EFFECTS OF FISH PREDATION ON SALMONIDS IN THE SACRAMENTO RIVER – SAN JOAQUIN DELTA AND ASSOCIATED ECOSYSTEMS

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EXECUTIVE SUMMARY

We examined a set of 24 papers and observed presentations by researchers to assess the status of information and potentially establish conclusions regarding the importance of fish predation on salmonid populations in the Delta. Available data and analyses have generated valuable information regarding aspects of the predation process in the Delta but do not provide unambiguous and comprehensive estimates of fish predation rates on juvenile salmon or steelhead nor on population-level effects for these species in the Delta. Recent survival studies are based on acoustic tagging of larger hatchery-raised fish from ~95 to >250 mm FL. Although it is assumed that much of the short-term (<30 d) mortality experienced by these fish is likely due to predation, there are few data establishing this relationship. Juvenile salmon are clearly consumed by fish predators and several studies indicate that the population of predators is large enough to effectively consume all juvenile salmon production. However, given extensive flow modification, altered habitat conditions, native and non-native fish and avian predators, temperature and dissolved oxygen limitations, and overall reduction in historical salmon population size, it is not clear what proportion of juvenile mortality can be directly attributed to fish predation. Fish predation may serve as the proximate mechanism of mortality in a large proportion of the population but the ultimate causes of mortality and declines in productivity are less clear. For example, stress caused by harsh environmental conditions or toxicants will render fish more susceptible to all sources of mortality including predation, disease or physiological stress. We also recommend a variety of structural changes to the manner in which research is performed in the Delta. These include creation of a system-wide GIS including layers for available physical, chemical and biological data including hatchery releases. Next, we recommend that methods be standardized for important research topics such as fish abundance estimates, tagging studies, dietary studies, etc. This process has recently been conducted by the National Ecological Observatory Network and their work could serve as a starting point for a similar process in the Delta. Our research indicated that it was difficult to locate information for many topics and we recommend creation of a searchable data repository for research conducted in the Delta, similar to that used by NSF Long-Term Ecological Research sites. Finally, we suggest a series of research topics that must be addressed to reach scientifically valid conclusions regarding the role of fish predation on salmonid populations in the Delta and provide examples of potential study designs from the literature.

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PANEL CHARGE*

The Expert Panel was charged with evaluating a series of pre-assigned papers on predation in the San Francisco Bay Delta Ecosystem (Appendix 1) and participating in a workshop conducted 22-24 July 2013 in which the panel also heard research presentations (Appendix 2) and public input. The panel was charged with answering the questions below, and these answers will be presented in separate sections or combined with other charges where appropriate. In addition, we have included a Background section which describes the ecological context of the Bay Delta system with respect to the salmonid-fish predator interaction. Although an extensive literature review on the general topic of how predation affects salmonid survival in the Delta was not part of our charge, we have included and commented on additional papers where appropriate to the subject at hand.

1. What is the ecological context of predation by fish on Central Valley salmonids, and what can be learned from other systems that could inform our understanding of predation on anadromous salmonids?

2. What do the available data and analyses tell us about the rates and population level effects of fish predation on Central Valley salmonids?

    A. Are there appropriate methods for estimation of predation rates and population level effects from the existing data?
    B. What biological and physical factors are likely to affect the impacts of predation on salmonids? Have these factors changed over time, and do they vary between the major basins (i.e., San Joaquin and Sacramento River)? Do these factors vary among the major reaches of the system (e.g., spawning areas, riverine reaches, delta, bay, ocean)?
    C. What is understood about the interactions among major factors influencing predation on salmonids (e.g., interactions among predators, hydrology and temperature, etc.)?

3. What related science is generally agreed upon; what are the key disagreements or uncertainties?
4. What future work (e.g., feasible scientific studies, modeling, and pilot experiments) should be done to address key knowledge gaps by testing clearly stated hypotheses to substantially reduce scientific uncertainties that lead to disagreement? Please provide guidance on appropriate study design and methods for estimating predation rates and population level effects.

*Because the charge questions deal with interwoven issues they will be addressed where most relevant rather than in the order presented in the charge.

