What caused the Sacramento River fall Chinook stock collapse?

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1 Executive summary

In April 2008, in response to the sudden collapse of Sacramento River fall Chinook salmon (SRFC) and the poor status of many west coast coho salmon populations, the Pacific Fishery Management Council (PFMC) adopted the most restrictive salmon fisheries in the history of the west coast of the U.S. The regulations included a complete closure of commercial and recreational Chinook salmon fisheries south of Cape Falcon, Oregon. Spawning escapement of SRFC in 2007 is estimated to have been 88,000, well below the PFMC's escapement conservation goal of 122,000-180,000 for the first time since the early 1990s. The situation was even more dire in 2008, when 66,000 spawners are estimated to have returned to natural areas and hatcheries. For the SRFC stock, which is an aggregate of hatchery and natural production, many factors have been suggested as potential causes of the poor escapements, including freshwater withdrawals (including pumping of water from the Sacramento-San Joaquin delta), unusual hatchery events, pollution, elimination of net-pen acclimatization facilities coincident with one of the two failed brood years, and large-scale bridge construction during the smolt outmigration (CDFG, 2008). In this report we review possible causes for the decline in SRFC for which reliable data were available.

Our investigation was guided by a conceptual model of the life history of fall Chinook salmon in the wild and in the hatchery. Our approach was to identify where and when in the life cycle abundance became anomalously low, and where and when poor environmental conditions occurred due to natural or human-induced causes. The likely cause of the SRFC collapse lies at the intersection of an unusually large drop in abundance and poor environmental conditions. Using this framework, all of the evidence that we could find points to ocean conditions as being the proximate cause of the poor performance of the 2004 and 2005 broods of SRFC. We recognize, however, that the rapid and likely temporary deterioration in ocean conditions is acting on top of a long-term, steady degradation of the freshwater and estuarine environment.

The evidence pointed to ocean conditions as the proximate cause because conditions in freshwater were not unusual, and a measure of abundance at the entrance to the estuary showed that, up until that point, these broods were at or near normal levels of abundance. At some time and place between this point and recruitment to the fishery at age two, unusually large fractions of these broods perished. A broad body of evidence suggests that anomalous conditions in the coastal ocean in 2005 and 2006 resulted in unusually poor survival of the 2004 and 2005 broods of SRFC. Both broods entered the ocean during periods of weak upwelling, warm sea surface temperatures, and low densities of prey items. Individuals from the 2004 brood sampled in the Gulf of the Farallones were in poor physical condition, indicating that feeding conditions were poor in the spring of 2005 (unfortunately, comparable data do not exist for the 2005 brood). Pelagic seabirds in this region with diets similar to juvenile Chinook salmon also experienced very poor reproduction in these years. In addition, the cessation of net-pen acclimatization in the estuary in 2006 may have contributed to the especially poor estuarine and marine survival of the

2005 brood.

Fishery management also played a role in the low escapement of 2007. The PFMC (2007) forecast an escapement of 265,000 SRFC adults in 2007 based on the escapement of 14,500 Central Valley Chinook salmon jacks in 2006. The realized escapement of SRFC adults was 87,900. The large discrepancy between the forecast and realized abundance was due to a bias in the forecast model that has since been corrected. Had the pre-season ocean abundance forecast been more accurate and fishing opportunity further constrained by management regulation, the SRFC escapement goal could have been met in 2007. Thus, fishery management, while not the cause of the 2004 brood weak year-class strength, contributed to the failure to achieve the SRFC escapement goal in 2007.

The long-standing and ongoing degradation of freshwater and estuarine habitats and the subsequent heavy reliance on hatchery production were also likely contributors to the collapse of the stock. Degradation and simplification of freshwater and estuary habitats over a century and a half of development have changed the Central Valley Chinook salmon complex from a highly diverse collection of numerous wild populations to one dominated by fall Chinook salmon from four large hatcheries. Naturally-spawning populations of fall Chinook salmon are now genetically homogeneous in the Central Valley, and their population dynamics have been synchronous over the past few decades. In contrast, some remnant populations of late-fall, winter and spring Chinook salmon have not been as strongly affected by recent changes in ocean conditions, illustrating that life-history diversity can buffer environmental variation. The situation is analogous to managing a financial portfolio: a well-diversified portfolio will be buffeted less by fluctuating market conditions than one concentrated on just a few stocks; the SRFC seems to be quite concentrated indeed.

Climate variability plays an important role in the inter-annual variation in abundance of Pacific salmon, including SRFC. We have observed a trend of increasing variability over the past several decades in climate indices related to salmon survival. This is a coast-wide pattern, but may be particularly important in California, where salmon are near the southern end of their range. These more extreme climate fluctuations put additional strain on salmon populations that are at low abundance and have little life-history or habitat diversity. If the trend of increasing climate variability continues, then we can expect to see more extreme variation in the abundance of SRFC and salmon stocks coast wide.

In conclusion, the development of the Sacramento-San Joaquin watershed has greatly simplified and truncated the once-diverse habitats that historically supported a highly diverse assemblage of populations. The life history diversity of this historical assemblage would have buffered the overall abundance of Chinook salmon in the Central Valley under varying climate conditions. We are now left with a fishery that is supported largely by four hatcheries that produce mostly fall Chinook salmon. Because the survival of fall Chinook salmon hatchery release groups is highly correlated among nearby hatcheries, and highly variable among years, we can expect to see more booms and busts in this fishery in the future in response to variation in the ocean environment. Simply increasing the production of fall

Chinook salmon from hatcheries as they are currently operated may aggravate this situation by further concentrating production in time and space. Rather, the key to reducing variation in production is increasing the diversity of SRFC.

There are few direct actions available to the PFMC to improve this situation, but there are actions the PFMC can support that would lead to increased diversity of SRFC and increased stability. Mid-term solutions include continued advocacy for more fish-friendly water management and the examination of hatchery practices to improve the survival of hatchery releases while reducing adverse interactions with natural fish. In the longer-term, increased habitat quantity, quality, and diversity, and modified hatchery practices could allow life history diversity to increase in SRFC. Increased diversity in SRFC life histories should lead to increased stability and resilience in a dynamic, changing environment. Using an ecosystem-based management and ecological risk assessment framework to engage the many agencies and stakeholder groups with interests in the ecosystems supporting SRFC would aid implementation of these solutions.

2 Introduction

In April 2008 the Pacific Fishery Management Council (PFMC) adopted the most restrictive salmon fisheries in the history of the west coast of the U.S., in response to the sudden collapse of Sacramento River fall Chinook (SRFC) salmon and the poor status of many west coast coho salmon populations. The PFMC adopted a complete closure of commercial and recreational Chinook fisheries south of Cape Falcon, Oregon, allowing only for a mark-selective hatchery coho recreational fishery of 9,000 fish from Cape Falcon, Oregon, to the Oregon/California border. Salmon fisheries off California and Oregon have historically been robust, with seasons spanning May through October and catches averaging over 800,000 Chinook per year from 2000 to 2005. The negative economic impact of the closure was so drastic that west coast Governors asked for $290 million in disaster relief, and the U.S. Congress appropriated $170 million.

Escapement of several west coast Chinook and coho salmon stocks was lower than expected in 2007 (PFMC, 2009), and low jack escapement in 2007 for some stocks suggested that 2008 would be at least as bad (PFMC, 2008). The most prominent example is SRFC salmon, for which spawning escapement in 2007 is estimated to have been 88,000, well below the escapement conservation goal of the PFMC (122,000–180,000 fish) for the first time since the early 1990s (Fig. 1). While the 2007 escapement represents a continuing decline since the recent peak escapement of 725,000 spawners in 2002, average escapement since 1983 has been about 248,000. The previous record low escapement, observed in 1992, is believed to have been due to a combination of drought conditions, overfishing, and poor ocean conditions (SRFCRT, 1994). Although conditions have been wetter than average over the 2000-2005 period, the spawning escapement of jacks in 2007 was the lowest on record, significantly lower than the 2006 jack escapement (the second lowest on record), and the preseason projection of 2008 adult spawner escapement was only 59,000[1] despite the complete closure of coastal and freshwater Chinook fisheries.

Low escapement has also been documented for coastal coho salmon during this same time frame. For California, coho salmon escapement in 2007 averaged 27% of parent stock abundance in 2004, with a range from 0% (Redwood Creek) to 68% (Shasta River). In Oregon, spawner estimates for the Oregon Coast natural (OCN) coho salmon were 30% of parental spawner abundance. These returns are the lowest since 1999, and are near the low abundances of the 1990s. Columbia River coho and Chinook stocks experienced mixed escapement in 2007 and 2008.

For coho salmon in 2007 there was a clear north-south gradient, with escapement improving to the north. California and Oregon coastal escapement was down sharply, while Columbia River hatchery coho were down only slightly (PFMC, 2009). Washington coastal coho escapement was similar to 2006. Even within the OCN region, there was a clear north-south pattern, with the north coast region (predominantly Nehalem River and Tillamook Bay populations) returning at 46%

[1] Preliminary postseason estimate for 2008 SRFC adult escapement is 66,000.

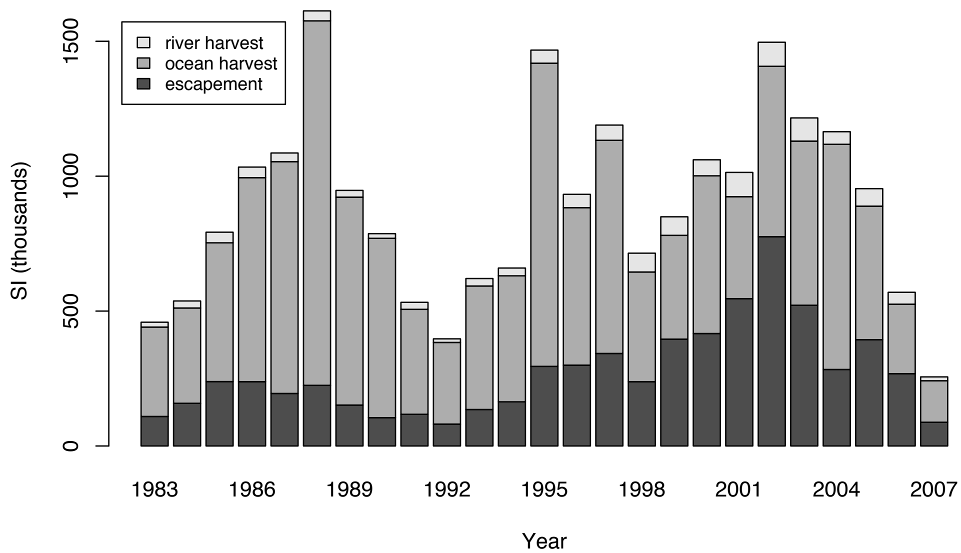

Figure 1: Sacramento River fall Chinook escapement, ocean harvest, and river harvest, 1983–2007. The sum of these components is the Sacramento Index (SI). From O'Farrell et al. (2009).

of parental abundance while the mid-south coast region (predominantly Coos and Coquille populations) returned at only 14% of parental abundance. The Rogue River population was only 21% of parental abundance. Low 2007 jack escapement for these three stocks in particular suggests a continued low abundance in 2008. In addition, Columbia River coho salmon jack escapement in 2007 was also near record lows.

There have been exceptions to these patterns of decline. Klamath River fall Chinook experienced a very strong 2004 brood, despite parent spawners being well below the estimated level necessary for maximum production. Columbia River spring Chinook production from the 2004 and 2005 broods will be at historically high levels, according to age-class escapement to date. The 2008 forecasts for Columbia River fall Chinook "tule" stocks are significantly more optimistic than for 2007. Curiously, Sacramento River late-fall Chinook escapement has declined only modestly since 2002, while the SRFC in the same river basin fell to record low levels.

What caused the observed general pattern of low salmon escapement? For the SRFC stock, which is an aggregate of hatchery and natural production (but probably dominated by hatchery production (Barnett-Johnson et al., 2007)), freshwater withdrawals (including pumping of water from the Sacramento-San Joaquin Delta), unusual hatchery events, pollution, elimination of net-pen acclimatization facilities coincident with one of the two failed brood years, and large-scale bridge construction during the smolt outmigration along with many other possibilities have been suggested as prime candidates causing the poor escapement (CDFG, 2008).

When investigating the possible causes for the decline of SRFC, we need to recognize that salmon exhibit complex life histories, with potential influences on their survival at a variety of life stages in freshwater, estuarine and marine habitats. Thus, salmon typically have high variation in adult escapement, which may be explained by a variety of anthropogenic and natural environmental factors. Also, environmental change affects salmon in different ways at different time scales. In the short term, the dynamics of salmon populations reflect the effects of environmental variation, e.g., high freshwater flows during the outmigration period might increase juvenile survival and enhance recruitment to the fishery. On longer time scales, the cumulative effects of habitat degradation constrain the diversity and capacity of habitats, extirpating some populations and reducing the diversity and productivity of surviving populations (Bottom et al., 2005b). This problem is especially acute in the Sacramento-San Joaquin basin, where the effects of land and water development have extirpated many populations of spring-, winter- and late-fall-run Chinook and reduced the diversity and productivity of fall Chinook populations (Myers et al., 1998; Good et al., 2005; Lindley et al., 2007).

Focusing on the recent variation in salmon escapement, the coherence of variations in salmon productivity over broad geographic areas suggests that the patterns are caused by regional environmental variation. This could include such events as widespread drought or floods affecting hydrologic conditions (e.g., river flow and temperature), or regional variation in ocean conditions (e.g., temperature, upwelling, prey and predator abundance). Variations in ocean climate have been increasingly recognized as an important cause of variability in the landings, abundance, and productivity of salmon (e.g, Hare and Francis (1995); Mantua et al. (1997); Beamish et al. (1999); Hobday and Boehlert (2001); Botsford and Lawrence (2002); Mueter et al. (2002); Pyper et al. (2002)). The Pacific Ocean has many modes of variation in sea surface temperature, mixed layer depth, and the strength and position of winds and currents, including the El Niño-Southern Oscillation, the Pacific Decadal Oscillation and the Northern Oscillation. The broad variation in physical conditions creates corresponding variation in the pelagic food webs upon which juvenile salmon depend, which in turn creates similar variation in the population dynamics of salmon across the north Pacific. Because ocean climate is strongly coupled to the atmosphere, ocean climate variation is also related to terrestrial climate variation (especially precipitation). It can therefore be quite difficult to tease apart the roles of terrestrial and ocean climate in driving variation in the survival and productivity of salmon (Lawson et al., 2004).

In this report we review possible causes for the decline in SRFC, limiting our analysis to those potential causes for which there are reliable data to evaluate. First, we analyze the performance of the 2004, 2005 and 2006 broods of SRFC and look for corresponding conditions and events in their freshwater, estuarine and marine environments. Then we discuss the impact of long-term degradation in freshwater and estuarine habitats and the effects of hatchery practices on the biodiversity of Chinook in the Central Valley, and how reduced biodiversity may be making Chinook fisheries more susceptible to variations in ocean and terrestrial climate. We end the report with recommendations for future monitoring, research, and conservation actions. The appendix answers each of the more than 40 questions posed to the committee and provides summaries of most of the data used in the main report (CDFG, 2008).

3 Analysis of recent broods

3.1 Review of the life history of SRFC

Naturally spawning SRFC return to the spawning grounds in the fall and lay their eggs in the low elevation areas of the Sacramento River and its tributaries (Fig. 2). Eggs incubate for a month or more in the fall or winter, and fry emerge and rear throughout the rivers, tributaries and the Delta in the late winter and spring. In May or June, the juveniles are ready for life in the ocean, and migrate into the estuary (Suisun Bay to San Francisco Bay) and on to the Gulf of the Farallones. Emigration from freshwater is complete by the end of June, and juveniles migrate rapidly through the estuary (MacFarlane and Norton, 2002). While information specific to the distribution of SRFC during early ocean residence is mostly lacking, fall Chinook in Oregon and Washington reside very near shore (even within the surf zone) and near their natal river for some time after ocean entry, before moving away from the natal river mouth and further from shore (Brodeur et al., 2004). SRFC are encountered in ocean salmon fisheries in coastal waters mainly between central California and northern Oregon (O'Farrell et al., 2009; Weitkamp, In review), with highest abundances around San Francisco. Most SRFC return to freshwater to spawn after two or three years of feeding in the ocean.

