lethal	Notes
Adult Migration	< 10ºC	10-20°C	20-21°C	>21-24°C	Migration usually stops when temperature climbs above 21ºC, with partial mortality occurring at 22-24ºC. Lethal temperature under most conditions is 24ºC. Fish observed moving at high temperatures are probably moving between cooler refuges.
Adult Holding	< 10ºC	10-16°C	16-21°C	> 21-24°C	Adults can experience heavy mortality above 21ºC under crowded conditions but will survive temperatures up to 24ºC for short periods of time. In some holding areas, maximum temperatures exceed 20ºC for over 50 days in summer.
Adult Spawning	< 13ºC	13-16°C	16-19°C	> 19°C	Egg viability is reduced with exposure to higher temperatures.
Embryo Incubation	< 9°C	9-13°C	13-17°C	> 17°C	This is the most temperature sensitive phase of the life cycle. American River salmon have 100% mortality > 16.7°C; Sac. River salmon mortality exceeded 82% > 13.9°C.
Juvenile Rearing	< 13°C	13-20°C	20-24°C	> 24°C	Past exposure (acclimation temperatures) has a large effect on thermal tolerance. Fish with high acclimation temperatures may survive 28-29ºC for short periods of time. Optimal conditions occur under fluctuating temperatures, with cooler temperatures usually at night. When food is abundant, juveniles may thrive at increased temperatures.
Smoltification	< 10ºC	10-19°C	19-24°C	> 24°C	Smolts may survive and grow at suboptimal temperatures but have a harder time avoiding predators; measured optimal temperatures are 13-17ºC (Marine and Cech 2004), but observations in the wild indicate a greater range.

Table 2. Chinook salmon thermal tolerances in fresh water. All lethal temperature data are presented as incipient upper lethal temperatures (IULT), which is a better indicator of natural conditions because experimental designs use a slower rate of change (ca. 1°C/day). Information largely from McCullough (1999).

From 1967 to 1991, an average of 250,000 adult fish returned to spawn with an additional 375,000 harvested each year in the commercial and sport fisheries (USFWS 2011). From 1992 to 2006, average escapement was nearly 400,000 with an annual average of 484,000 harvested by fisheries. In 2007, escapement plummeted to fewer than 100,000 fish with about 121,000 harvested in fisheries, prompting the first-ever closure of the California ocean salmon fishery. Returns dropped to 71,000 in 2008 and, in 2009, escapement reached a record low of 53,000 spawners, even as the ocean fisheries remained closed. Escapement in 2010 increased to 163,000 with a limited ocean fishing season and harvest of 20,400 fish. Central Valley escapement continued to rebound to approximately 228,000 fish in 2011 and 340,000 fish in 2012, and peaked at 447,000 in 2013 before dropping to 256,000 in 2014 and 152,000 in 2015, the last season for which data is available (CDFW GrandTab 2017).