SECTION 1

1A The Ecological Context of Predation -- the Delta Environment: physical factors affecting predation by fishes on salmonids
1B What can be learned from other systems?

1A The Ecological Context of Predation -- the Delta Environment: physical factors affecting predation by fishes on salmonids

The Sacramento River – San Joaquin Delta is the largest estuarine system on the west coast of the Americas. By recent definitions (areas less than 7.6 m in elevation, Whipple et al. 2012), the Delta comprises an area of 3238 km^2 and is both one of the most productive agricultural regions in the United States as well as being one of the most important western habitats for wildlife, fishes and invertebrates. The Delta has high biodiversity, with more than 700 species recorded from this unique habitat. This system also provides essential rearing habitat for imperiled Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) and also serves as a transit zone for these species as they emigrate to their adult habitat in the Pacific Ocean. Both the rearing and migratory functions of the Delta have been strongly affected by a long history of water withdrawals, land conversion, and introductions of invasive species. Historical anthropogenic impacts and ecology of the Delta have recently been reviewed by Whipple et al. (2012), so we will not review that information extensively.

The Delta is fed primarily by the Sacramento and San Joaquin Rivers. In general, the Sacramento River has better water quality than the San Joaquin; the latter is more strongly affected by municipal and water export processes. Although both rivers experience withdrawals and upstream inputs from agricultural uses, the Sacramento River has lower specific conductance, alkalinity, nitrate concentration, dissolved organic carbon, and orthophosphate concentrations (Whipple et al. 2012). In addition, the concentration of selenium is an order of magnitude lower in the Sacramento River than the San Joaquin (Monsen et. al 2007). The Sacramento River, does, however, have higher mercury concentrations than the San Joaquin as a result of historic mining operations (Luoma et al. 2008). The relative contributions of Sacramento River and San Joaquin waters to the Delta depend on multiple factors including: rainfall, river volumes, pumping plant export rates, gate operations, and seasonal barrier placement in the south Delta (Monsen et al. 2007). Because the Delta has a complex geography and hydrology that creates significant spatial heterogeneity in ecological processes such as fish predation rates, we have divided the system into six regions, each with unique physical characteristics. Figure 1 depicts the spatial locations of the different regions.

Region 1: North Delta

The North Delta region includes the main stem Sacramento River, Sacramento River Deep Water Ship Channel, Steamboat, Sutter, and Miner Sloughs. Fresh water is delivered from the Sacramento River and exits through the Cache Slough Complex (Region 2) and the Mokelumne River Region (Region 3). The majority of inflow to the Delta comes from the Sacramento River (Healey et al. 2008) and this is a major migration pathway for Chinook salmon both as adults moving upriver to spawn and for juveniles moving downstream to reach the ocean (Perry et al. 2013). Two significant hydrologic features within this region are the Sacramento River connections at the Delta Cross Channel (DCC) and at Georgiana Slough. The DCC was built to divert Sacramento River water into the Central Delta (Region 4) via the Mokelumne region (Region 3) to prevent salinity intrusion in the Central (Region 4) and South Delta (Region 5). The gates of the DCC are normally open except when migratory salmonids are in the region in accordance to State Water Resources Control Board Decision 1641. Georgiana Slough is a second connecting channel that diverts Sacramento River water to the Central Delta (Region 4). Despite generally strong riverine flow, a tidal signal is present throughout Region 1. On the Sacramento River itself, the transition between unidirectional flow and reverse flows occurs around Georgiana Slough and the DCC. The exact location of this transition is a function of flow in the Sacramento River as well as DCC gate operations (Monsen 2001). There are no open, shallow water habitats in this region and channels are typically wide (50-200 m), armored with rip-rap, and leveed. The levees were originally built for flood control for the City of Sacramento and small, riverside farming communities.