A large portion of the SRFC contributing to ocean fisheries is raised in hatcheries (Barnett-Johnson et al., 2007), including Coleman National Fish Hatchery (CNFH) on Battle Creek, Feather River Hatchery (FRH), Nimbus Hatchery on the American River, and the Mokelumne River Hatchery. Hatcheries collect fish that ascend hatchery weirs, breed them, and raise progeny to the smolt stage. The state hatcheries transport >90% of their production to the estuary in trucks, where some smolts usually are acclimatized briefly in net pens and others released directly into the estuary; Coleman National Fish Hatchery (CNFH) usually releases its production directly into Battle Creek.

3.2 Available data

A large number of datasets are potentially relevant to the investigation at hand. These are summarized in Table 1.

3.3 Conceptual approach

The poor landings and escapement of Chinook in 2007 and the record low escapement in 2008 suggests that something unusual happened to the SRFC 2004 and 2005 broods, and more than forty possible causes for the decline were evaluated by the committee. Poor survival of a cohort can result from poor survival at one or more stages in the life cycle. Life cycle stages occur at certain times and places, and an examination of possible causes of poor survival should account for the temporal and spatial distribution of these life stages. It is helpful to consider a conceptual model of a cohort of fall-run Chinook that illustrates how various anthropogenic and natural factors affect the cohort (Fig. 3). The field of candidate causes can be narrowed by looking at where in the life cycle the abundance of the cohort became unusually low, and by looking at which of the causal factors were at unusual levels for these broods. The most likely causes of the decline will be those at unusual levels at a time and place consistent with the unusual change in abundance.

In this report, we trace through the life cycle of each cohort, starting with the parents of the cohort and ending with the return of the adults. Coverage of life stages and possible causes for the decline varies in depth, partly due to differences in the information available and partly to the committee's belief in the likelihood that particular life stages and causal mechanisms are implicated in the collapse. Each potential factors identified by CDFG (2008) is, however, addressed individually in the Appendix. Before we delve into the details of each cohort, it is worthwhile to list some especially pertinent observations relative to the 2004 and 2005 broods:

- Near-average numbers of fall Chinook juveniles were captured at Chipps Island

Table 1: Summary of data sources used in this report.

Data type	Period	Source
Time series of ocean harvest, river harvest and escapement	1983-2007	PFMC
Coded wire tag recoveries in fisheries and hatcheries	1983-2007	PSMFC
Fishing effort	1983-2007	PSMFC
Bycatch of Chinook in trawl fisheries	1994-2007	NMFS
Hatchery releases and operations	varies	CDFG, USFWS
Catches of juvenile salmon in survey trawls near Chipps Island	1977-2008	USFWS
Recovery of juvenile salmon in fish salvage operations at water export facilities	1997-2007	DWR
Time series of river conditions (discharge, temperature, turbidity) at various points in the basin	1990-2007	USGS, DWR
Time series of hydrosystem operations (diversions and exports)	1955-2007	DWR, USBR
Abundance of striped bass	1990-2007	CDFG
Abundance of pelagic fish in Delta	1993-2007	CDFG
Satellite-based observations of ocean conditions (sea surface temperature, winds, phytoplankton biomass)	various	NOAA, NASA
Observations of estuary conditions (salinity, temperature, Chl, dissolved O_2)	1990-2007	USGS
Zoolankton abundance in the estuary	1990-2007	W. Kimmerer, SFSU
Ship-based observations of physical and biological conditions in the ocean (abundance of salmon prey items, mixed layer depth)	1983-2007	NOAA
Ocean winds and upwelling	1967-2008	NMFS
Abundance of marine mammals	varies	NMFS
Abundance of groundfish	1970-2005	NMFS
Abundance of salmon prey items	1983-2005	NMFS
Condition factor of juvenile Chinook in estuary and coastal ocean	1998-2005	NOAA
Seabird nesting success	1971-2005	PRBO

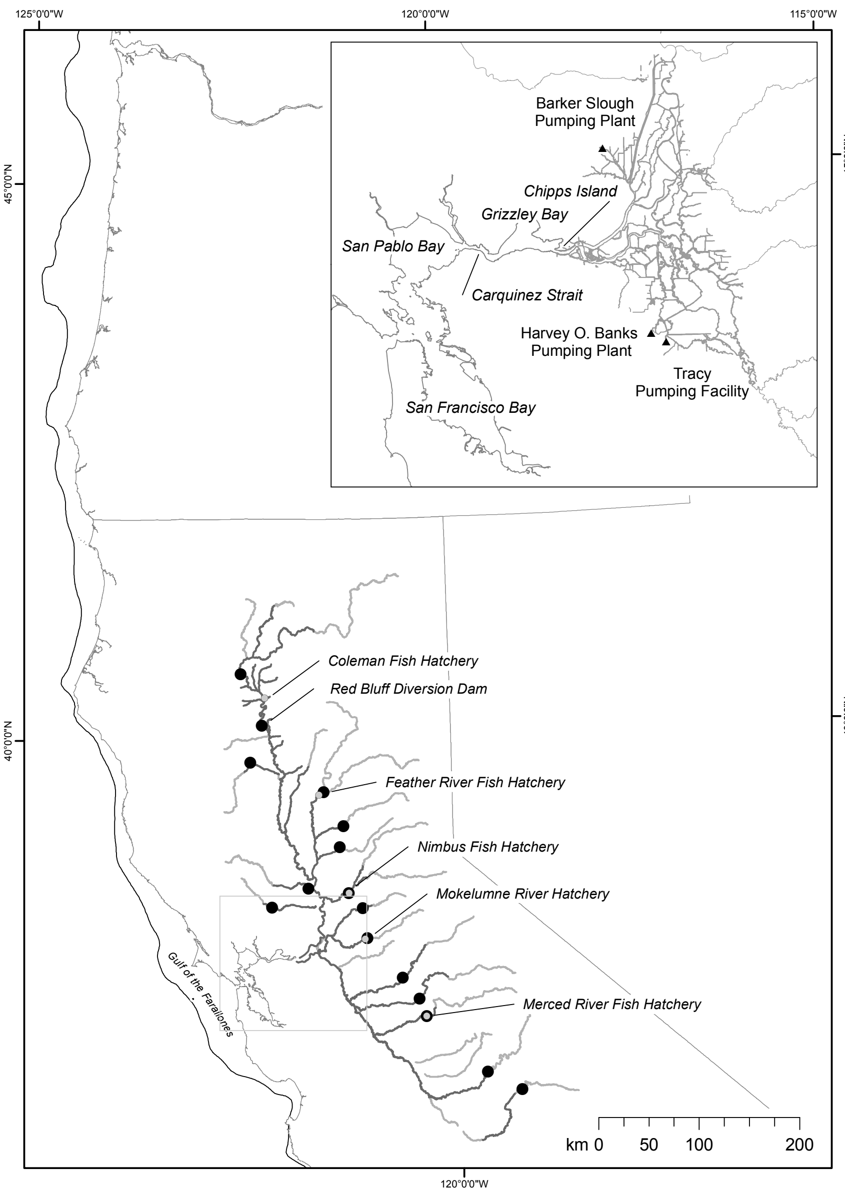

Figure 2: Map of the Sacramento River basin and adjacent coastal ocean. Inset shows the Delta and bays. Black dots denote the location of impassable dams; black triangle denote the location of major water export facilities in the Delta. The contour line indicates approximately the edge of the continental shelf.

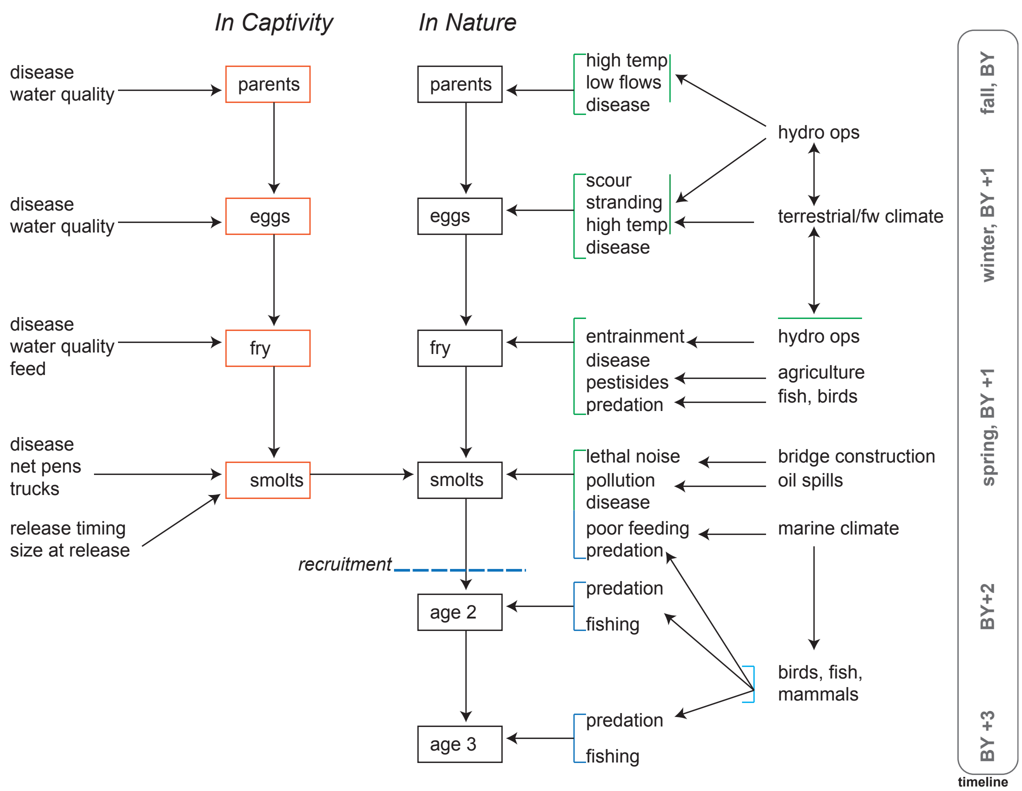

Figure 3: Conceptual model of a cohort of fall-run Chinook and the factors affecting its survival. Orange boxes represent life stages in the hatchery, and black boxes represent life stages in the wild.

- Near-average numbers of SRFC smolts were released from state and federal hatcheries

- Hydrologic conditions in the river and estuary were not unusual during the juvenile rearing and outmigration periods (in particular, drought conditions were not in effect)

- Although water exports reaches record levels in 2005 and 2006, these levels were not reached until June and July, a period of time which followed outmigration of the vast majority of fall Chinook salmon smolts from the Sacramento system

- Survival of Feather River fall Chinook from release into the estuary to recruitment to fisheries at age two was extremely poor

- Physical and biological conditions in the ocean appeared to be unusually poor for juvenile Chinook in the spring of 2005 and 2006

- Returns of Chinook and coho salmon to many other basins in California, Oregon and Washington were also low in 2007 and 2008.

From these facts, we infer that unfavorable conditions during the early marine life of the 2004 and 2005 broods is likely the cause of the stock collapse. Freshwater factors do not appear to be implicated directly because of the near average abundance of smolts at Chipps Island and because tagged fish released into the estuary had low survival to age two. Marine factors are further implicated by poor returns of coho and Chinook in other west coast river basins and numerous observations of anomalous conditions in the California Current ecosystem, especially nesting failure of seabirds that have a diet and distribution similar to that of juvenile salmon.

In the remainder of this section, we follow each brood through its lifecycle, bringing relatively more detail to the assessment of ocean conditions during the early marine phase of the broods. While we are confident that ocean conditions are the proximate cause of the poor performance of the 2004 and 2005 broods, human activities in the freshwater environment have played an important role in creating a stock that is vulnerable to episodic crashes; we develop this argument in section 4.

3.4 Brood year 2004

3.4.1 Parents

The possible influences on the 2004 brood of fall-run Chinook began in 2004, with the maturation, upstream migration and spawning of the brood's parents. Most significantly, 203,000 adult fall Chinook returned to spawn in the Sacramento River and its tributaries in 2004, slightly more than the 1970-2007 mean of 195,000; escapement to the Sacramento basin hatcheries totaled 80,000 adults (PFMC, 2009). In September and October of 2004, water temperatures were elevated by about

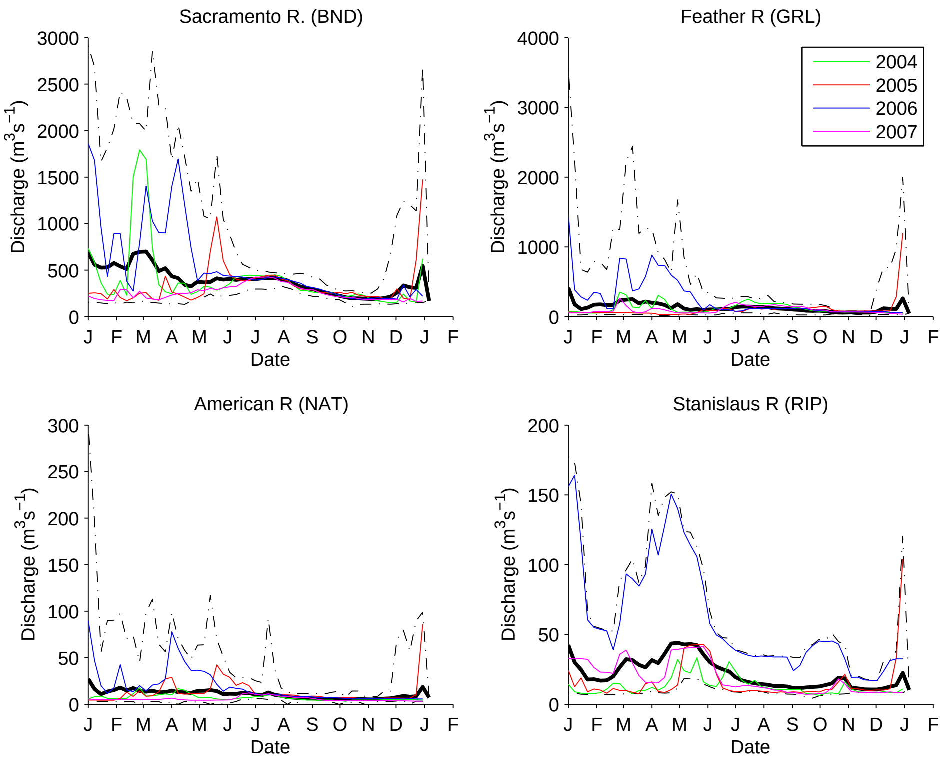

Figure 4: Discharge in regulated reaches of the Sacramento River, Feather River, American River and Stanislaus River in 2004-2007. Heavy black line is the weekly average discharge over the period of record for the stream gage (indicated in parentheses in the plot titles); dashed black lines indicate weekly maximum and minimum discharges. Data from the California Data Exchange Center, `http://cdec.water.ca.gov`.

1°C above average at Red Bluff, but remained below 15.5°C. Temperatures inhibiting the migration of adult Chinook are significantly higher than this (McCullough, 1999). Flows were near normal through the fall and early winter (Fig. 4). Escapement to the hatcheries was near record highs, and no significant changes to broodstock selection or spawning protocols occurred. Carcass surveys on the Sacramento River showed very low levels of pre-spawning mortality in 2004 (D. Killam, CDFG, unpublished data). It therefore appears that factors influencing the parents of the 2004 brood were not the cause of the poor performance of that brood.