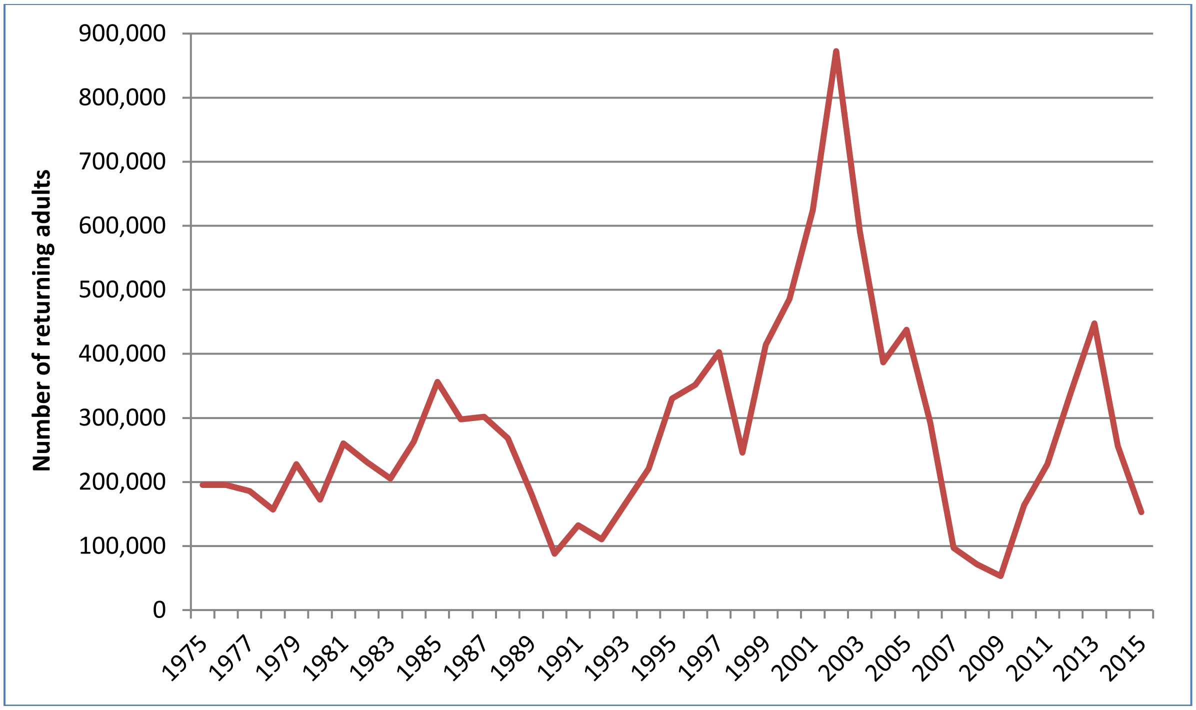

Figure 1. Estimated escapement (hatcheries plus in-river) of adult fall-run Chinook salmon in Central Valley rivers and streams. From: CDFW GrandTab, March 2017.

The effects of hatchery production on abundance and population dynamics of CV fall-run Chinook has been poorly documented, but improvements in tagging and monitoring programs since 2007 are enabling a better analysis of stock composition in the CV. Data from the CV Fractional Marking Program (Kormos et al. 2012, Palmer-Zwahlen and Kormos 2015) and otolith michrochemistry (Barnett-Johnson et al. 2007, Johnson et al. 2012) indicate that the vast majority of fall-run Chinook salmon are of hatchery origin (Figure 2). Stray rates between river basins are variable, but in most cases quite high (Kormos et al. 2012, Palmer-Zwahlen and Kormos 2015). Genetic evidence suggests that CV fall-run Chinook populations are now genetically homogenous and that natural origin and hatchery are fish indistinguishable from each other (Williamson and May 2003, Lindley et a l. 2009). Taken together, the evidence suggests that decades of hatchery production meant to augment natural stocks has instead replaced them.

Factors Affecting Status: Widespread and intensive development of the CV over the last 150 years has simplified river, floodplain, and estuarine habitats, altered ecological processes (i.e., hydrology, sediment transport, nutrient cycling) and fundamentally altered the CV Chinook salmon complex, from a diverse collection of numerous wild populations employing diverse life histories to one dominated by fall-run Chinook salmon produced in four large hatcheries (Lindley et al. 2009). Important factors continuing to threaten the viability of CV fall-run Chinook salmon include:

Dams. Large dams on the Sacramento River and its tributaries have blocked fall-run Chinook salmon access to much of their historical spawning grounds. Habitat downstream of the dams has been greatly altered. Regulated flows and resulting water temperatures are sometimes unsuitable for spawning and rearing. Gravels once washed down from upstream areas are now trapped in reservoirs, reducing spawning substrate below dams. Large quantities of gravel are now trucked to spawning areas below many dams to improve spawning habitat. Many large dams also have flow requirements for salmon spawning, egg incubation, rearing, and juvenile emigration. All restoration actions downstream of dams require regular, human intervention and their effectiveness at the population level is not well documented (Mesick 2001, Wheaton et al. 2004).