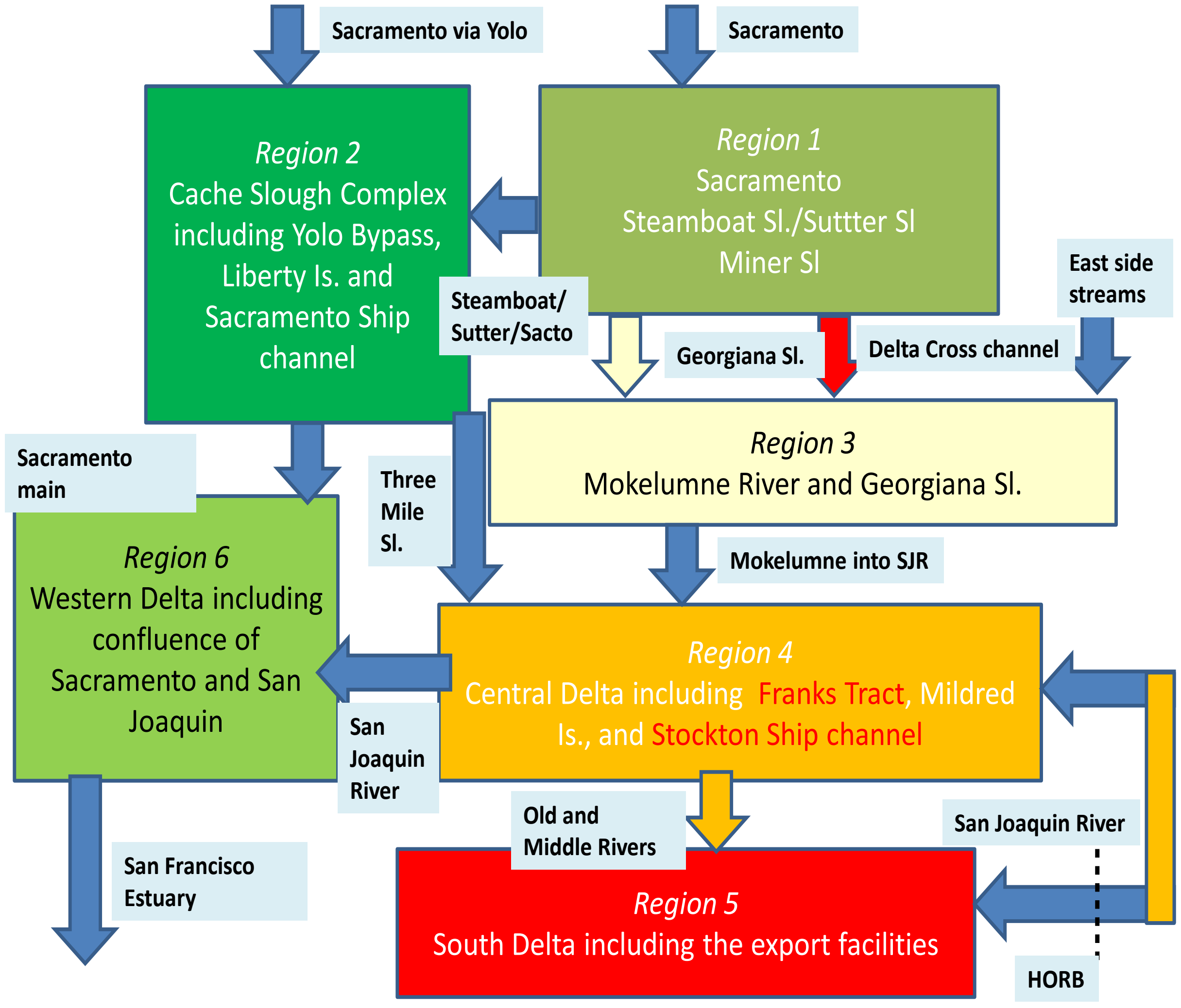

Figure 1: The six hydrologic/predation regions of the Sacramento – San Joaquin Delta. Based on the literature we synthesized hydrologic units (regions) and they hypothesized predation risk from low (green) to moderate (yellow) to high (red).