3.4.2 Eggs

The naturally-spawned portion of the 2004 brood spent the egg phase in the gravel from October 2004 through March 2005 (Vogel and Marine, 1991). Water temperatures at Red Bluff were within the optimal range for egg incubation for most of this period, with the exception of early October. Flows were below average throughout the incubation period, but mostly above the minimum flow levels observed for the last 20 years or so. It is therefore unlikely that the eggs suffered scouring flows; we have no information about redd dewatering, although flows below the major dams are regulated to prevent significant redd dewatering.

In the hatcheries, no unusual events were noted during the incubation of the eggs of the 2004 brood. Chemical treatments of the eggs were not changed for the 2004 brood.

3.4.3 Fry, parr and smolts

As noted above, flows in early 2005 were relatively low until May, when conditions turned wet and flows rose to above-normal levels (Fig. 4). Higher spring flows are associated with higher survival of juvenile salmon (Newman and Rice, 2002). Water temperature at Red Bluff was above the 1990-2007 average for much of the winter and spring, but below temperatures associated with lower survival of juvenile life stages (McCullough, 1999). In 2005, the volume of water pumped from the Delta reached record levels in January before falling to near-average levels in the spring, then rising again to near-record levels in the summer and fall (Fig. 5,top), but only after the migration of fall Chinook smolts was nearly complete (Fig. 8). Water diversions, in terms of the export:inflow ratio (E/I), fluctuated around the average throughout the winter and spring (Fig. 5,bottom). Statistical analysis of coded-wire-tagged releases of Chinook to the Delta have shown that survival declines with increasing exports and increasing E/I at time of release (Kjelson and Brandes, 1989; Newman and Rice, 2002).

Releases of Chinook smolts were at typical levels for the 2004 brood, with a high proportion released into the bay, and of these, a not-unusual portion acclimatized in net pens prior to release (Fig. 6). No significant disease outbreaks or other problems with the releases were noted.

Systematic trawl sampling near Chipps Island provides an especially useful dataset for assessing the strength of a brood as it enters the estuary[2]. The USFWS typically conducts twenty-minute mid-water trawls, 10 times per day, 5 days a week. An index of abundance can be formed by dividing the total catch per day by the total volume swept by the trawl gear. Fig. 7 shows the mean annual CPUE from 1976 to 2007; CPUE in 2005 was slightly above average. The timing of catches of juvenile fall Chinook at Chipps Island was not unusual in 2005 (Fig. 8). Had the survival of the 2004 brood been unusually poor in freshwater, catches at Chipps Island should have been much lower than average, since by reaching that location, fish have survived almost all of the freshwater phase of their juvenile life.

There are two reasons, however, that apparently normal catches at Chipps Island could mask negative impacts that occurred in freshwater. One possibility is that catches were normal because the capture efficiency of the trawl was much higher than usual. The capture efficiency of the trawl, as estimated by the recovery rate of coded-wire-tagged Chinook, is variable among years, but the recovery rate of Chinook released at Ryde in 2005 was about average (P. Brandes, USFWS, unpublished data). This suggests that the actual abundance of fall Chinook passing

[2]Catches at Chipps Island include naturally-produced fish and CNFH hatchery fish released at Battle Creek; almost all fish from the state hatcheries are released downstream of Chipps Island.

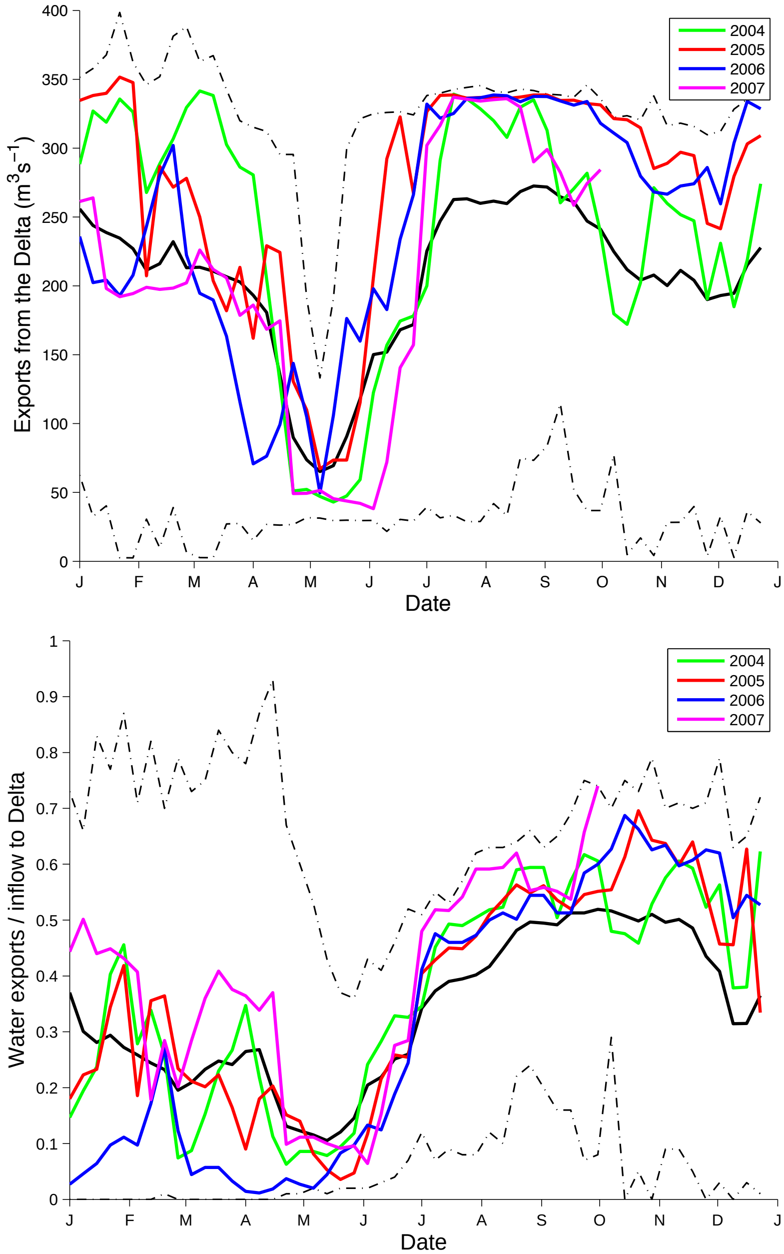

Figure 5: Weekly average export of freshwater from the Delta (upper panel) and the ratio of exports to inflows (bottom panel). Heavy black line is the weekly average discharge over the 1955-2007 period; dashed black lines indicate maximum and minimum weekly average discharges. Exports, as both rate and proportion, were higher than average in all years in the summer and fall, but near average during the spring, when fall Chinook are migrating through the Delta. Flow estimates from the DAYFLOW model (`http://www.iep.ca.gov/dayflow/`).

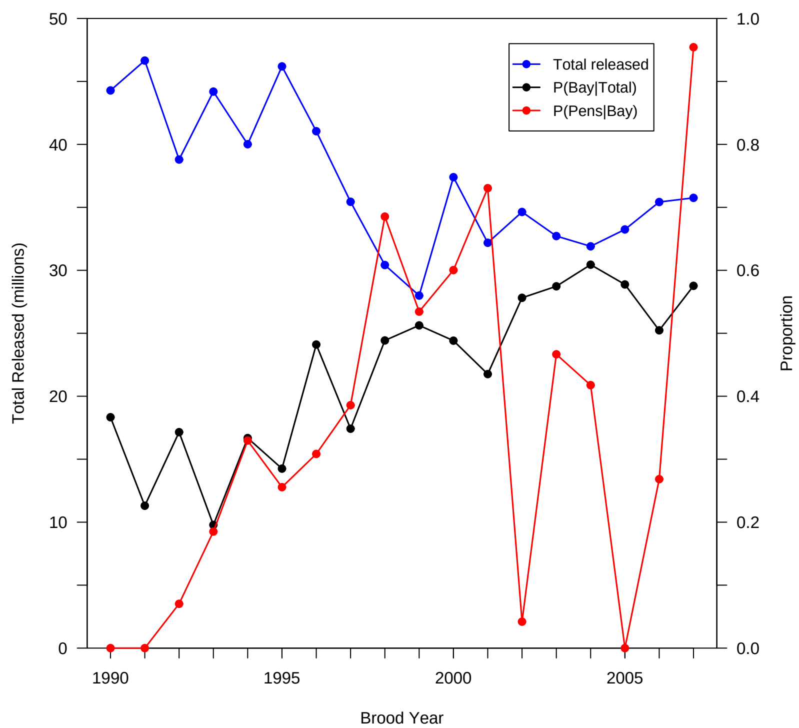

Figure 6: Total releases of hatchery fall Chinook, proportion of releases made to the bay, and the proportion of bay releases acclimatized in net pens. Unpublished data of CDFG and USFWS.

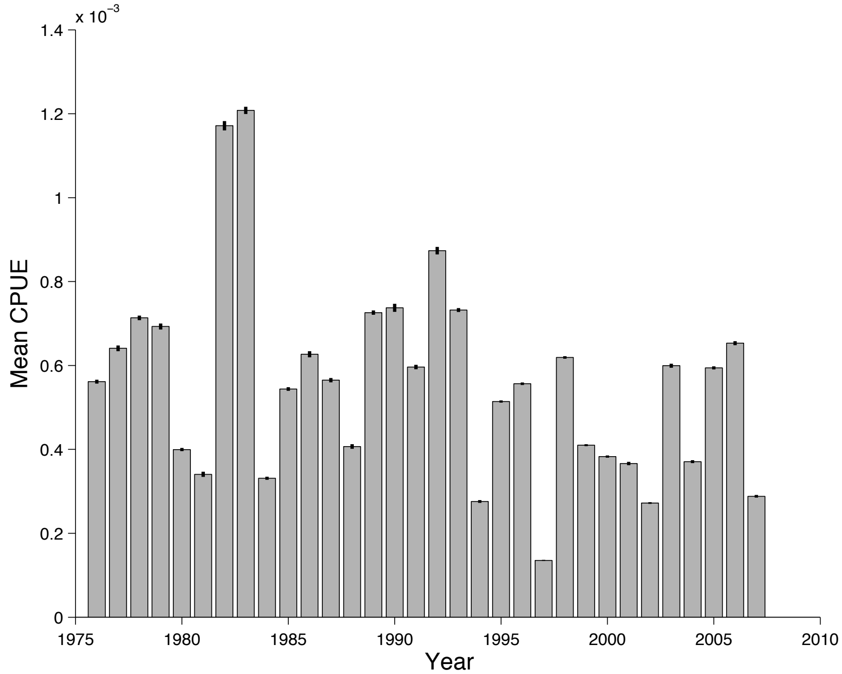

Figure 7: Mean annual catch-per-unit effort of fall Chinook juveniles at Chipps Island by USFWS trawl sampling conducted between January 1 and July 18. Error bars indicate the standard error of the mean. USFWS, unpublished data.

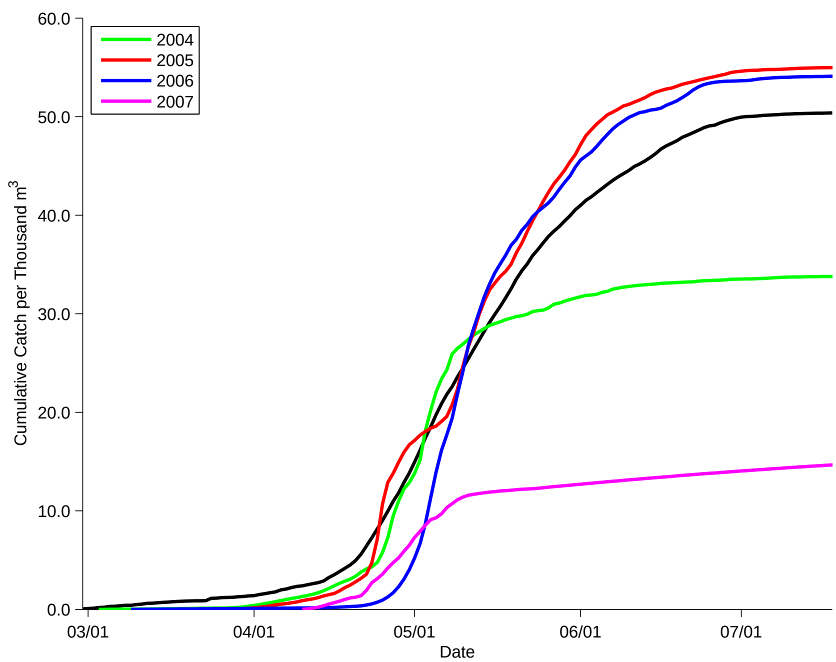

Figure 8: Cumulative daily catch per unit effort (CPUE) of fall Chinook juveniles at Chipps Island by USFWS trawl sampling. Black line shows the mean cumulative CPUE for 1976-2007.

Chipps Island was not low. The other explanation is that the effects of freshwater stressors result in delayed mortality that manifests itself after fish pass Chipps Island. Delayed mortality from cumulative stress events has been hypothesized to explain the relatively poor survival to adulthood of fish that successfully pass more hydropower dams on the Columbia River (Budy et al., 2002). However, there is no *direct* evidence, to date, for delayed mortality in Chinook from the Columbia River (ISAB, 2007), and its causes remain a mystery. In any case, we do not have the data to test this hypothesis for SRFC.

3.4.4 Early ocean

Taken together, two lines of evidence suggest that something unusual befell the 2004 brood of fall Chinook in either the bay or the coastal ocean. First, near-average numbers of juveniles were observed at Chipps Island (Fig. 8), and the state hatcheries released normal numbers of smolts into the bay. Second, survival of FRH smolts to age two was very low for the 2004 brood, only 8% that of the 2000 brood (Fig. 9; see the appendix for the rationale and details behind the survival rate index calculations), and the escapement of jacks from the 2004 brood was also very low in 2006 (Fig. 10). The Sacramento Index of for 2007 was quite close to that expected by the escapement of jacks in 2006 (see appendix), indicating that the unusual mortality occurred after passing Chipps Island and prior to recruitment to the fishery at age two. Environmental conditions in the bay were not unusual in 2005 (see appendix), suggesting that the cause of the collapse was likely in the ocean. Before reviewing conditions in the ocean, it is helpful to consider a conceptual model of physical and biological processes that characterize upwelling ecosystems, of which the California Current is an example.

Rykaczewski and Checkley (2008) provides such a model (Fig. 11). Several factors, operating at different scales, influence the magnitude and distribution of primary and secondary productivity[3] occurring in the box. At the largest scale, the winds that drive upwelling ecosystems are generated by high-pressure systems centered far offshore that generate equator-ward winds along the eastern edge of the ocean basin (Barber and Smith, 1981). The strength and position of pressure systems over the globe change over time, which is reflected in various climate indices such as the Southern Oscillation Index and the Northern Oscillation index (Schwing et al., 2002), and these large-scale phenomena have local effects on the California Current. One effect is determining the source of the water entering the northern side of the box in Fig. 11. This source water can come from subtropical waters (warmer and saltier, with subtropical zooplankton species that are not particularly rich in lipids) or from subarctic waters (colder and fresher, with subarctic zooplankton species that are rich in lipids) (Hooff and Peterson, 2006). Where the source water comes from is determined by physical processes acting at the Pacific Ocean basin scale. The productivity of the source water entering the box is also influenced by coastal upwelling occurring in areas to the north.

[3]Primary production is the creation of organic material by phytoplankton; secondary production is the creation of animal biomass by zooplankton.