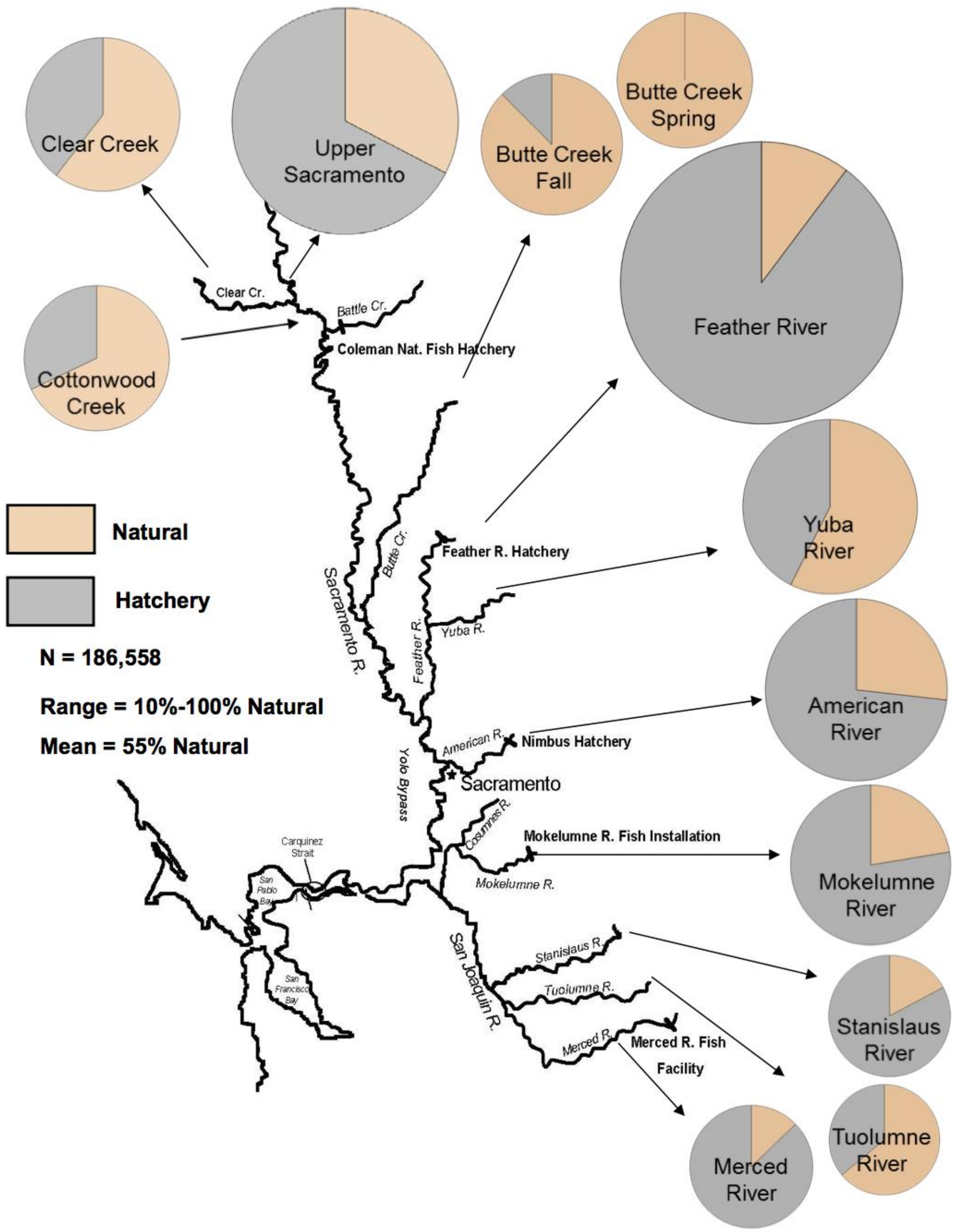

Figure 2. 2012 Fall-run Chinook salmon escapement, hatchery and natural proportions. From: DFW 2015, Fig. 3 pg. 18.

Agriculture. There are a large number of agricultural diversions along the Sacramento and San Joaquin Rivers and their tributaries, as well as in the Delta, which entrain juvenile salmon. Although most large diversions have been screened at considerable effort and expense to prevent entrainment, many small to medium diversions remain unscreened. Moyle and Israel (2005) noted that fish screens on rivers are subject to failure and may create holding areas for salmon predators (e.g., catfishes, striped bass, etc.). They also acknowledged that, despite their numbers, small diversions, even cumulatively, probably do not kill many salmon, unless they are on small tributaries. In general, the higher the proportion of flow taken by an unscreened diversion, the more likely the diversion is to have a negative impact on local salmon populations through entrainment.

The largest diversions in the Central Valley are those of the State Water Project (SWP) and the federal Central Valley Project (CVP) in the south Delta, which export water for both agricultural and urban use. Large pumping plants in the south Delta change the hydrology of the upper channels, resulting in substantial modifications in flow directions (Nichols et al. 1986). Pumping thus increases the likelihood of out-migrating smolts entering the interior Delta where longer routes, impaired water quality, higher predation rates, and entrainment lead to higher mortality rates (Perry et al. 2010). These pumping plants also entrain large numbers of fall-run Chinook salmon (as well as salmon of other runs), especially from San Joaquin River tributaries (Kimmerer 2008). Zeug and Cavallo (2014) found a strong positive correlation between the amount of water diverted and entrainment rates at diversion facilities. The largest diversions in the CV have louver screens that divert salmon to be "salvaged" by capture, trucking, and then released downstream in the Delta. However, both direct and indirect mortality associated with salvage operations is likely high because many stressed, disoriented salmon are eaten by predators immediately after release (Kimmerer 2008). Another cause of direct mortality is the high predation rates in Clifton Court Forebay, from which the SWP pumps water prior to it reaching the SWP salvage facility.

Agriculture also contributes to loss of juvenile habitat by limiting access, via an extensive network of flood protection levees, to the shallow, high-productivity habitats needed for rearing and protection from predators during migration. In addition to reduced access to floodplains, construction of levees to channelize rivers has had multiple effects, including simplifying bank structure through use of rip-rap, removal of large wood which creates cover, and reduction in shade. Recent studies have demonstrated the importance of floodplains for increased juvenile salmon growth and survival (Sommer et al. 2001, Jeffres et al. 2008). Inundation of floodplains increases water residence time, allowing it to warm compared to the relatively cool water in river channels. This in turn facilitates greater decomposition of terrestrial vegetation and increases primary production in the form of algal phytoplankton (Ahearn et al. 2006, Grosholz and Gallo 2006). Detrital decomposition and algal primary production are the primary sources of carbon that fuel aquatic food webs and supports zooplankton and other invertebrate populations, which, in turn, are the primary source of food for juvenile fish. Fish food densities are typically far greater on floodplains than in the river (Jeffres 2016, Corline et al. 2017).