Water quality in Region 1 is high when compared to the Delta as a whole. Water quality regulations keep salinity in the region well below 2 ppt throughout the year, with salinities at Freeport typically around 0 (0.1 ppt). Nonetheless, the Sacramento River at Freeport contributes the majority of sediment to the Delta system. Typically, suspended sediment concentration (SSC) is in the range of 10-50 mg/L, but can exceed 200 mg/L during wintertime high flow events. Sediment concentrations in the Sacramento River have decreased by half from 1957-

2001 and total suspended solids have decreased 50% from 1975-1995 (Schoellhamer et al. 2013).

Region 2: Cache Slough Complex

Region 2 includes the Cache Slough complex and surrounding areas (i.e., Liberty Island, Yolo Bypass and the Sacramento River Ship channel). Cache Slough connects to the Western Delta (Region 6) via the main stem Sacramento River. To the south, Three Mile Slough also connects the region to the Central Delta (Region 4). This region derives its water from the Sacramento River via either the North Delta (Region 1) or in the winter from the Yolo Bypass. The Cache Slough region is isolated from the remainder of the Delta and is a higher quality habitat for native fishes. (Larry Brown, presentation). The main shallow water habitats in Region 2 are Liberty Island and Holland Tract. Liberty Island, formally agricultural land flooded in the mid-1990's, is the focus of several research projects including BREACH III (http://www.science.calwater.ca.gov/publications/sci_news_0410_liberty.html). Region 2 shares generally higher water quality characteristics with Region 1 and the Cache Slough region is considered to have better water quality than the remainder of the Delta. Water enters the region via Yolo Bypass in the winter, and is the second largest source of sediment for the Delta. The open-water habitats do not have large concentrations of submerged aquatic vegetation.

Region 3: Mokelumne River and Georgiana Slough

This region is composed of Georgiana Slough and the North and South Mokelumne rivers. The Sacramento River is the primary water source in this region, via diversions through Georgiana Slough and the DCC. The Cosumnes and Mokelumne Rivers also contribute water to this region but the volumes are substantially lower than those from the Sacramento River. The channel landscape in Region 3 is mostly rip-rapped levees. Channel widths range from 50-150 m wide with some dead-end sloughs connecting to the South Mokelumne River on the eastern side of the region. There are no significant shallow water habitats in this region. Region 3 is tidally influenced throughout. Region 3 has a very light suspended sediment load because little sediment is transferred from the Sacramento River (Region #1) via the DCC. In addition, the Cosumnes and Mokelumne Rivers only contribute about 3% of the overall sediment discharge to the Delta (Schoellhamer et al. 2013).

Region 4: Central Delta

The Central Delta consists of the San Joaquin River between Three Mile Slough and Stockton, Old and Middle rivers, and the two primary open-water regions of the Delta, Franks Tract and Mildred Island (Lucas et al. 2002). Region 4 receives water from the Mokelumne (Region 3), and the Cache Slough complex via Three Mile Slough (Region 2). This region is connected to the Western Delta via the San Joaquin River with connections from Big Break and False River (Franks Tract). Because of export operations, the tidally-averaged flow in Old and Middle rivers is upstream towards the South Delta (Region 5). Water flows within the Central Delta region are a function of Sacramento River and San Joaquin River flows, seasonal barrier placement in the South Delta, and water export rates. Monsen et al. (2007) provides a thorough description of how these conditions affect water inflow and outflow in Region 4. In general, the Old and Middle Rivers are fed by Sacramento River water when regional water barriers are open and export pumps in operation. If the Head of Old River Barrier (HORB) is in place, the Middle River will likely contain San Joaquin River water. Both Franks Tract and Mildred Island were agricultural land prior to levee failure and inundation. In both cases, the islands have remained flooded and represent extensive open-water shallow habitats connected to adjacent channels via levee breaks. The eastern levee of Franks Tract has eroded so there is a direct connection to the Old River.