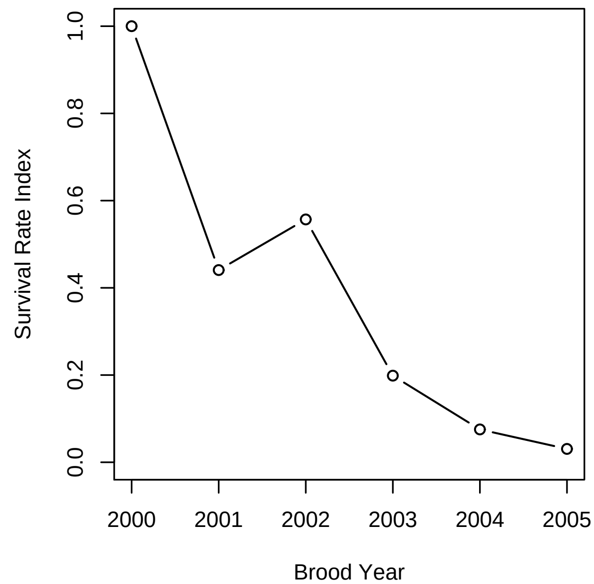

Figure 9: Index of FRH fall Chinook survival rate between release in San Francisco Bay and age two based on coded-wire tag recoveries in the San Francisco major port area recreational fishery; brood years 2000-2005. The survival rate index is recoveries of coded-wire tags expanded for sampling divided by the product of fishing effort and the number of coded-wire tags released, relative to the maximum value observed (brood year 2000).

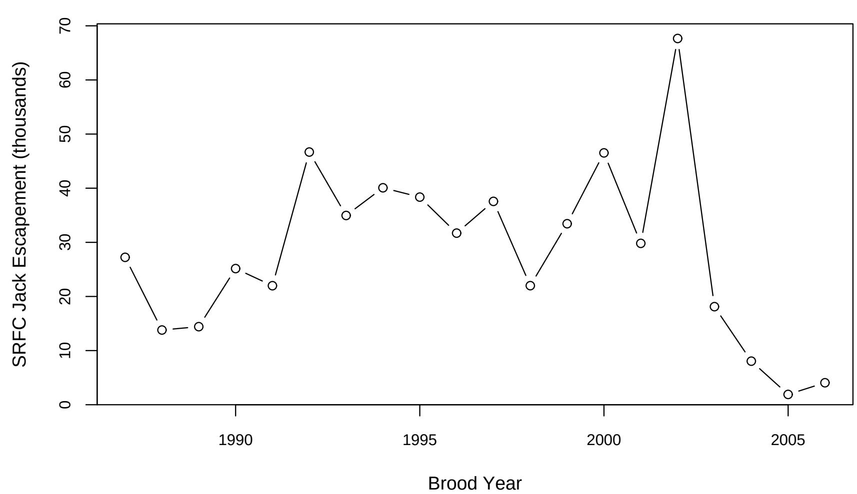

Figure 10: Escapement of SRFC jacks. Escapements in 2006 (brood year 2004) and 2007 (brood year 2005) were record lows at the time. Escapement estimate for 2008 (brood year 2006) is preliminary.

Within the box, productivity also depends on the magnitude, direction, spatial and temporal distribution of the winds (e.g., Wilkerson et al., 2006). Northwest winds drive surface waters away from the shore by a process called Ekman flow, and are replaced from below by colder, nutrient-rich waters near shore through the process of coastal upwelling. Northwest winds typically become stronger as one moves away from shore, a pattern called positive windstress curl, which causes offshore upwelling through a processes called Ekman pumping. The vertical velocities of curl-driven upwelling are generally much smaller than those of coastal upwelling, so nutrients are supplied to the surface waters at a lower rate by Ekman pumping (although potentially over a much larger area). Calculations by Dever et al. (2006) indicate that along central California, coastal upwelling supplies about twice the nutrients to surface waters as curl-driven upwelling. The absolute magnitude of the wind stress also affects mixing of the surface ocean; wind-driven mixing brings nutrients into the surface mixed layer but deepens the mixed layer, potentially limiting primary production by decreasing the average amount of light experienced by phytoplankton.

Yet another factor influencing productivity is the degree of stratification[4] in the upper ocean. This is partly determined by the source waters– warmer waters increase the stratification, which impedes the effectiveness of wind-driven upwelling and mixing. The balance of all of these processes determines the character of the pelagic food web, and when everything is "just right", highly productive and short food chains can form and support productive fish populations that are characteristic of coastal upwelling ecosystems (Ryther, 1969; Wilkerson et al., 2006).

It is also helpful to consider how Chinook use the ocean. Juvenile SRFC typically enter the ocean in the springtime, and are thought to reside in near shore waters, in the vicinity of their natal river, for the first few months of their lives in the sea (Fisher et al., 2007). As they grow, they migrate along the coast, remaining over the continental shelf mainly between central California and southern Washington (Weitkamp, In review). Fisheries biologists believe that the time of ocean entry is especially critical to the survival of juvenile salmon, as they are small and thus vulnerable to many predators (Pearcy, 1992). If feeding conditions are good, growth will be high and starvation or the effects of size-dependent predation may be lower. Thus, we expect conditions at the time of ocean entry and near the point of ocean entry to be especially important in determining the survival of juvenile fall Chinook.

The timing of the onset of upwelling is critical for juvenile salmon that migrate to sea in the spring. If upwelling and the pelagic food web it supports is well-developed when young salmon enter the sea, they can grow rapidly and tend to survive well. If upwelling is not well-developed or if its springtime onset is delayed, growth and survival may be poor. As shown next, most physical and biological measures were quite unusual in the northeast Pacific, and especially in the Gulf of the Farallones, in the spring of 2005, when the 2004 brood of fall Chinook entered the ocean.

[4] Stratification is the layering of water of different density.

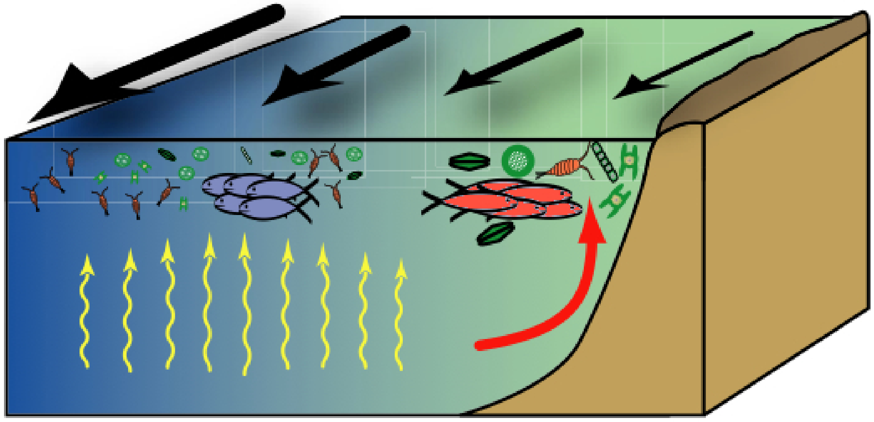

Figure 11: Conceptual diagram displaying the hypothesized relationship between wind-forced upwelling and the pelagic ecosystem. Alongshore, equatorward wind stress results in coastal upwelling (red arrow), supporting production of large phytoplankters and zooplankters. Between the coast and the wind-stress maximums, cyclonic wind-stress curl results in curl-driven upwelling (yellow arrows) and production of smaller plankters. Black arrows represent winds at the ocean surface, and their widths are representative of wind magnitude. Young juvenile salmon, like anchovy (red fish symbols), depend on the food chain supported by large phytoplankters, whereas sardine (blue fish symbols) specialize on small plankters. Growth and survival of juvenile salmon will be highest when coastal upwelling is strong. Redrawn from Rykaczewski and Checkley (2008).

Figure 12 shows temperature and wind anomalies for the north Pacific in the April-June period of 2005-2008. There were southwesterly anomalies in wind speed throughout the California Current in May of 2005, and sea surface temperature (SST) in the California Current was warmer than normal. This indicates that upwelling-inducing winds were abnormally weak in May 2005. By June of 2005, conditions off of California were more normal, with stronger than usual northwesterly winds along the coast.

Because Fig. 12 indicates that conditions were unusual in the spring of 2005 throughout the California Current and also the Gulf of Alaska, we should expect to see wide-spread responses by salmon populations inhabiting these waters at this time. This was indeed the case. Fall Chinook in the Columbia River from brood year 2004 had their lowest escapement since 1990, and coastal fall Chinook from Oregon from brood year 2004 had their lowest escapement since either 1990 or the 1960s, depending on the stock. Coho salmon that entered the ocean in the spring of 2005 also had poor escapement.

Conditions off north-central California further support the hypothesis that ocean conditions were a significant reason for the poor survival of the 2004 brood of fall Chinook salmon. The upper two panels of Fig. 13 show a cumulative upwelling index (CUI;Schwing et al. (2006)), an estimate of the integrated amount of upwelling for the growing season, for the nearshore ocean area where fall Chinook juveniles initially reside (39°N) and the coastal region to the north, or “upstream”

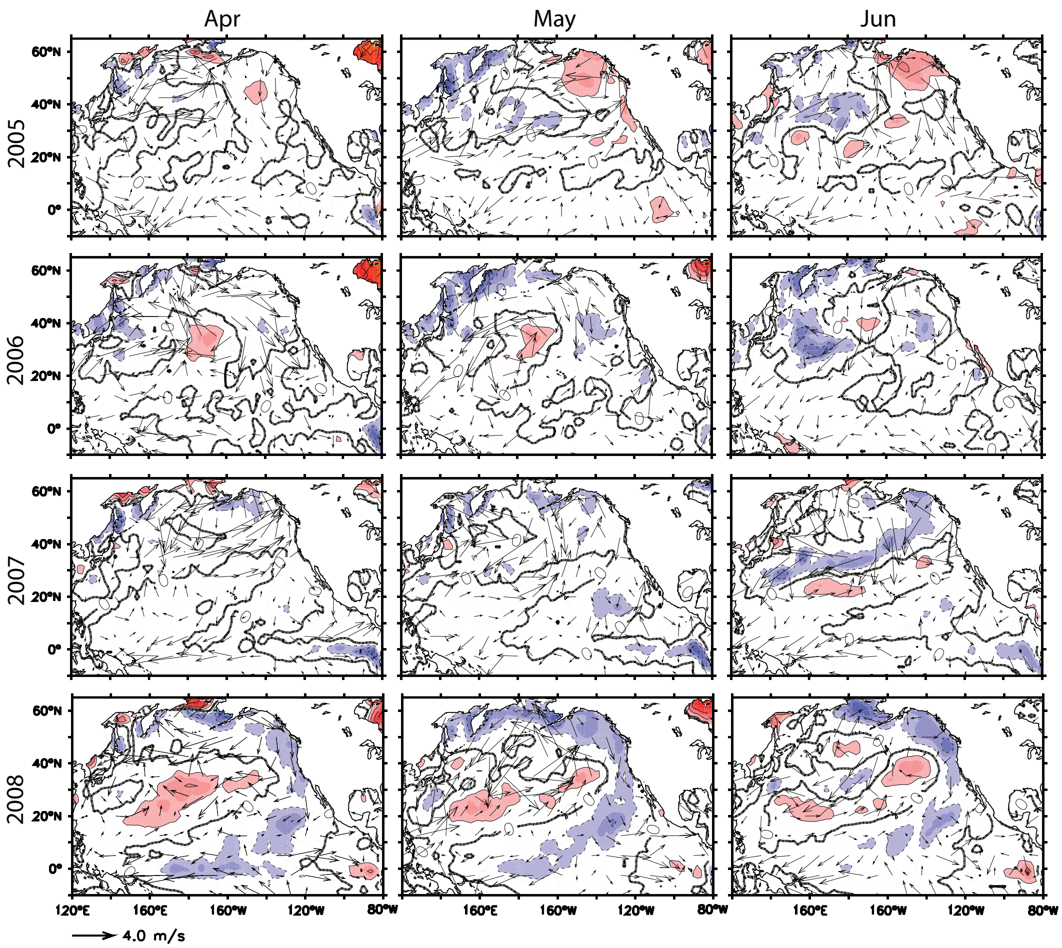

Figure 12: Sea surface temperature (colors) and wind (vectors) anomalies for the north Pacific for April-June in 2005-2008. Red indicates warmer than average SST; blue is cooler than average. Note the southwesterly wind anomalies (upwelling-suppressing) in May 2005 and 2006 off of California, and the large area of warmer-than-normal water off of California in May 2005. Winds and surface temperatures returned to near-normal in 2007, and become cooler than normal in spring 2008 along the west coast of North America.

(42°N). Typically, upwelling-favorable winds are in place by mid-March, as shown by the start dates of the CUI. In 2005, upwelling-favorable winds were unseasonably weak in early spring, and did not become firmly established until late May and June further delayed to the north. The resulting deficit in the CUI (Fig. 13, lower two panels) is thought to have resulted in a delayed spring bloom, reduced biological productivity, and a much smaller forage base for Chinook smolts. The low and delayed upwelling was also expressed as unusually warm sea-surface temperatures in the spring of 2005 (Fig. 14).

The anomalous spring conditions in 2005 and 2006 were also evident in surface trajectories predicted from the OSCURS current simulations model[5]. The model computes the daily movement of water particles in the North Pacific Ocean surface layer from daily sea level pressures (Ingraham and Miyahara, 1988). Lengths and directions of trajectories of particles released near the coast are an indication of the strength of offshore surface movement and upwelling. Fig. 15 shows particle trajectories released from three locations March 1 and tracked to May 1 for 2004, 2005, 2006 and 2007. In 2005 and 2006 trajectories released south of 42°N stayed near coast; a situation suggesting little upwelling over the spring.

The delay in 2005 upwelling to the north of the coastal ocean habitat for these smolts is particularly important, because water initially upwelled off northern California and Oregon advected south, providing the source of primary production that supports the smolts prey base. Transport in spring 2005 (Fig. 15b) supports the contention that the water encountered by smolts emigrating out of SF Bay originated from off northern California, where weak early spring upwelling was particularly notable.

Some of the strongest evidence for the collapse of the pelagic food chain comes from observations of seabird nesting success on the Farallon Islands. Nearly all Cassin's auklets, which have a diet very similar to that of juvenile Chinook, abandoned their nests in 2005 because of poor feeding conditions (Sydeman et al., 2006; Wolf et al., 2009). Other notable observations of the pelagic foodweb in 2005 include: emaciated gray whales (Newell and Cowles, 2006); sea lions foraging far from shore rather than their usual pattern of foraging near shore (Weise et al., 2006); various fishes at record low abundance, including common salmon prey items such as juvenile rockfish and anchovy (Brodeur et al., 2006); and dinoflagellates becoming the dominant phytoplankton group in Monterey Bay, rather than diatoms (MBARI, 2006). While the overall abundance of anchovies was low, they were captured in an unusually large fraction of trawls, indicating that they were more evenly distributed than normal (NMFS unpublished data). The overall abundance of krill observed in trawls in the Gulf of the Farallones was not especially low, but krill were concentrated along the shelf break and sparse inshore.

Observations of size, condition factor (K, a measure of weight per length) and total energy content (kilojoules (kJ) per fish, from protein and lipid contents) of juvenile salmon offer direct support for the hypothesis that feeding conditions in

[5]Live access to OSCURS model, Pacific Fisheries Environmental Laboratory. Available at `www.pfeg.noaa.gov/products/las.html`. Accessed 26 December 2007.