In addition, juvenile salmonids may use less energy to maintain themselves on floodplains than they would in the mainstem Sacramento River, further reducing energy expenditure and increasing growth rates. For these reasons, growth rates for juvenile Chinook rearing in floodplain habitats exceed those rearing in riverine habitats (Sommer et al 2001, Jeffres et al. 2008, Katz et al. *in press*). In turn, larger out-migrants result in higher survival rates in the ocean (Unwin 1997, McCormick et al. 1998, Hayes et al. 2008, Williams et al. 2016). The rapid growth facilitated by inundated floodplain habitat is particularly important for fall-run which enter the lower river and Delta as small fish. However, there are very few floodplains now available to salmonid juveniles, which likely has a profound negative impact on survival and recruitment of naturally-spawned fall-run juveniles produced annually in the Central Valley.

A relatively new threat is the use of pyrethroid pesticides, which are particularly toxic to fish. Although mortality events are periodically recorded, the interacting effects of multiple pollutants on juvenile salmon survival are largely unknown. Even if pollutants are sublethal in concentration, they can stress both adult and juvenile fish, making them more vulnerable to disease, predation, and other stressors (Eder et al. 2008).

Urbanization. Urbanization can simplify habitats and degrade water quality conditions for Chinook salmon. Water diversions, levees (and their maintenance) and channel straightening all contribute to habitat simplification. Juvenile salmon are exposed to toxic materials discharged into rivers from urban and agricultural sources. Of particular concern is the poor water quality observed seasonally in the Stockton Deepwater Ship Channel. The channel serves as an area of concentration of pollutants from agricultural wastewater, discharges from the City of Stockton's sewage treatment facilities, storm drains, and other sources. Low dissolved oxygen levels in the fall have been shown to delay adult fall-run immigration into the San Joaquin basin.

Mining. Historical (and, to a lesser degree, ongoing) gold and gravel mining have dramatically altered many CV streams. Hydraulic and dredge mining in the 19th and early 20th centuries caused major morphological and hydrological changes in many rivers, degrading salmon spawning and rearing habitats. Many of these waterways are still recovering. In the past, Iron Mountain Mine, northwest of Redding, drained highly acidic water laden with heavy metals into the Sacramento River, resulting in acute mortality to Chinook salmon. Although discharge is now highly controlled, failure of the Spring Creek retention reservoir could result in severe impacts to aquatic life in large reaches of the Sacramento River.

Instream mining. Deep gravel pits in a number of rivers (e.g. Tuolumne, Merced, San Joaquin) reduce water velocities and allow for the aggregation of predatory fishes, potentially increasing mortality of juvenile salmon moving downstream.

Estuary alteration. Millions of naturally produced juvenile fall-run Chinook migrate into the estuary every year, but very few of them survive to return as adults (Williams 2012). Historically, juvenile fall-run Chinook salmon probably entered the estuary in February-June, and spent varying amounts of time there, in diverse habitats. However, loss of habitat diversity in the San Francisco Estuary has limited life history diversity and the best strategy for juvenile salmon today seems to be to move through the estuary as quickly as possible.

Despite long-term monitoring, causes of high mortality rates as fish pass through the estuary are poorly understood. General observations suggest that rearing conditions in the estuary are often poor. Juvenile fall run Chinook grow slowly in length (mean 0.33 mm per day) and hardly at all in weight during their passage from Chipps Island to the Golden Gate (MacFarlane 2005). Survival tends to be highest during wet years, when passage through the estuary is more rapid (Brandes and McLain 2001, Baker and Morhardt 2001) and fish are literally "flushed" through the system. Flooding in wet years also increases wetted off channel and floodplain habitats throughout the watershed resulting in greater floodplain contribution to river food webs and increasing rearing habitats in Sutter and Yolo Bypasses and the Delta, which likely has a positive effect on growth and survival.

Harvest. CV fall-run Chinook salmon support commercial and sport fisheries along the

California and Oregon coasts and freshwater sport fisheries in rivers of the Central Valley. Hatchery fish can sustain higher harvest rates than natural origin fish, but not all hatchery fish are visually marked, making it impossible to decipher between the two at the time of capture. It is, therefore, possible that existing recreational fisheries, in spite of being highly regulated and managed, may harvest natural-origin fish at unsustainable rates (Williams 2006). Wild-spawned fish, while a fraction of the overall fall-run, may be of particular importance in maintaining genetic attributes that increase life history diversity and adaptability to localized selection processes, particularly in the face of changing environmental conditions, such as those predicted under climate change (e.g., Hayhoe et al. 2004, Mote et al. 2005).