There are significant water quality issues in Region 4 including sediment inputs, turbidity, dissolved oxygen and salinity. Region 4 receives little sediment from either the Sacramento River or San Joaquin Rivers. Water quality issues in Franks Tract are a function of submerged aquatic vegetation (Underwood et al. 2006) which increases significantly during summer months. The presence of large amounts of submerged aquatic vegetation (SAV) creates a multifaceted feedback loop involving hydrodynamics and water clarity, because SAV: 1) reduces wave action via attenuation, 2) reduces flow via increasing drag in the water column, 3) reduces vertical stress in the water column, and consequently increases sediment deposition and decreasing turbidity. Not only does SAV decrease turbidity locally, but when water that has been in the SAV-laden Franks Tract mixes with water in the adjacent channels via tidal exchange, turbidity also decreases in these channels because of dilution with low turbidity water (Schoellhamer et al. 2013). The Stockton Ship Channel historically has been a location of low dissolved oxygen. Aerators were installed in the center of the San Joaquin River as a solution to this water quality problem. The HORB also facilitates increased dissolved oxygen levels via increasing freshwater flows in this tidal region (Monsen et al. 2007).

Region 5: South Delta

The South Delta includes the San Joaquin River from Stockton to Vernalis, Old and Middle Rivers, the State Water Project export facilities including Clifton Court Forebay and the Central Valley Project. Clifton Court Forebay is the only open-water, shallow habitat in this region. The South Delta is connected to the Central Delta (Region 4) and the San Joaquin River enters the eastern side of the region by way of the HORB. Region 5 has complex flows affected by both natural and water management activities. The seasonal temporary barriers (Middle River, Old River and Grant Line Canal), Clifton Court Forebay radial gate operations, and water export pumps control circulation and mixing. When seasonal barriers are inactive, San Joaquin River water travels west towards the export facilities and north towards Stockton. In extreme low flow conditions, the San Joaquin River between Old River and Stockton may become tidal with reversed flows (Burau et al. 2000). When the HORB is active, San Joaquin River water is directed north towards Stockton. The three seasonal barriers (Old River at Tracy, Middle River, and Grant Line Canal) maintain water levels for agricultural diversions within Region 5 during the summer and fall dry season. These barriers effectively isolate the South Delta region, creating a temporary reservoir consisting of the Old, Middle and Grant Line channels. The activities of the export facilities direct tidal flows in both Old and Middle Rivers upstream towards their intake structures. The circulation patterns of Clifton Court Forebay and the export facilities were recently modeled by MacWilliams and Gross (2013). The circulation patterns in CCFB will be discussed further in the future work section.

Water quality in Region 5 is regulated to conform to drinking and agricultural water quality standards. Because the primary water source is the San Joaquin River, salinities frequently are higher in this region than in the Regions 1-3 (Monsen et al. 2007). There also are significant agricultural water returns, which are high in both salt and dissolved organic carbon. The San Joaquin River provides about 20 percent of the sediment to the Delta. This sediment remains in the San Joaquin Channel by Stockton rather than moving into the South Delta at the head of Old

River. The sediment signal from the San Joaquin attenuates more rapidly than the Sacramento River signal and is almost completely gone at Stockton (Schoellhamer et al. 2013).

Region #6: Western Delta

The Western Delta includes the confluence of the Sacramento and San Joaquin Rivers. Water comes from the main Sacramento River (Region 2) and San Joaquin (Region 4) rivers and is also connected to San Francisco Estuary. This is a highly energetic tidal region and represents the transition zone from freshwater to estuarine ecosystem. An important physical marker, X2 (2 ppt salinity at the bottom of the water column) is often found in the region in the late summer and fall. The Sacramento River at the confluence often contains high suspended sediment concentrations whereas the San Joaquin River has very low SSC (Schoellhamer et al. 2013).

1B What can be learned from other systems?

What related science is generally agreed upon and where do uncertainties lie?

How do major factors influencing predation on salmonids interact?

We have briefly reviewed the literature on: 1) population-level effects, 2) salmonid ecology and food web processes and 3) predator removal studies to assess what is generally agreed upon by biologists and where uncertainties remain. In addition, we address interactions among major factors affecting fish predation on salmonid prey.