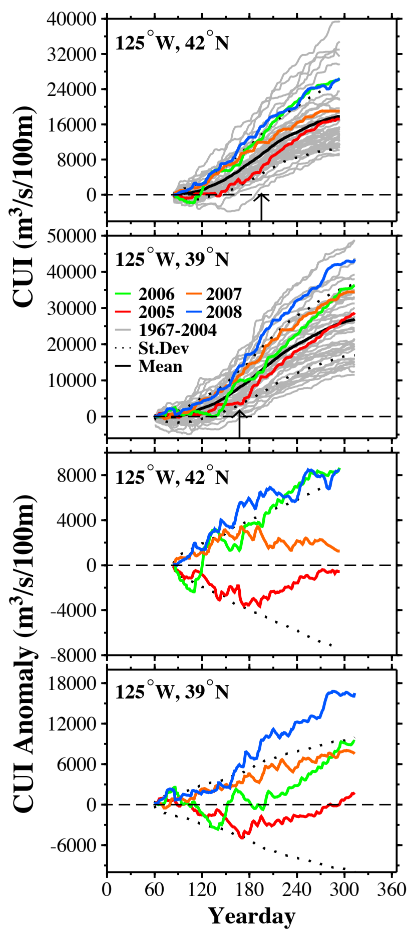

Figure 13: Cumulative upwelling index (CUI) and anomalies of the CUI at 42°N (near Brookings, Oregon) and 39°N (near Pt. Arena, California). Gray lines in the upper two panels are the individual years from 1967-2004. Black line is the average, dashed lines show the standard deviation. Arrow indicates the average time of maximum upwelling rate. The onset of upwelling was delayed in 2005 and remained weak through the summer; in 2006, the onset of upwelling was again delayed but became quite strong in the summer. Upwelling in 2007 and 2008 was stronger than average.

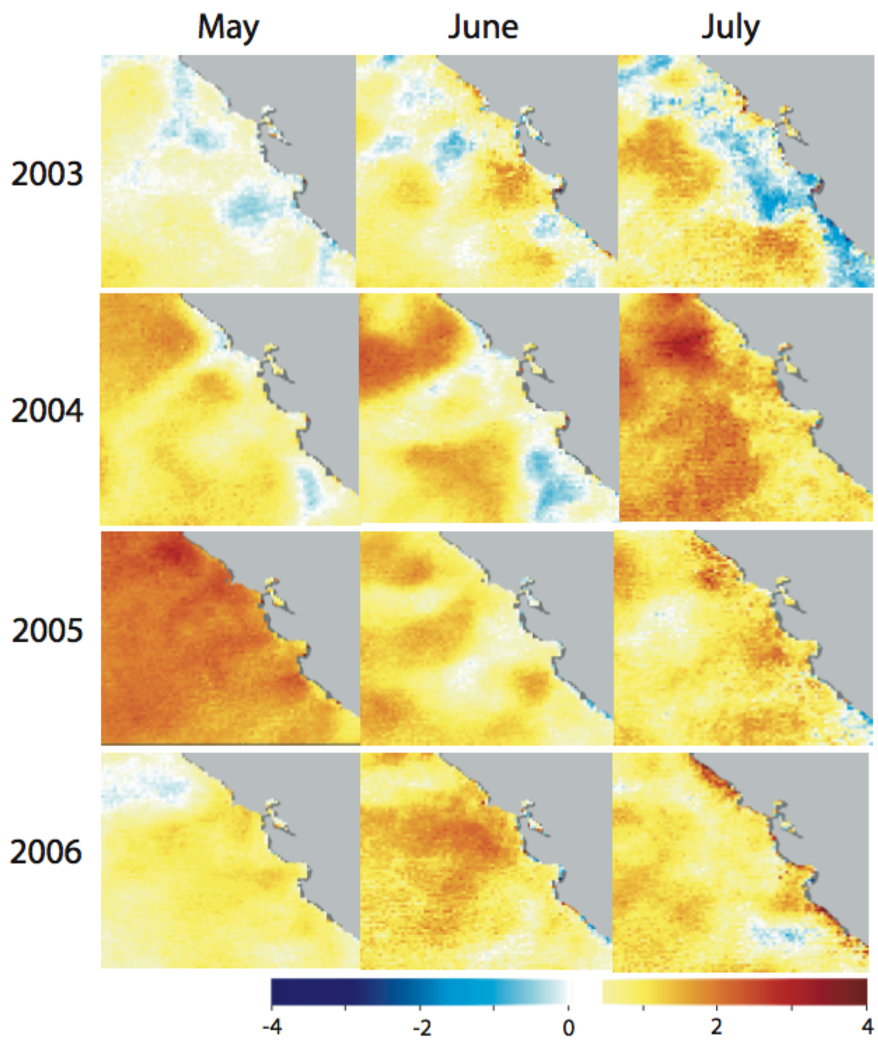

Figure 14: Sea surface temperature anomalies off central California in May-July of 2003-2006.

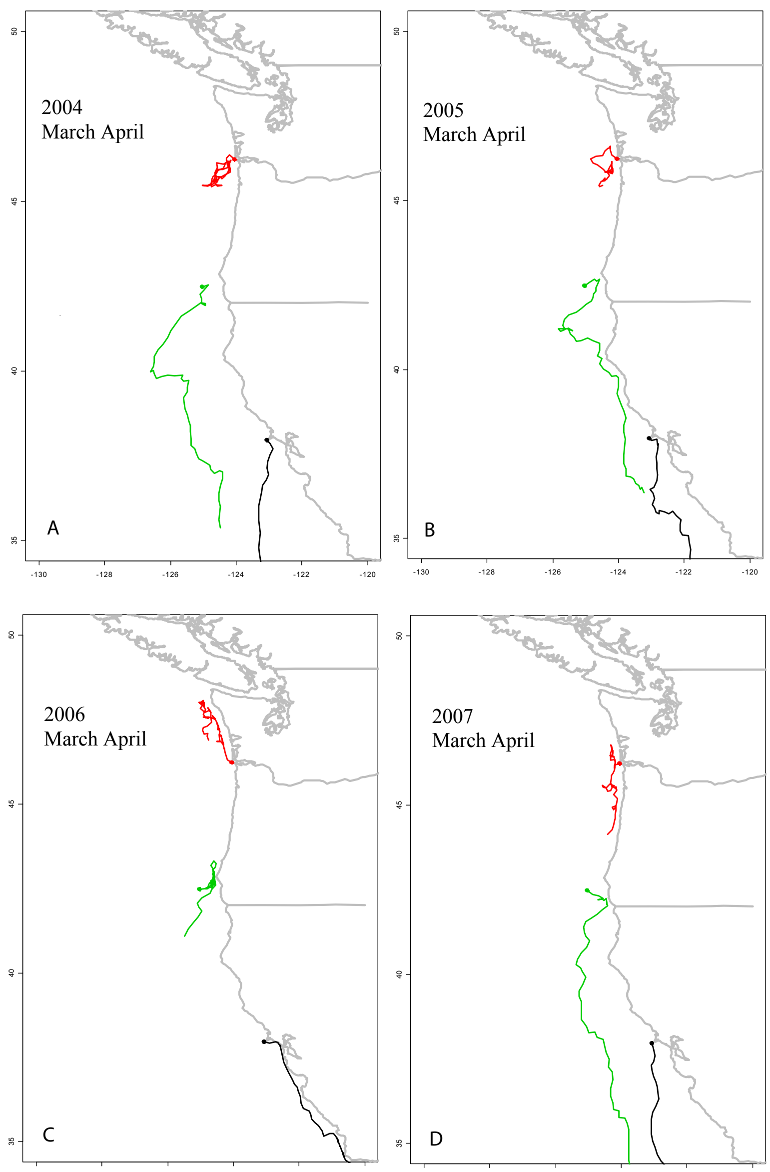

Figure 15: Surface particle trajectories predicted from the OSCURS current model. Particles released at 38°N, 43°N and 46°N (dots) were tracked from March 1 through May 1 (lines) for 2004-2007.

the Gulf of the Farallones were poor for juvenile salmon in the summer of 2005. Variation in feeding conditions for early life stages of marine fishes has been linked to subsequent recruitment variation in previous studies, and it is hypothesized that poor growth leads to low survival (Houde, 1975). In 2005, length, weight, K, and total energy content of juvenile Chinook exiting the estuary during May and June, when the vast majority of fall-run smolts enter the ocean, was similar to other observations made over the 1998-2005 period (Fig. 16). However, size, K, and total energy content in the summer of 2005, after fish had spent approximately one month in the ocean, were all significantly lower than the mean of the 8-year period. These data show that growth and energy accumulation, processes critical to survival during the early ocean phase of juvenile salmon, were impaired in the summer, but recovered to typical values in the fall. A plausible explanation is that poor feeding conditions and depletion of energy reserves in the summer produced low growth and energy content, resulting in higher mortality of juveniles at the lower end of the distribution. By the fall, however, ocean conditions and forage improved and size, K, and total energy content had recovered to typical levels in survivors.

Taken together, these observations of the physical and biological state of the coastal ocean offer a plausible explanation for the poor survival of the 2004 brood. Due to unusual atmospheric and oceanic conditions, especially delayed coastal upwelling, the surface waters off of the central California coast were relatively warm and stratified in the spring, with a shallow mixed layer. Such conditions do not favor the large, colonial diatoms that are normally the base of short, highly productive food chains, but instead support greatly increased abundance of dinoflagellates (MBARI, 2006; Rykaczewski and Checkley, 2008). The dinoflagellate-based food chain was likely longer and therefore less efficient in transferring energy to juvenile salmon, juvenile rockfish and seabirds, which all experienced poor feeding conditions in the spring of 2005. This may have resulted in outright starvation of young salmon, or may have made them unusually vulnerable to predators. Whatever the mechanism, it appears that relatively few of the 2004 brood survived to age two. These patterns and conditions are consistent with Gargett's (1997) "optimal stability window" hypothesis, which posits that salmon stocks do poorly when water column stability is too high (as was the case for the 2004 and 2005 broods) or too low, and with Rykaczewski and Checkley's (2008) explanation of the role of offshore, curl-driven upwelling in structuring the pelagic ecosystem of the California Current. Strong stratification in the Bering Sea was implicated in the poor escapement of sockeye, chum and Chinook populations in southwestern Alaska in 1996-97 (Kruse, 1998).

3.4.5 Later ocean

In the previous section we presented information correlating unusual conditions in the Gulf of the Farallones, driven by unusual conditions throughout the north Pacific in the spring of 2005, that caused poor feeding conditions for juvenile fall Chinook. It is possible that conditions in the ocean at a later time, such as the spring of 2006, may have also contributed to or even caused the poor performance of the

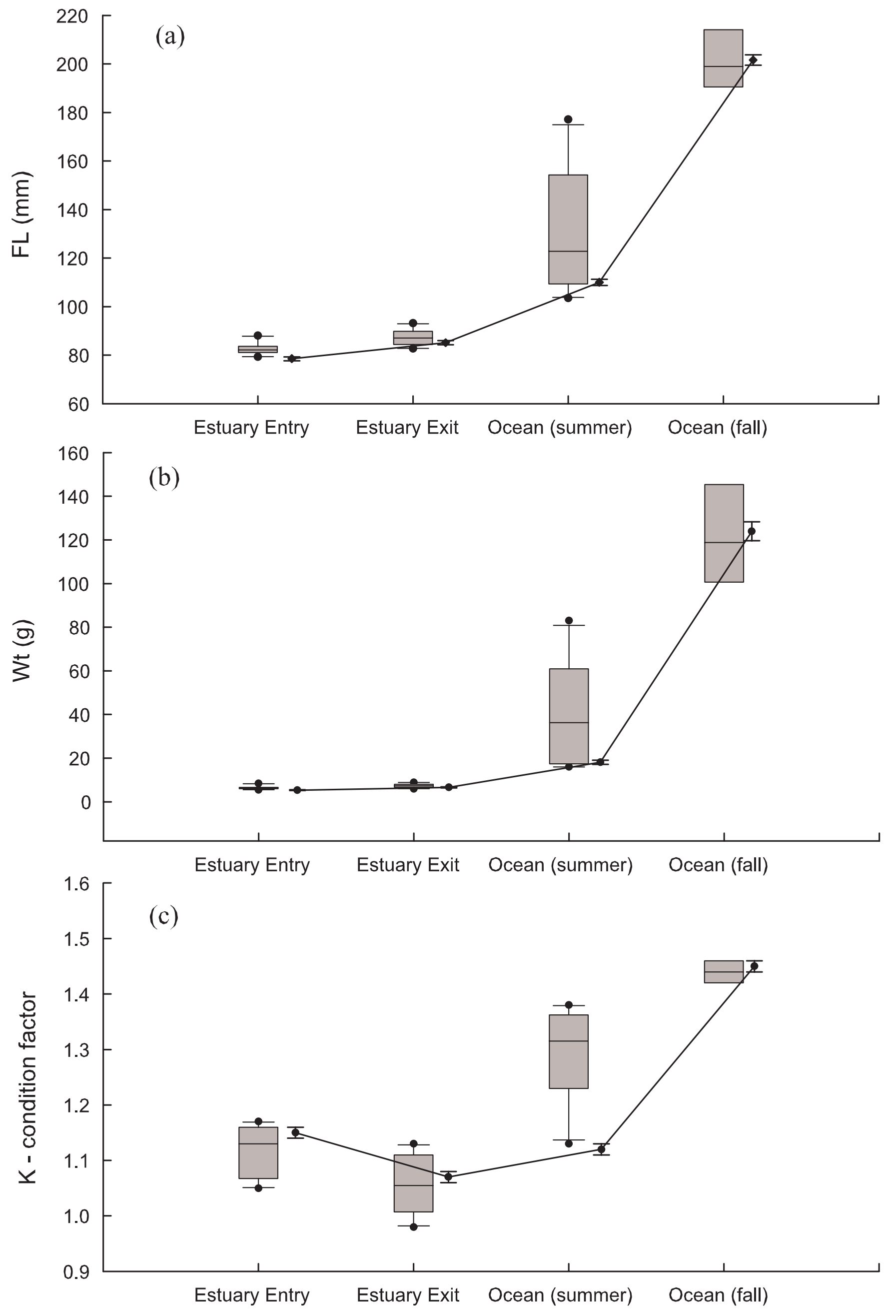

Figure 16: Changes in (a) fork length, (b) weight, and (c) condition (K) of juvenile Chinook salmon during estuarine and early ocean phases of their life cycle. Boxes and whiskers represent the mean, standard deviation and 90% central interval for fish collected in San Francisco Estuary (entry = Suisun Bay, exit = Golden Gate) during May and June and coastal ocean between 1998-2004; points connected by the solid line represent the means (± 1 SE) of fish collected in the same areas in 2005. Unpublished data of B. MacFarlane.

2004 brood. This is because fall Chinook spend at least years at sea before returning to freshwater, and thus low jack escapement could arise due to mortality or delayed maturation caused by conditions during the second year of ocean life. While it is generally believed that conditions during early ocean residency are especially important (Pearcy, 1992), work by Kope and Botsford (1990) and Wells et al. (2008) suggests that ocean conditions can affect all ages of Chinook. As discussed below in section 3.5.4, ocean conditions in 2006 were also unusually poor. It is therefore plausible that mortality of sub-adults in their second year in the ocean may have contributed to the poor escapement of SRFC in 2007.

Fishing is another source of mortality to Chinook that could cause unusually low escapement (discussed in more detail in the appendix). The PFMC (2007) forecasted an escapement of 265,000 SRFC adults in 2007 based on the escapement of 14,500 Central Valley Chinook jacks in 2006. The realized escapement of SRFC adults was 87,900. The error was due mainly to the over-optimistic forecast of the pre-season ocean abundance of SRFC. Had the pre-season ocean abundance forecast been accurate and fishing opportunity further constrained by management regulation in response, so that the resulting ocean harvest rate was reduced by half, the SRFC escapement goal would have been met in 2007. Thus, fishery management, while not the cause of the 2004 brood weak year-class strength, contributed to the failure to achieved the SRFC escapement goal in 2007.