Fisheries also affect Chinook salmon populations through continual removal of larger and older individuals. This selection results in spawning runs made up primarily of two and three-year-old fish, which are smaller and, therefore, produce fewer eggs per female. The removal of older fish also removes much of the buffering that salmon populations have against natural disasters, such as severe drought, that may eliminate an entire cohort. Under natural conditions, four- and five-year-old fish residing in the ocean help buffer against population declines due to short-term environmental changes. In order to protect the low stock of CV fall-run Chinook salmon, ocean salmon fisheries were greatly restricted in 2006-2010 by the National Marine Fisheries Service and the Pacific Fisheries Management Council (*Congressional Record*, 50 CFR Part 660). The Chinook salmon sport fishery in the Sacramento River system was also restricted during this period. In 2011-2016 ocean and inland fisheries were not limited by low abundance of CV fall-run Chinook. However, the effects of the five-year drought (2011-2016) have likely impacted CV fall-run Chinook and the 2017 commercial ocean season has again been canceled.

Hatcheries. Over 2 billion juvenile salmon have been released from Central Valley hatcheries since 1946 (Huber and Carlson 2015). Analysis of coded wire tags recovered from returning adults indicates that hatchery-produced fish contribute the vast majority of total CV fall-run production (Kormos et al. 2012; Mohr and Satterthwaite 2013; Palmer-Zwahlen and Kormos 2013). Otolith analyses support these findings. Barnett- Johnson et al. (2007) showed that only 6% of 158 fall- run Chinook taken from the Pacific Ocean in 2002 were naturally produced, while Johnson et al. (2012) found that approximately 90% of fall-run Chinook returning to spawn in the Mokelumne River were of hatchery origin.

Increasingly juvenile Chinook salmon from Central Valley hatcheries are being trucked closer to the ocean and released downstream of the Delta in San Pablo and Grizzly bays (CDFW 2014, Huber and Carlson 2015). From 2007 to 2013, 54 percent of all hatchery fish in California were released off-site (PSMFC 2013). During the drought (2012-2016) the proportion of trucking juvenile Chinook increased dramatically. Transporting smolts improves survival, but it also increases straying rates in returning adults (Williams 2012). High straying rates contribute to homogenization of population structure and reductions in fitness by increasing gene flow among populations in different streams, thus reducing fitness of individuals, decreasing the reproductive capacity of populations, and eroding the biocomplexity of the entire CV fall-run Chinook salmon run. The homogenizing influence of hatcheries has made the fall-run more susceptible to adverse conditions, such as drought and corresponding low flows in freshwater habitats, or periods of reduced upwelling in coastal waters (Moyle et al. 2008, Carlson et al. 2011, Satterthwaite and Carlson 2015).

In general, the negative effects of hatchery production on wild stocks can be divided into ecological and genetic impacts, although the two interact considerably. Ecological effects include competition, predation, and disease transfer from hatchery stocks to wild populations

(Allendorf and Ryman 1987). Competition between hatchery and naturally-produced Chinook can reduce abundance (Pearsons and Temple 2010), growth rate (Williams 2006) and survival of wild juveniles in river, estuarine and marine habitats (Nickelson et al. 1986, Levin et al. 2001, Levin and Williams 2002, Nickelson 2003). Hatchery releases can even exceed the carrying capacity of ocean habitats, particularly in times of low ocean productivity (Beamish et al. 1997, Levin et al. 2001), resulting in high ocean mortality (Beamish et al. 1997, Heard 1998, Kaeriyama 2004).

Genetic effects include the loss of genetic diversity that facilitate adaptation to changing habitats by sustaining diverse behavior and life history strategies. Hatchery propagation has narrowed this behavioral variation in hatchery stocks (most fish are released over a short time period), leaving them vulnerable to climatic anomalies (ocean conditions, drought, etc.), and human alterations of the landscape. Hatchery propagation has also resulted in domestication of the stock, favoring a salmon genome that is well adapted to comparatively stable hatchery conditions, but may be less fit under variable natural conditions.

Alien species. For the past 150 years, numerous species have been introduced to the Central Valley. Probably most significant to these introductions are predatory fishes, including striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieu*), and spotted bass (*Micropterus punctulatus*). Striped bass are known to prey on large numbers of juvenile salmon at diversion structures such as the Red Bluff Diversion Dam, or where hatcheries release large numbers of juvenile fish. The three bass species can also be important predators, particularly when they inhabit in-channel gravel pits or other obstacles to juvenile salmon migration.