3.4.6 Spawners

Jack returns and survival of FRH fall Chinook to age two indicates that the 2004 brood was already at very low abundance before they began to migrate back to freshwater in the fall 2007. Water temperature at Red Bluff was within roughly 1°C of normal in the fall, and flows were substantially below normal in the last 5 weeks of the year. We do not believe that these conditions would have prevented fall Chinook from migrating to the spawning grounds, and there is no evidence of significant mortalities of fall Chinook in the river downstream of the spawning grounds.

3.4.7 Conclusions for the 2004 brood

All of the evidence that we could find points to ocean conditions as being the proximate cause of the poor performance of the 2004 brood of fall Chinook. In particular, delayed coastal upwelling in the spring of 2005 meant that animals that time their reproduction so that their offspring can take advantage of normally bountiful food resources in the spring, found famine rather than feast. Similarly, marine mammals and birds (and juvenile salmon) which migrate to the coastal waters of northern California in spring and summer, expecting to find high numbers of energetically-rich zooplankton and small pelagic fish upon which to feed, were also impacted. Another factor in the reproductive failure and poor survival of fishes and seabirds may have been that 2005 marked the third year of chronic warm conditions in the northern California Current, a situation which could have led to a general reduction in health of fish and birds, rendering them less tolerant of adverse ocean conditions.

3.5 Brood year 2005

3.5.1 Parents

In 2005, 211,000 adult fall Chinook returned to spawn in the Sacramento River and its tributaries to give rise to the 2005 brood, almost exactly equal to the 1970-2007 mean (Fig. 1). Pre-spawning mortality in the Sacramento River was about 1% of the run (D. Killam, CDFG, unpublished data). River flows were near normal through the fall, but rose significantly in the last weeks of the year. Escapement to Sacramento basin hatcheries was near record highs, but this did not result in any significant problems in handling the broodstock.

3.5.2 Eggs

Flows in the winter of 2005-2006 were higher than usual, with peak flows around the new year and into the early spring on regulated reaches throughout the basin. Flows generally did not reach levels unprecedented in the last two decades (Fig. 4; see appendix for more details), but may have resulted in stream bed movement and subsequent mortality of a portion of the fall Chinook eggs and pre-emergent fry. Water temperature at Red Bluff in the spring was substantially lower than normal, probably prolonging the egg incubation phase, but not so low as to cause egg mortality (McCullough, 1999).

3.5.3 Fry, parr and smolts

The spring of 2006 was unusually wet, due to late-season rains associated with a cut-off low off the coast of California and a ridge of high pressure running over north America from the southwest to the northeast. This weather pattern generated high flows in March and April 2006 (Fig. 4) and a very low ratio of water exports to inflows to the Delta (Fig. 5). Water temperatures in San Francisco Bay were unusually low, and freshwater outflow to the bay was unusually high (see appendix). These conditions, while anomalous, are not expected to cause low survival of smolts migrating through the bay to the ocean. It is conceivable that the wet spring conditions had a delayed and indirect negative effect on the 2005 brood. For example, surface runoff could have carried high amounts of contaminants (pesticide residues, metals, hydrocarbons) into the rivers or bay, and these contaminants could have caused health problems for the brood that resulted in death after they passed Chipps Island. However, since both the winter and spring had high flows the concentrations of pollutants would likely have been at low levels if present. We found no evidence for or against this hypothesis.

Total water exports at the state and federal pumping facilities in the south Delta were near average in the winter and spring, but the ratio of water exports to inflow to the Delta (E/I) was lower than average for most of the winter and spring, only rising to above-average levels in June. Total exports were near record levels throughout the summer and fall of 2006, after the fall Chinook emigration period.

Catch-per-unit-effort of juvenile fall Chinook in the Chipps Island trawl sampling was slightly higher than average in 2006, and the timing of catches was very similar to the average pattern, with perhaps a slight delay (roughly one week) in migration timing.

Releases from the state hatcheries were at typical levels, although in a potentially significant change in procedure, fish were released directly into Carquinez Strait and San Pablo Bay without the usual brief period of acclimatization in net pens at the release site. This change in procedure was made due to budget constraints at CDFG. Acclimatization in net pens has been found to increase survival of release groups by a factor of 2.6, (CDFG, unpublished data) so this change may have had a significant impact on the survival of the state hatchery releases. CNFH released near-average numbers of smolts into the upper river, with no unusual problems noted.

Conditions in the estuary and bays were cooler and wetter in the spring of 2006 than is typical. Such conditions are unlikely to be detrimental to the survival of juvenile fall Chinook.

3.5.4 Early ocean

Overall, conditions in the ocean in 2006 were similar to those in 2005. At the north Pacific scale, northwesterly winds were stronger than usual far offshore in the northeast Pacific during the spring, but weaker than normal near shore (Fig. 12). The seasonal onset of upwelling was again delayed in 2006, but this anomaly was more distinct off central California (Fig. 13). Unlike 2005, however, nearshore transport in 2006 was especially weak (Fig. 15b). In contrast to 2005, conditions unfavorable for juvenile salmon were restricted to central California, rather than being a coast-wide phenomenon (illustrated in Fig. 13, where upwelling was delayed later at 39°N than 42°N). Consequently, we should expect to see corresponding latitudinal variation in biological responses in 2006.

These relatively poor conditions, following on the extremely poor conditions in 2005, had a dramatic effect on the food base for juvenile salmon off central CA. Once again, Cassin's auklets on the Farallon Islands experienced near-total reproductive failure. Krill, which were fairly abundant but distributed offshore near the continental shelf break in 2005, were quite sparse off central California in 2006 (see appendix). Juvenile rockfish were at very low abundance off central California, according to the NMFS trawl surveys (see appendix). These observations indicate feeding conditions for juvenile salmon in the spring of 2006 off central California were as bad as or worse than in 2005.

Consistent with the alongshore differences in upwelling and SST anomalies, and with better conditions off of Oregon and Washington, abundance of juvenile spring Chinook, fall Chinook and coho were four to five times higher in 2006 than in 2005 off of Oregon and Washington (W. Peterson, NMFS, unpublished data from trawl surveys). Catches of juvenile spring Chinook and coho salmon in June 2005 were the lowest of the 11 year time series; catches of fall Chinook were the third lowest. Similarly, escapement of adult fall Chinook to the Columbia River in 2007 for the fish that entered the sea in 2005 was the lowest since 1993 but escapement in 2008 was twice as high as in 2007. A similar pattern was seen for Columbia River spring Chinook. Cassin's auklets on Triangle Island, British Columbia, which suffered reproductive failure in 2005, fared well in 2006 (Wolf et al., 2009).

Estimated survival from release to age two for the 2005 brood of FRH fall Chinook was 60% lower than the 2004 brood, only 3% of that observed for the 2000 brood (Fig. 9). We note that the failure to acclimatize the bay releases in net pens may explain the difference in survival of the 2004 and 2005 Feather River releases, but would not have affected survival of naturally produced or CNFH smolts. Jack escapement from the 2005 brood in 2007 was extremely low. Unfortunately, lipid and condition factor sampling of juvenile Chinook in the estuary, bays and Gulf of the Farallones was not conducted in 2006 due to budgetary and ship-time constraints.

3.5.5 Later ocean

Ocean conditions improved in 2007 and 2008, with some cooling in the spring in the California Current in 2007, and substantial cooling in 2008. Data are not yet available on the distribution and abundance of salmon prey items, but it is likely that feeding conditions improved for salmon maturing in 2008. However, improved feeding conditions appear to have had minimal benefit to survival after recruitment to the fishery, because the escapement of 66,000 adults in 2008 was very close to the predicted escapement (59,000) based on jack returns in 2007. Fisheries were not a factor in 2008 (they were closed).

3.5.6 Spawners

As mentioned above, about 66,000 SRFC adults returned to natural areas and hatcheries in 2008. Although detailed data have not yet been assembled on freshwater and estuarine conditions for the fall of 2008, the Sacramento Valley has been experiencing severe drought conditions, and river temperatures were higher than normal and flows have been lower than normal. Neither of these conditions are beneficial to fall Chinook and may have impacted the reproductive success of the survivors of the 2005 brood.

3.5.7 Conclusions for the 2005 brood

For the 2005 brood, the evidence suggests again that ocean conditions were the proximate cause of the poor performance of that brood. In particular, the cessation of coastal upwelling in May of 2006 was likely a serious problem for juvenile fall Chinook entering the ocean in the spring. In contrast to 2005, anomalously poor ocean conditions were restricted to central California. The poorer performance of the 2005 brood relative to the 2004 brood may be partly due to the cessation of net-pen acclimatization of fish from the state hatcheries.

3.6 Prospects for brood year 2006

In this section, we briefly comment on some early indicators of the possible performance of the 2006 brood. The abundance of adult fall Chinook escaping to the Sacramento River, its tributaries and hatcheries in 2006 had dropped to 168,000, a level still above the minimum escapement goal of 122,000. Water year 2007 (which started in October 2006) was categorized as "critical"[6], meaning that drought conditions were in effect during the freshwater phase of the 2006 brood. While the levels of water exports from the Delta were near normal, inflows were below normal, and for much of the winter, early spring, summer and fall of 2007, the E/I ratio was above average. During the late spring, when fall Chinook are expected to be migrating through the Delta, the E/I ratio was near average. Ominously, catches of fall Chinook juveniles in the Chipps Island trawl survey in 2007 were about half that observed in 2005 and 2006. A tagging study conducted by NMFS and UC Davis found that survival of late-fall Chinook from release in Battle Creek (upper Sacramento River near CNFH) to the Golden Gate was roughly 3% in 2007; such survival rates are much lower than have been observed in similar studies in the Columbia River (Williams et al., 2001; Welch et al., 2008).

Ocean conditions began to improve somewhat in 2007, with some cooling evident in the Gulf of Alaska and the eastern equatorial Pacific. The California Current was roughly 1°C cooler than normal in April and May, but then warmed to above-normal levels in June-August 2007. The preliminary estimate of SRFC jack escapement was 4,060 (Fig. 10, PFMC (2009)), double that of the 2005 brood, but still the second lowest on record and a level that predicts an adult escapement in 2009 at the low end of the escapement goal absent any fishing in 2009. A survival rate estimate from release to age two is not possible for this brood due to the absence of a fishery in 2008, but jack returns will provide some indication of the survival of this brood[7].

3.7 Is climate change a factor?

An open question is whether the recent unusual conditions in the coastal ocean are the result of normal variation or caused in some part by climate change. We tend to think of the effects of climate change as a trajectory of slow, steady warming. Another potential effect is an increased intensity and frequency of many types of rare events (Christensen et al., 2007). Along with a general upward trend in sea surface temperatures, the variability of ocean conditions as indexed by the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and the NINO34 index appears to be increasing (N. Mantua, U. Washington, unpublished data).

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[6] California Department of Water Resources water year hydrological classification indices, `http://cdec.water.ca.gov/cgi-progs/iodir2/WSIHIST`

[7] Proper cohort reconstructions are hindered because of inadequate sampling of tagged fish in the hatchery and on the spawning grounds, and high rates of straying.

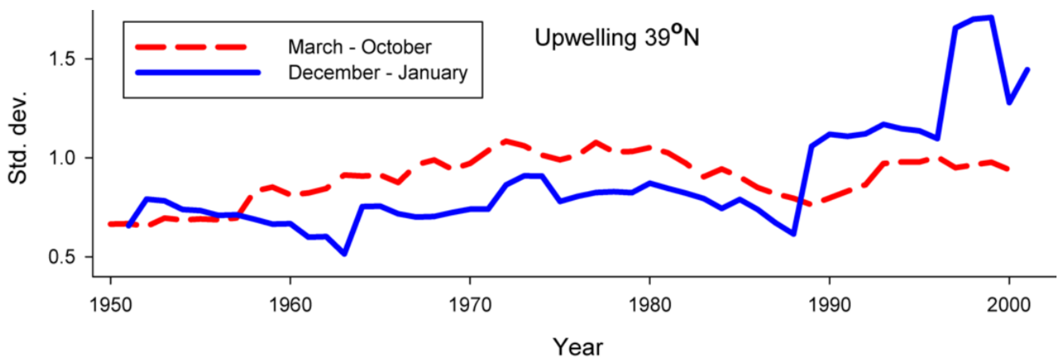

Figure 17: Changes in interannual variation in summer and winter upwelling at 39°N latitude, 1946 - 2007. Summer upwelling shows a possible decadal-scale oscillation. Winter upwelling (downwelling) shows a sharp increase starting in the late 1980s. The graph shows 11-year moving average standard deviations of standardized time series.

Winter upwelling at 39°N, off the California coast, took a jump upward in the late 1980s (Fig. 17). Whether there is a direct causative relationship between this pattern and recent volatility in SRFC escapement is a matter for further investigation, but there is a similar pattern of variability in environmental indices and salmon catch and escapement coast wide. While not evident in all stocks (Sacramento River winter Chinook escapement variability is going down, for example) the general trend for salmon stocks from California to Alaska is one of increasing variability (Lawson and Mantua, unpublished data). The well-recognized relationship between salmon survival and ocean conditions suggests that the variability in SRFC escapement is at least partly linked to the variability in ocean environment.

In the Sacramento River system there are other factors leading to increased variability in salmon escapements, including variation in harvest rates, freshwater habitat simplification, and reduced life history diversity in salmon stocks (discussed in detail in the section 4). In addition, freshwater temperature and flow patterns are subject to the same forces that drive variability in the ocean environment (Lawson et al., 2004), although they are modified significantly in the Central Valley by the water projects. These factors, in combination with swings in ocean survival, would tend to increase the likelihood of extreme events such as the unusually high escapements of the early 2000s and the recent low escapements that are the subject of this report.

3.8 Summary

A broad body of evidence suggests that anomalous conditions in the coastal ocean in 2005 and 2006 resulted in unusually poor survival of the 2004 and 2005 broods of SRFC. Both broods entered the ocean during periods of weak upwelling, warm sea surface temperatures, and low densities of prey items. Pelagic seabirds with diets similar to juvenile Chinook also experienced very poor reproduction in these years. A dominant role for freshwater factors as proximate causes of poor survival for the 2004 and 2005 broods were ruled out by observations of near-normal freshwater conditions during the period of freshwater residency, near-normal numbers of juvenile fall-run Chinook entering the estuary, and typical numbers of juvenile fall Chinook released from hatcheries. However, as Lawson (1993) reasoned, long-term declines in the condition of freshwater habitats are expected to result in increasingly severe downturns in abundance during episodes of poor ocean survival (Fig. 18). In the following section, we explain how human activities may be making the Central Valley Chinook salmon stock complex more susceptible to natural stressors.

4 The role of anthropogenic impacts

So far, we have restricted our analysis to the question of whether there were unusual conditions affecting Sacramento River fall-run Chinook from the 2004 and 2005 broods that could explain their poor performance, reaching the conclusion that unfavorable ocean conditions were the proximate cause. But what about the ultimate causes?

4.1 Sacramento River fall Chinook

With regard to SRFC, anthropogenic effects are likely to have played a significant role in making this stock susceptible to collapse during periods of unfavorable ocean conditions. Historical modifications have eliminated salmon spawning and rearing habitat, decreased total salmon abundance, and simplified salmon biodiversity (McEvoy, 1986; Yoshiyama et al., 1998, 2001; Williams, 2006a). To the extent that these changes have concentrated fish production and reduced the capacity of populations to spread mortality risks in time and space, we hypothesize that the Central Valley salmon ecosystem has become more vulnerable to recurring stresses, including but not limited to periodic shifts in the ocean environment.

Modifications in the Sacramento River basin since early in the nineteenth century have reduced the quantity, quality, and spatial distribution of freshwater habitat for Chinook. Large dams have blocked access to spawning habitat upriver and disrupted geomorphic processes that maintain spawning and rearing habitats downstream. Levees have disconnected flood plains, and bank armoring and dewatering of some river reaches have eliminated salmon access to shallow, peripheral habitats. By one estimate at least 1700 km or 48% of the stream lengths available to salmon for spawning, holding, and migration (not including the Delta) have been lost from the 3500 km formerly available in the Central Valley (Yoshiyama et al., 2001).

One of the most obvious alterations to fall Chinook habitat has been the loss of shallow-water rearing habitat in the Delta. Mid-nineteenth century land surveys suggest that levee construction and agricultural conversion have removed all but about 5% of the 1,300 km^2 of Delta tidal wetlands (Williams, 2006a). Because growth rates in shallow-water habitats can be very high in the Central Valley (Sommer et al., 2001; Jeffres et al., 2008), access to shallow wetlands, floodplains and stream channel habitats could increase the productive capacity of the system. From this perspective, the biggest problem with the state and federal water projects is not

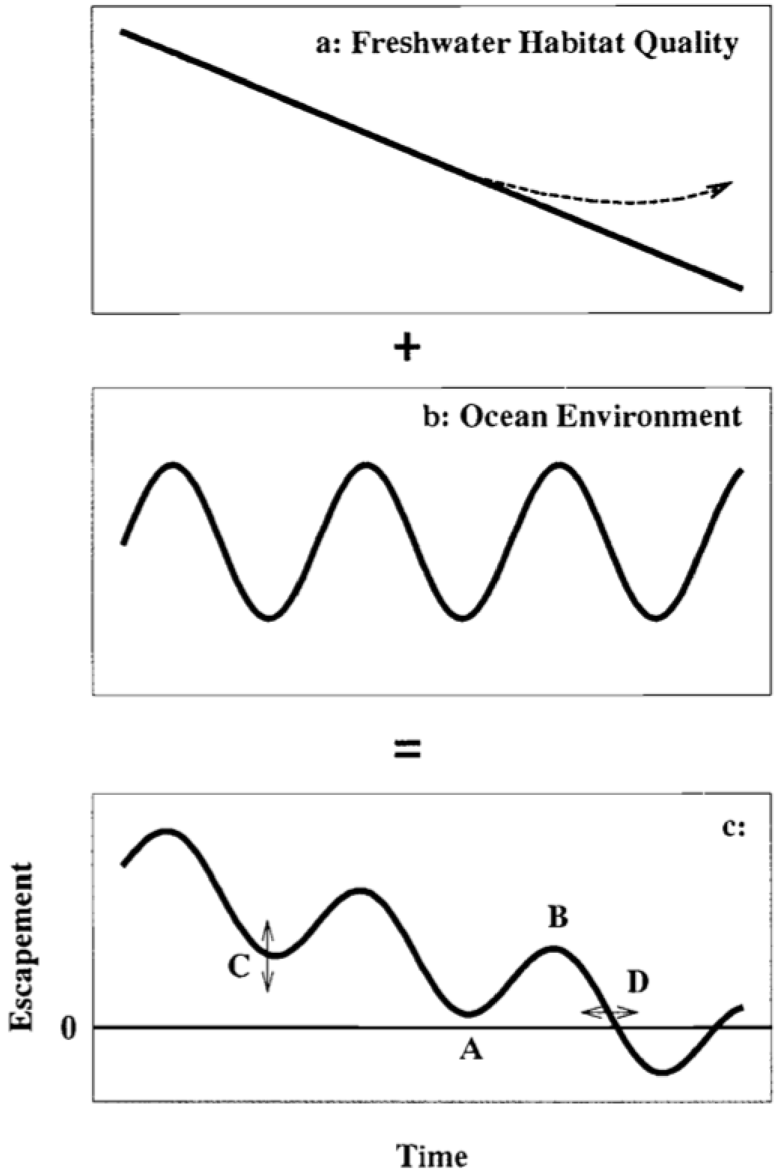

Figure 18: Conceptual model of effects of declining habitat quality and cyclic changes in ocean productivity on the abundance of salmon. a: trajectory over time of habitat quality. Dotted line represents possible effects of habitat restoration projects. b: generalized time series of ocean productivity. c: sum of top two panels where letters represent the following: A = current situation, B = situation in the future, C = change in escapement from increasing or decreasing harvest, and D = change in time of extinction from increasing or decreasing harvest. Copied from Lawson (1993).

that they kill fish at the pumping facilities, but that by engineering the whole system to deliver water from the north of the state to the south while preventing flooding, salmon habitat has been greatly simplified.

Although historical habitat losses undoubtedly have reduced salmon production in the Central Valley ecosystem, other than commercial harvest records, quantitative abundance estimates did not become available until the 1940s, nearly a century after hydraulic gold mining, dam construction, and other changes had drastically modified the habitat landscape. Harvest records indicate that high volumes of fish were harvested by nineteenth-century commercial river fisheries. From the 1870s through early 1900s, annual in-river harvest in the Central Valley often totaled four to ten million pounds of Chinook, approaching or exceeding the total annual harvest by statewide ocean fisheries in recent decades (Yoshiyama et al., 1998). Maximum annual stock size (including harvest) of Central Valley Chinook salmon before the twentieth century has been estimated conservatively at 1-2 million spawners with fall-run salmon totals perhaps reaching 900,000 fish (Yoshiyama et al., 1998). In recent decades, annual escapement of SRFC, which typically accounts for more than 90% of all fall Chinook production in the Central Valley, has remained relatively stable, totaling between 100,000 and 350,000 adults in most years from the 1960s through the 1990s. However, escapement began to fluctuate more erratically in the present decade, climbing to a peak of 775,000 in 2002 but then falling rapidly to near-record lows thereafter (Fig. 1).

Beyond the effects of human activities on production of SRFC are the less obvious influences on biodiversity. The diversity of life histories in Chinook (variations in size and age at migration, duration of freshwater and estuarine residency, time of ocean entry, etc.) has been described as a strategy for spreading mortality risks in uncertain environments (Healey, 1991). Diverse habitat types allow the expression of diverse salmon rearing and migration behaviors (Bottom et al., 2005b), and life history diversity within salmon stocks allows the stock aggregate to be more resilient to environmental changes (Hilborn et al., 2003).

Juvenile SRFC have adopted a variety of rearing strategies that maximize use of the diverse habitat types throughout the basin, including: (1) fry ($<$ 50 mm fork length) migrants that leave soon after emergence to rear in the Delta or in the estuarine bays; (2) fingerling migrants that remain near freshwater spawning areas for several months, leaving at larger sizes ($>$ 60 mm fork length) in the spring but passing quickly through the Delta; and (3) later migrants, including some juveniles that reside in natal streams through the summer or even stay through the winter to migrate as yearlings (Williams, 2006a). Today most SRFC exhibit fry-migrant strategies, while the few yearling migrants occur in areas where reservoir releases maintain unusually low water temperatures. Historical changes reduced or eliminated habitats that supported diverse salmon life histories throughout the basin. Passage barriers blocked access to cool upper basin tributaries, and irrigation diversions reduced flows and increased water temperatures, eliminating cool-water refugia necessary to support juveniles with stream-rearing life histories (Williams, 2006a). The loss of floodplain and tidal wetlands in the Delta eliminated a considerable amount of habitat for fry migrants, a life history strategy that is not very effective in the absence of shallow-water habitats downstream of spawning areas. Similar fresh water and estuarine habitat losses have been implicated in the simplification of Chinook life histories in the Salmon (Bottom et al., 2005a) and Columbia River basins (Bottom et al., 2005b; Williams, 2006b). In Oregon's Salmon River, an extensive estuarine wetland restoration program has increased rearing opportunities for fry migrants, expanding life history diversity in the Chinook population, including the range of times and sizes that juveniles now enter the ocean (Bottom et al., 2005a). Re-establishing access to shallow wetland and floodplain habitats in the Sacramento River and Delta similarly could extend the time period over which SRFC reach sufficient sizes to enter the ocean, strengthening population resilience to a variable ocean environment.

Hatchery fish are a large and increasing proportion of SRFC (Barnett-Johnson et al., 2007), and a rising fraction of the population is spawning in hatcheries (Fig. 19). The Central Valley salmon hatcheries were built and operated to mitigate the loss of habitat blocked by dams, but may have inadvertently contributed to the erosion of biodiversity within fall Chinook. In particular, the release of hatchery fish into the estuary greatly increases the straying of hatchery fish to natural spawning areas (CDFG and NMFS, 2001). Central Valley fall Chinook are almost unique[8] among Chinook ESUs in having little or no detectable geographically-structured genetic variation (Williamson and May, 2005). There are two plausible explanations for this. One is that Central Valley fall Chinook never had significant geographical structuring because of frequent migration among populations in response to highly variable hydrologic conditions (on a microevolutionary time scale). The other explanation is that straying from hatcheries to natural spawning areas has genetically homogenized the ESU. One implication of the latter explanation is that populations of SRFC may have lost adaptations to their local environments. It is also likely that hatchery practices cause unintentional evolutionary change in populations (Reisenbichler and Rubin, 1999; Bisson et al., 2002), and high levels of gene flow from hatchery to wild populations can overcome natural selection, reducing the genetic diversity and fitness of wild populations.

Another consequence of the hatchery mitigation program was the subsequent harvest strategy, which until the 1990s was focused on exploiting the aggregate stock, with little regard for the effects on naturally produced stocks. For many years, Central Valley Chinook stocks were exploited at rates averaging more than 60 percent in ocean and freshwater fisheries (Myers et al., 1998). Such levels may not be sustainable for natural stocks, and could result in loss of genetic diversity, contributing to the homogeneity of Central Valley fall Chinook stocks. Harvest drives rapid changes in the life history and morphological phenotypes of many organisms, with Pacific salmon showing some of the largest changes (Darimont et al., 2009). An evolutionary response to the directional selection of high ocean harvest is expected, including reproduction at an earlier age and smaller size and spawning earlier in the season (reviewed by Hard et al. (2008)). A truncated age structure

[8]The exception to this rule is Sacramento River winter-run Chinook, which now spawn only in the mainstem Sacramento River below Keswick Reservoir.

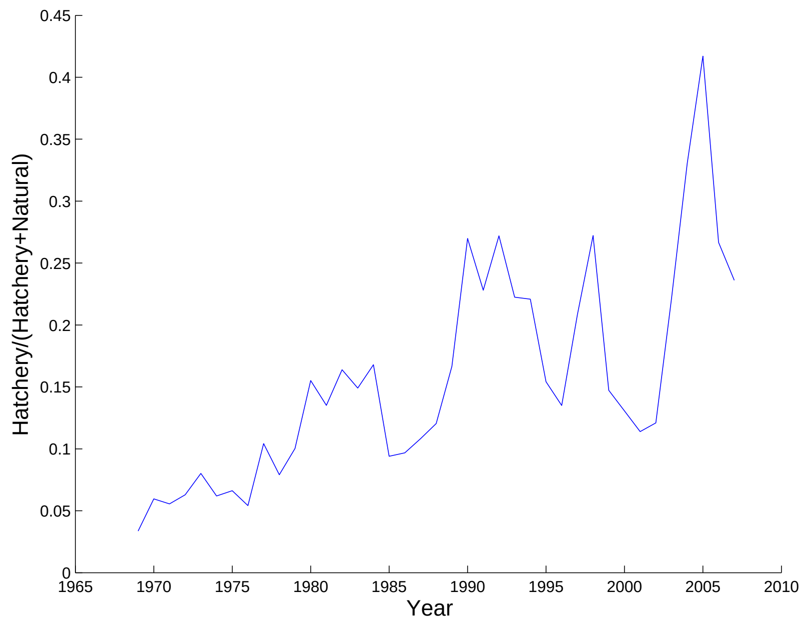

Figure 19: The fraction of total escapement of SRFC that returns to spawn in hatcheries.

may also increase variation in population abundance (Huusko and Hyvärinen, 2005; Anderson et al., 2008).

Hatchery practices also may cause the aggregate abundance of hatchery and natural fish to fluctuate more widely. Increased variability arises in two ways. First, high levels of straying from hatcheries to natural spawning areas can synchronize the dynamics of the hatchery and natural populations. Second, hatcheries typically strive to standardize all aspects of their operations, releasing fish of a similar size at a particular time and place, which hatchery managers believe will yield high returns to the fishery on average. Such strategies can have strong effects on age at maturation through effects on early growth (Hankin, 1990), reducing variation in age at maturity. A likely product of this approach is that the high variation in survival among years and high covariation in survival and maturation among hatchery releases within years may create boom and bust fluctuations in salmon returns, as hatchery operations align, or fail to align, with favorable conditions in stream, estuarine or ocean environments.

Hankin and Logan's (2008) analysis of survival rates from release to ocean age 2 of fall-run Chinook released from Iron Gate, Trinity River and Cole Rivers hatcheries provides an example. Survival of 20+ brood years of fingerling releases ranged from 0.0002 to 0.046, and yearling releases ranged from 0.0032 to 0.26, a 230-fold and 80-fold variation in survival, respectively. Hankin and Logan (2008) found that survival covaried among release groups, with the highest covariation between groups released from the same hatchery at nearly the same time, although covariation among releases from different hatcheries made at similar times was substantial. Because Central Valley fall Chinook are dominated by hatchery production, and Central Valley hatcheries release most of their production at similar times, this finding is significant: very high variation in ocean abundance and escapement *should be expected* from the system as currently operated.

A similar mechanism has been proposed to explain the collapse of coho salmon fisheries along the Oregon coast following the 1976 ocean regime shift. Cumulative habitat loss, overharvest, and the gradual replacement of diverse wild populations and life histories with a few hatchery stocks left coho salmon vulnerable to collapse when ocean conditions suddenly changed (Lawson, 1993; Lichatowich, 1999; Williams, 2006b)). The situation is analogous to managing a financial portfolio: a well-diversified portfolio will be buffeted less by fluctuating market conditions than one concentrated on just a few stocks; the SRFC seems to be quite concentrated indeed.

4.2 Other Chinook stocks in the Central Valley

Sacramento River fall Chinook have been the most abundant stock of Chinook salmon off of central California in recent decades, but this has not always been the case. Sacramento River winter Chinook, late-fall Chinook and especially spring Chinook once dominated the production of Chinook from the Central Valley (Fisher, 1994), but over the decades have dwindled to a few remnant populations mostly now under the protection of the Endangered Species Act (Lindley et al., 2004). The causes for these declines are the same as those that have affected fall Chinook, but because these other stocks spend some portion of their life in freshwater during the summer, they have been more strongly impacted by impassable dams that limit access to cold-water habitats.

Spring-run Chinook were once the most abundant of the Central Valley runs, with large populations in snow-melt and spring-fed streams in the Sierra Nevada and southern Cascades, respectively (Fisher, 1994). Spring-run Chinook have been reduced from perhaps 18 major populations spawning in four distinct ecoregions within the Central Valley to three remnant populations inhabiting a single ecoregion (Lindley et al., 2007). Winter-run Chinook were less abundant than spring Chinook, spawning in summer months in a few spring-fed tributaries to the upper Sacramento River. Perhaps four distinct populations of winter Chinook have been extirpated from their historical spawning grounds, with survivors founding a population in the tailwaters of Shasta Dam (Lindley et al., 2004). The historical distribution of late-fall-run Chinook is less clear, but their life history requires cool water in summer, and thus their distribution has probably also been seriously truncated by impassable dams at low elevations in the larger tributaries.

An examination of the population dynamics of extant Central Valley Chinook populations illustrates that if spring, winter and late-fall Chinook contributed significantly to the fishery, the aggregate abundance of Chinook in central California waters would be less variable. Populations of Central Valley fall-run Chinook exhibited remarkably similar dynamics over the past two decades, while other runs of Central Valley Chinook did not (Fig. 20 and 21). Almost all fall Chinook populations reached peak abundances around 2002, and have all been declining rapidly since then. In contrast, late-fall, winter and naturally-spawning spring Chinook populations have been increasing in abundance over the past decade, although escapement in 2007 was down in some of them and the growth of these populations through the 1990s and 2000s has to some extent been driven by habitat restoration efforts. This begs the question of why have these other stocks responded differently to recent environmental variation.