Factor	Rating	Explanation
Major dams	Medium	Dams prohibit access to many historical spawning areas, alter flows, and simplify stream geomorphology; however, flow releases generally provide adequate water quality and temperatures below major dams.
Agriculture	Medium	Diverted water reduces stream flow and entrains juvenile salmon; levees protecting agricultural lands limit salmon access to floodplains, tidal marshes, and other important habitats.
Grazing	Low	Relatively little grazing takes place on the CV valley floor.
Rural/ residential development	Low	Generally minimal impact on large river systems (e.g., Sacramento), but increasingly connected to urbanized areas.
Urbanization	Medium	Urban areas widespread and growing in many portions of historical range; urban landscapes generally simplify habitats, impair aquatic ecosystem function and pollute streams.
Instream mining	Medium	Gravel pits in rivers are a problem in some locations, particularly in the San Joaquin River basin.
Mining	Medium	Legacy effects of hydraulic and hard rock gold mining remain; impacts may still be severe at a local scale. For instance, toxic run off from Iron Mountain Mine remains a perpetual threat.
Transportation	Medium	Most smaller Chinook streams have roads and railroads along them, often leading to habitat simplification.
Logging	Low	Little logging in the CV although logging may affect upper portions of CV watersheds.
Fire	Low	Fire may affect upper portions of CV watersheds and effects can be propagated downstream.
Estuary alteration	Medium	The Delta and Estuary are greatly altered and current physical and water habitat conditions impact effective migration of adults and juveniles in both river basins.
Recreation	Low	Recreation can disturb redds and spawners.
Harvest	Medium	Ocean and inland fisheries may harvest natural-origin (wild spawned) fish at unsustainable rates.
Hatcheries	High	CV fall-run Chinook are genetically homogenized.
Alien species	Medium	Introduced species increase predation, competition, and decrease food supply but do not threaten fall-run with extinction.

Table 3. Major anthropogenic factors limiting, or potentially limiting, viability of populations of Central Valley fall-run Chinook salmon. Factors were rated on a five-level ordinal scale where a factor rated “critical” could push a species to extinction in 3 generations or 10 years, whichever is less; a factor rated “high” could push the species to extinction in 10 generations or 50 years whichever is less; a factor rated “medium” is unlikely to drive a species to extinction by itself but contributes to increased extinction risk; a factor rated “low” may reduce populations but extinction is unlikely as a result. Certainty of these judgments is high. See methods section for explanation.

Effects of Climate Change: Climate change is one of the most significant emerging threats to the persistence of CV salmon (Williams 2006, Katz et al. 2012). At the southern edge of the Chinook salmon range, the CV fall-run already experiences environmental conditions near the limit of its tolerance, making it highly vulnerable to climate change (Moyle et al. 2008). Thus, small thermal increases in summer water temperatures will result in suboptimal or lethal conditions and consequent reductions in distribution and abundance (Ebersole et al. 2001, Roessig et al. 2004). Changes in precipitation in California may also significantly alter CV fall-run habitats. Climate change models predict that a larger proportion of annual precipitation will fall as rain, rather than snow, running off quickly and earlier in the season. With less water stored in snowpack, reservoirs will potentially have less water available for fishery releases, particularly during summer and fall months. The available water is also likely to be warmer. During summer and fall, high water temperatures will be exacerbated due to the lower base flows resulting from reduced snowpack (Hamlet et al. 2005, Stewart et al. 2005).

For fall-run Chinook salmon, adults may have to ascend streams later in the season and juveniles may leave earlier, narrowing the window of time for successful spawning and rearing. Snowpack losses are expected to be increasingly significant at lower elevations, with elevations below 3,000 m suffering reductions of as much as 80% (Hayhoe et al. 2004). Consequently, in the long-term, changes in stream flow and temperature are expected to be much greater in the Sacramento River and its tributaries, which are fed by the relatively lower Cascades and northern Sierra Nevada, than are changes in rivers to the south, which are fed by snowpack that is expected to remain more consistent in the higher elevations of the southern Sierra Nevada (Mote et al. 2005).

One of the least understood effects of climate change is the impact on ocean conditions. However, the implications of predicted rises in sea level and temperature, along with changes in wind patterns, ocean currents, and upwelling, all suggest major impacts to CV salmon populations while in the ocean environment. Ocean survival rates in California salmon have been closely linked to several cyclical patterns of regional sea surface temperature, such as the Pacific Decadal Oscillation, El Niño Southern Oscillation (Beamish 1993, Hare and Francis 1995, Mantua et al. 1997, Mueter et al. 2002), and the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008). With increasing temperatures, the concentration of zooplankton (the primary food source for juvenile salmonids entering the ocean) may decrease, resulting in lower salmon survival (McGowan et al. 1998, Hays et al. 2005). Smolt-to-adult survival is also strongly correlated with upwelling in the Gulf of the Farallones, driven by strong winds during the spring and fall (Scheuerell and Williams 2005). Between 2005-2008, short-term anomalies in ocean conditions, resulting in decreased upwelling during critical times of year, were the likely proximate cause of low ocean survival for CV Chinook salmon (Barth et al. 2007, Lindley et al. 2009). Thus, as climate change results in more variable upwelling conditions, salmon populations may fluctuate more widely.

Status Score = 2.7 out of 5.0. High Concern. The Central Valley fall-run Chinook is listed as a species of special concern by NMFS and CDFW. The NMFS status review concluded that "…high hatchery production combined with infrequent monitoring of natural production make assessing the sustainability of natural production problematic, resulting in substantial uncertainty regarding this ESU (Myers et al. 1998)."