The answer may have two parts. One part has to do with hatcheries. As discussed above, hatcheries may be increasing the covariation of fall Chinook populations by erasing genetic differences among populations that might have caused the populations to respond differently to environmental variation. They may be further synchronizing the demographics of the naturally-spawning populations through straying of hatchery fish into natural spawning areas, a problem exacerbated by outplanting fish to the Delta and bays. Finally, hatchery practices minimize variation in size, condition and migration timing, which should tend to increase variation in survival rates because "bet hedging" is minimized.

The other part of the answer may lie in the observation that the other runs of Chinook have life history tactics that differ in important ways from fall Chinook. While named according to the time of year that adults enter freshwater, each run type of Central Valley Chinook has a characteristic pattern of habitat use across space and time that leads to differences in the time and size of ocean entry. For example, spring-run Chinook juveniles enter the ocean at a broader range of ages (with a portion of some populations migrating as yearlings) than fall Chinook, due to their use of higher elevations and colder waters. Winter run Chinook spawn in summer, and the juveniles enter the ocean at a larger size than fall Chinook, due to their earlier emergence and longer period of freshwater residency. Late-fall-run Chinook enter freshwater in the early winter, and spawn immediately, but juveniles migrate as yearlings the following winter. Thus, if ocean conditions at the time of ocean entry are critical to the survival of juvenile salmon, we should expect that populations from different runs should respond differently to changing ocean conditions because they enter the ocean at different times and at different sizes.

In conclusion, the development of the Sacramento-San Joaquin watershed has greatly simplified and truncated the once-diverse habitats that historically supported a highly diverse assemblage of populations. The life history diversity of this historical assemblage would have buffered the overall abundance of Chinook salmon in the Central Valley under varying climate conditions. We are now left with a fishery that is supported largely by four hatcheries that produce mostly fall Chinook salmon. Because the survival of fall Chinook salmon hatchery release groups is highly correlated among nearby hatcheries, and highly variable among years, we can expect to see more booms and busts in this fishery in the future in response to variation in the ocean environment. Simply increasing the production of fall Chinook salmon from hatcheries as they are currently operated may aggravate this situation by further concentrating production in time and space. Rather, the key to reducing variation in production is increasing the diversity of SRFC. In the following section, we make some recommendations towards this goal.

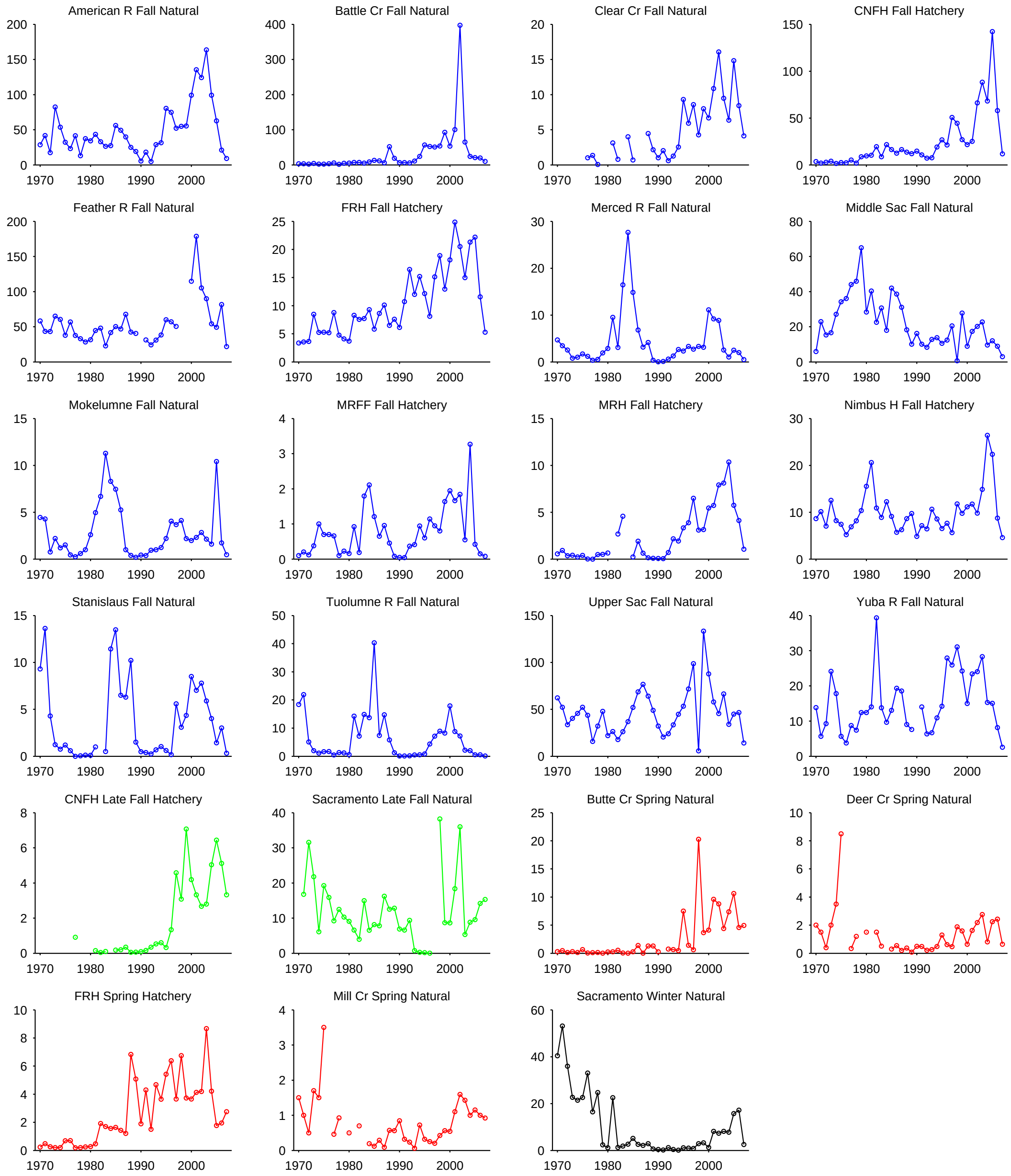

Figure 20: Escapement trends in selected populations of Chinook since 1970. Plots are color-coded according to run timing. Y- axis is thousands of fish; X-axis is year. CNFH = Coleman National Fish Hatchery; FRH = Feather River Hatchery; MRFF = Merced River Fish Facility; MRH = Mokelumne River Hatchery.

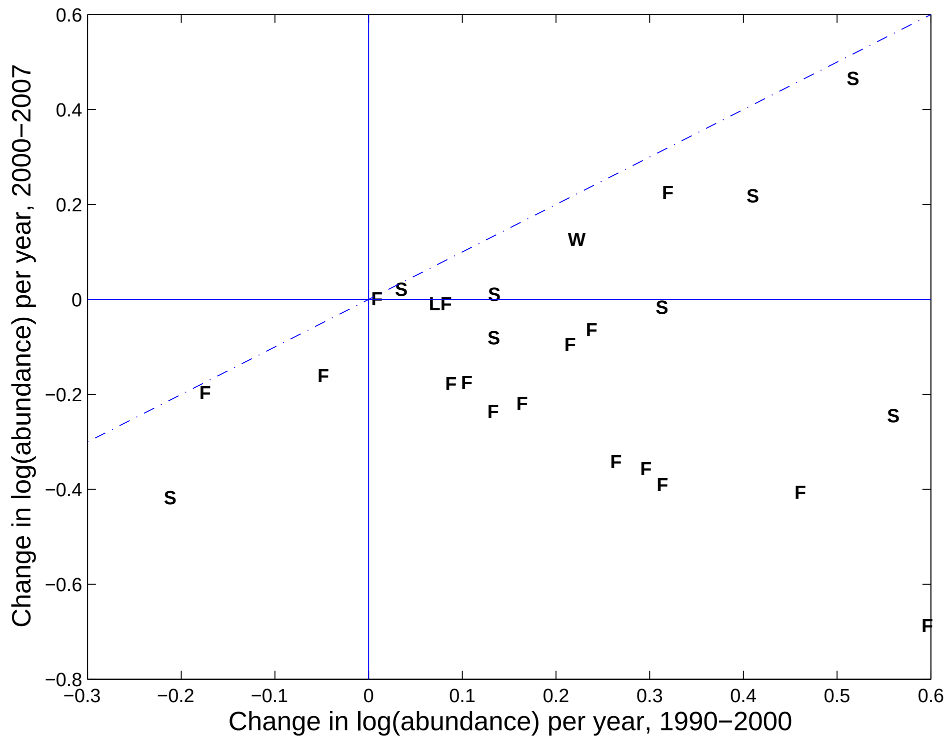

Figure 21: Escapement trends in the 1990s and 2000s of various populations of Chinook. F = fall Chinook, S = spring Chinook, LF= late fall Chinook, W= winter Chinook. If populations maintained constant growth rates over the 1990-2007 period, they would fall along the dashed diagonal line. All populations fall below the diagonal line, showing that growth rates are lower in the 2000s than in the 1990s, and fall Chinook populations have tended to decline the fastest in the 2000s.

5 Recommendations

In this section, we offer recommendations in three areas. First, we identify major information gaps that hindered our analysis of the 2004 and 2005 broods. Filling these gaps should lead to a better understanding of the linkages between survival and environmental conditions. Second, we offer some suggestions on how to improve the resilience of SRFC and the Central Valley Chinook stock complex. While changes in harvest opportunities are unavoidable given the expected fluctuations in environmental conditions, it is the panel's opinion that reducing the volatility of abundance, even at the expense of somewhat lower average catches, would benefit the fishing industry and make fishery disasters less likely. Finally, we point out that an ecosystem-based management and ecological risk assessment framework could improve management of Central Valley Chinook stocks by placing harvest management in the broader context of the Central Valley salmon ecosystem, which is strongly influenced by hatchery operations and management of different ecosystem components, including water, habitat and other species.

5.1 Knowledge Gaps

We are confident in our conclusion that unusual conditions in the coastal ocean in 2005 and 2006 caused the poor performance of the 2004 and 2005 broods. Our case could have been strengthened further, however, with certain kinds of information that are not currently available. Chief among these is the need for constant fractional marking and tagging of hatchery production, and adequate sampling of fish on the natural spawning grounds. Such information would better identify the contribution of hatcheries to the ocean fishery and natural spawning escapement, survival rates of different hatchery release groups, and the likely degree to which hatchery populations are impacting naturally-spawning populations. Central Valley hatcheries have recently started a constant-fractional marking program for fall Chinook, and CDFG is currently planning how to improve in-river sampling for mark and tag recovery. These efforts are critical to improved assessment of SRFC in the future.

CDFG has also recently begun to determine the age of returns to the river, which will allow stock assessment scientists to produce cohort reconstructions of the natural stocks in addition to hatchery stocks. Cohort reconstructions provide better survival estimates than the method used in this report (releases of tagged juvenile and recovery of tagged fish at age-two in recreational fisheries) because they are based on many more tag recoveries and provide estimates of fishery mortality and maturation rates.

In the case of the 2004 and 2005 broods, freshwater factors did not appear to be the direct cause of the collapse, but future collapses may have multiple contributing causes of similar importance. In such cases, it would be extremely valuable to have reach-specific survival rates like those routinely available for several salmonid species in the Columbia River and recently available for late-fall Chinook and steelhead in the Sacramento River. This would provide powerful and direct information about when and where exceptional mortality occurs.

Observations of growth and energetic condition of Chinook in the estuary and ocean provided valuable evidence for the 2004 brood, but were unavailable for the 2005 and later broods, due to funding limitations.

5.2 Improving resilience

It appears that the abundance of SRFC is becoming increasingly variable (Fig. 17). Exceptionally high abundance of SRFC may not seem like a serious problem (although it does create some problems), but exceptionally low abundances are treated as a crisis. The panel is concerned that such crises are to be expected at a frequency much higher than is acceptable, and that this frequency may be increasing with time due to changes in the freshwater environment, the ocean environment, and the SRFC stock itself. The main hope of reducing this volatility is increasing the diversity within and among the populations of fall Chinook in the Central Valley. There are a number of ways to increase diversity.

Perhaps the most tractable area for increasing diversity is in changing hatchery operations. We recommend that a hatchery science review panel, be formed to review hatchery practices in the Central Valley. The panel should address a number of questions, including the following:

1. assess impacts of outplanting and broodstock transfers among hatcheries on straying and population structure and evaluate alternative release strategies

2. evaluate alternative rearing strategies to increase variation in timing of outmigration and age at maturity

3. assess whether production levels are appropriate and if they could be adjusted according to expected ocean conditions

Ongoing efforts to recover listed Chinook ESUs and increase natural production of anadromous fish in the Central Valley (e.g., the fisheries programs of the Central Valley Project Improvement Act) are also relevant to the problem and should be supported. In particular, efforts to increase the quantity and diversity of spawning and rearing habitats for fall Chinook are likely to be effective in increasing the diversity of life history tactics in that stock.

The PFMC should consider creating specific conservation objectives for natural populations of SRFC. Especially in coordination with revised hatchery operations and habitat restoration, managing for natural production could increase diversity within Central Valley fall Chinook. Because conditions for reproduction and juvenile growth are more variable within and among streams than hatcheries, natural production can be expected to generate a broader range of outmigration and age-at-maturity timings. If straying from hatcheries to natural areas is greatly reduced, the population dynamics of natural populations would be less similar to the dynamics of the hatchery populations, which would smooth the variation of the stock aggregate.

5.3 Synthesis

Addressing hatcheries, habitat and harvest independently would provide benefits to Central Valley Chinook, but addressing them together within a holistic framework is likely to be much more successful. The fisheries management community is increasingly recognizing the need to move towards an ecosystem based management approach. While there is still much uncertainty about what this should entail, the ecosystem-based management and ecological risk assessment (EBM/ERA) approach used by the south Florida restoration program (e.g., Harwell et al., 1996; Gentile et al., 2001) is readily applicable to management of Central Valley Chinook. That approach could lead stakeholders to a common view of the different problems afflicting Central Valley Chinook, identify and organize the information needed to effectively manage the ecosystem, better connect this information to decision-making, and reduce the uncertainty surrounding our decisions.

At the core of the EBM/ERA approach are conceptual models of how the system works. The current fishery management regime for SRFC has some features of adaptive management, in that there are clearly stated goals and objectives for the fisheries, monitoring and evaluation programs, and an analytic framework for connecting the data to decisions about operation of the fishery. If one were to make explicit the conceptual model underlying SRFC harvest management, it would include hatcheries that maintain a roughly constant output of fish coupled with ocean and in-river fisheries operating on aggregate stock abundance. The goal is to maximize harvest opportunities in the current year within constraints posed by various weak stocks, which do not include naturally-spawning populations of SRFC. The panel feels that it would be useful to expand this conceptual model to include naturally-spawning populations, revised hatchery operations, habitat effects, ocean effects, and climate change. Also, resource managers might consider changing the goal of management from maximizing harvest opportunity for the current year to reducing fluctuations in opportunity from year to year and maintaining the stability of the system for the long term. Both of these goals require viable and productive populations of wild salmon. Not all of the factors in the revised system would be subject to control by fisheries managers, but including them in the model would at least make clear the contribution of these factors to the problem of effectively managing Chinook salmon fisheries.

The panel is well aware that the resource management institutions are not well-equipped to pursue this approach, and that many of the actions that could improve the status and resilience of Central Valley Chinook are beyond the authority of the PFMC or any other single agency or entity. Nonetheless, significantly improving the resilience of Central Valley Chinook and the sustainability of California's Chinook salmon fishery will require resource managers and stakeholders to work together, and EBM/ERA offers a framework for facilitating such cooperation.

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