Metric	Score	Justification
Area occupied	2	Most populations sustained by hatcheries with some indication of natural self-sustaining populations in the upper Sacramento River watershed, Clear and Butte creeks.
Estimated adult abundance	4	Annual spawning returns generally exceed 100,000 fish.
Intervention dependence	2	The majority of remaining spawning and rearing habitat is dependent on instream flow releases from major dams, gravel augmentation and other ongoing efforts; population appears largely dependent on hatchery augmentation.
Tolerance	3	Moderate physiological tolerance.
Genetic risk	2	High hatchery production has resulted in genetic homogenization reducing overall fitness.
Climate change	3	Least vulnerable of CV Chinook runs to extirpation although models suggest dramatic changes to lower elevation CV rivers and streams will have negative effects.
Anthropogenic threats	2	1 High, 9 Medium threats.
Average	2.7	19/7.
Certainty	4	Well studied although still much uncertainty about ocean stage.

Table 4. Metrics for determining the status of Central Valley fall-run Chinook salmon, where 1 is a major negative factor contributing to status, 5 is a factor with no or positive effects on status, and 2-4 are intermediate values. Certainty of these judgments is high. See methods section for explanation.

Management Recommendations: There are three general directions where management actions could improve status: (1) improving information (2) improving habitat, and (3) and changing hatchery practices.

Improving information. All hatchery winter- and late-fall Chinook are adipose fin-clipped and implanted with coded-wire tags (CWTs) in the cartilage of their snout. Beginning in 2007, 25% percent of the roughly 32 million fall-run Chinook produced annually in CV hatcheries have been similarly marked. When an adipose fin-clipped salmon is harvested or a carcass recovered, CWT data can be read with the origin of the fish surmised. This fractional marking allows fishery managers to estimate the relative proportion of hatchery to naturally produced fish caught in commercial and recreational fisheries and returning to Central Valley rivers and hatcheries. Fractional marking data can also be used to determine straying rates of groups of tagged fish released from different hatcheries or compare stray rates between fish from the same hatchery released in different locations or at different times. However, because only 25% of hatchery fish are marked, most hatchery fish and natural origin (wild) salmon are still indistinguishable, which makes implementing management actions to benefit wild Chinook salmon nearly impossible.

A major step towards improving management of Central Valley Chinook salmon stocks would be to mark all hatchery fish with an adipose fin clip. Periodic checks of 'marked' fish are needed to determine the actual percentage that are marked. A fraction of these fish should be CWT tagged. Marking of all hatchery fish has been implemented successfully in Idaho, Oregon and Washington, and in all the Great Lakes. In California, total marking is supported by the American Fisheries Society, California-Nevada Chapter (2009) which argues that the practice would provide the following benefits:

- All hatchery fish would be instantly and visibly distinguishable from wild salmon
- Implanted internal tags in a fraction of adipose-clipped fish would continue to allow data collection on hatchery of origin, stock, race, and age as is with current fractional marking programs
- Wild fish could be distinguished and allowed selective access to limited spawning habitats
- Visual determination allows improved targeting of wild stocks for genetic monitoring
- Hatcheries could better control and manage spawning of hatchery and wild fish to minimize domestication effects

Another potential benefit of marking all hatchery fish is that it would allow experimentation with a fishery in which only marked (hatchery) fish are kept. A mark-selective fishery could provide a flexible and cost-effective management tool for sport (and possibly commercial) fisheries for fall-run Chinook and could accelerate recovery of ESA-listed Central Valley Chinook stocks. However, potentially high mortality rates of released fish, due to stress and marine mammal predation, may also make a mark-selective fishery controversial.

Ocean data. There is also a need to improve monitoring of salmon in the marine ecosystem off the California coast. Currently, our understanding of how ocean conditions affect salmon is largely educated guesswork with guesses often made long (sometimes years) after an event affecting the fish has occurred. An investment in better knowledge should have large pay-offs for better salmon management and population recovery.

Habitat diversity and a return to resiliency. Habitat diversity is essential to maintaining life history diversity in salmon populations. In the Central Valley, where a majority of salmon habitat has been lost behind either dams or levees, conservation strategies that restore and improve physical habitat quality, extent, and connectivity are essential tools in improving the resiliency of wild anadromous salmonid populations in a rapidly changing world.

Attaining volitional passage to spawning and rearing habitat above Central Valley rim dams is important for the long-term viability of Central Valley salmon populations as wild fish. Likewise, implementing ecologically designed flow regimes, which mimic natural flow patterns, would improve conditions for salmon and other native fish below dams. On Putah Creek (Solano County) a flow regime designed to mimic the seasonal timing of natural increases and decreases in stream flow helped reestablish native fishes and reduce the abundance of alien (nonnative) fishes 20 km below the Putah Creek Diversion Dam. Importantly, restoration of native fishes only required a small increase in the total volume of water delivered downstream (Kiernan et al. 2012). Better management of New Melones reservoir to increase San Joaquin River fall-run Chinook smolt survival could include increasing releases during wet years to better mimic natural spring releases. Such actions would also benefit downstream water quality needs.

Today, the Central Valley is a patchwork of agricultural lands and communities located on former floodplains and wetlands, which are now mostly separated from rivers by high, steep levees. As a consequence, access to ancestral floodplain habitats by juvenile salmon and other native fishes has been greatly diminished. Restoring connectivity between river channels and seasonal habitat such as oxbows, side channels, riparian terraces, and floodplains should be a high priority for restoration projects. Redesigning and managing the last large-scale floodplains still connected to the Sacramento River (i.e., Sutter and Yolo Bypasses) for salmon is an obvious start. On the San Joaquin River, reconnection of Paradise Cut and wildlife refuge floodplains are essential steps to expanding life history diversity, increasing growth, and increasing seasonal habitat for salmonids. Setting back levees where feasible improves flood protection and increases floodplain habitat for fish and wildlife. Farmland on the "dry side" of levees can also be better managed for the benefit of fish and aquatic ecosystems if winter fields are intentionally inundated to mimic natural flood patterns that produce large quantities of invertebrates which can be drained back to river channels to help support downstream aquatic food webs in the river and Delta.

By restoring or mimicking natural riverine processes, ecological flow regimes and floodplain reconnection can create and maintain a dynamic mosaic of habitat types in the Central Valley and re-expose native fishes to selection regimes similar to those under which they evolved and to which they are adapted. But restoration actions alone will never result in recovery of self-sustaining, naturally produced populations of Central Valley fall-run Chinook, as long as large numbers of straying hatchery fall-run continue to spawn in the wild.

Improving hatchery practices. Where large numbers of "domesticated" hatchery fish interbreed with naturally spawning fish, populations average only about half the number of returning offspring per spawner when compared with wild counterparts (Christie et al. 2014). Today, fall-run populations breeding in different Central Valley rivers are genetically indistinguishable (Williamson and May 2005). This means that current hatchery practices continue to limit the reproductive and adaptive potential of naturally produced fall run, severely limiting the potential for recovery and inhibiting their ability to adapt to inevitable changes in habitat conditions.

Emerging understanding of the dangers of domestication selection indicates that every effort must be made to segregate natural spawning and hatchery stocks. At the same time, hatchery practices must be redesigned in order to ensure that when introgression inevitably occurs, the fitness costs to naturally reproducing populations will be low.

The following management alternatives could help alleviate the demographic and genetic impacts of hatcheries on natural populations. These reforms, if implemented ***along with*** landscape-level habitat restoration, would increase the likelihood of recovering naturally produced self-sustaining populations of Central Valley fall-run Chinook and could benefit California fisheries.

Separate hatchery from wild populations. End or reduce gene flow between hatchery and naturally reproducing spawning groups. This is essential for recovery of naturally reproducing, locally adapted stocks. Two alternatives for segregating hatchery and naturally reproducing gene pools include: (1) physical segregation via active sorting at weirs or dams whereby only non-hatchery fish are passed upstream above barriers. This active sorting would only be possible if all hatchery fish were visually marked or if another "real-time" tests of hatchery origin were available and/or (2) switch to hatchery brood stocks that are divergent from local genomes; when hybridization between naturally produced individuals and hatchery strays inevitably occurs, the hybrid progeny inherit a genome unfit for local conditions, experience extremely high mortality rates, and are rapidly culled from the naturally reproducing gene pool. Broodstock for artificial propagation under this scenario should be selected from distant locations where life history characters (especially migratory timing) are incompatible with California streams. This would be a marked departure from current practices which aim to make hatchery broodstocks as similar as possible to naturally produced populations. While intended to reduce the ill effects of domestication selection on "wild" populations, the outcome of current practice may in reality produce the opposite effect by allowing domesticated alleles to thoroughly permeate the naturally-reproducing population and therefore significantly reduce the reproductive capacity of the entire population.

End trucking to limit straying. End off-site releases of hatchery salmon imprinted to return to hatcheries in the upper watershed. A salmon's ability to "home" to a natal river is a result of juvenile fish imprinting on sequential stream odors and other cues on their downstream migrations to the ocean. They then follow these olfactory clues in reverse order when returning as adults. Trucked hatchery fish, however, are returning to upper watersheds without the benefit of this map which they failed to acquire as smolts because they were transported. The result is a high rate of straying to other rivers where they interbreed with wild stocks.

Estuarine imprinting. Move artificial production facilities from the top of the watershed where ecological and genetic impacts of hatchery fish on wild populations are greatest to estuarine locations (imprinting fish to local streams using net pens) where interaction between hatchery and wild stocks will be minimized.

Harvest all hatchery fish. Establish highly efficient terminal fisheries to harvest all hatchery fish returning to estuarine imprinting locations as possible before they impact or interbreed with wild stocks. Increasing the efficiency of artificial propagation saves money, increases the return on investment, and could reinvigorate California's commercial fisheries while limiting genetic dilution of wild gene pools and minimizing competition with natural fish.

Phase out some hatchery programs. Where adverse impacts are deemed to outweigh benefits after careful consideration, close production hatcheries.

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