What Are Population-Level effects and How Can They Be Detected

The effects of predation on a population may be determined at varying of levels of ecological realism ranging from simple estimates (total number of prey consumed) to more comprehensive measures (annual percent reduction in reproductive adults due to predation). When reasonable accuracy is necessary, even simple approaches present substantial logistical difficulties in field settings. For example, population-level parameters such as abundance, survivorship, or production may be estimated at varying levels of spatial, temporal or population complexity. Beginning simply, one could determine a change in a single demographic parameter such as juvenile abundance at one location, for example, Chipps Island. Increasing in complexity, an investigator might attempt to determine cumulative survivorship to a particular life stage, such as time of marine entry. Scaling up in complexity a researcher could estimate cumulative survivorship across all life-history stages of a cohort at a single location or time. The final level of complexity involves quantifying cohort-specific survivorship at multiple spatial scales over ecologically significant time spans (decades) and documents long-term patterns of population variation and ultimately persistence and extinction risk.

Nonetheless quantifying a population-level effect, such as a long-term decline in juvenile survivorship, does not necessarily identify the mechanism behind the change. Indeed, identification of the mechanism(s) producing variations in population-level phenomena requires significant additional work ranging from low (correlation analysis, results are consistent with hypothesis X) to high (experimentation results only are consistent with hypothesis X) levels of inferential power. In this specific case where estimates of the effects of fish predation on salmonid populations are desired, we would also require: 1) fishery-independent estimates of predator abundance and variation with reasonable precision and accuracy, and 2) robust estimates of overall prey consumption by fish predators (numerical and proportional estimates of the total prey population consumed) or for a particular life stage of interest (i.e. juvenile emigrants). Although we have reduced the data needs for identification of the effects of fish predation down to two steps, there are multiple studies required in each step to achieve estimates with high accuracy and precision. For example, to quantify step two, data will be required for functional and numerical responses of fish predators coupled with annual estimates of prey abundance and productivity. Although this will produce an estimate of mortality contributed by fish predation, the final estimate must be compared to total mortality to quantify whether or not fish predation is a “significant” contributor to total mortality. Indeed, mortality from fish predation may be small compared to mortality imposed by impingement at water extraction facilities, or disease. Finally, predation may be a compensatory process whereby a reduction in fish predation is compensated for by an increase in avian predation. Consequently, it is not safe to assume that demonstrating a fish predation effect at the population level and undertaking management options to reduce this effect, will definitely result in subsequent increases in adult salmonids.

A central tenet of fisheries biology is that most population regulation in marine fishes occurs in a few critical life history stages (Cushing 1996; Houde 1989). Population regulation may be intrinsic (density-dependent responses) or extrinsic (density-independent environmental variation) or more commonly, a function of both processes. In the present context, we need to know the life history stages that primarily are responsible for observed variation in juvenile-to-adult ratios, and the relative extent to which improvements in emigration survivorship will translate into population level effects (e.g. population growth rate). Also, if density dependence is present in the adult phase of salmonid life histories then this may counteract the benefits of improved survivorship of emigrants (Kimmerer, et al. 2000). If population control is driven by density-independent processes acting on non-juvenile life history stages (egg/alevin mortality due to flooding), the fluctuations in population size produced by these interactions will have to be included in any management strategy that involves predator reduction.

The Basics of Predation

Fundamentally, the predation process can be broken down into several components (Fig. 2) including search and encounter rates, pursuit and attack rates, capture and handling, and ultimately consumption. These components are all affected by factors such as prey abundance, spatial and temporal overlap of prey, habitat complexity, turbidity, and behavioral, physiological, and morphological adaptation which facilitate (predator) or inhibit (prey) the predation process. Although many fish predators are opportunistic feeders (Gerking 1994), differences in prey characteristics (e.g., morphology, behavior and energy content) also affect prey choice (Gill 2003). All else being equal, foraging theory predicts that predators should select prey that maximize their net energy gain (Wootton 1990; Grossman 2013). In the case of juvenile salmonid prey in the Delta, predators may display positive selectivity for these species because they are energy-rich (Hartman and Brandt 1995), are easily handled (i.e., soft-rayed and fusiform) and potentially naïve to invasive predators (Kuehne and Olden 2012). This naiveté of salmonids to invasive predators occurs in other regions where lake trout and northern pike feed disproportionately on salmonids despite apparently higher abundance of native catostomid prey (Johnson and Martinez 2000; Johnson et al. 2002; Lepak et al. 2012a).

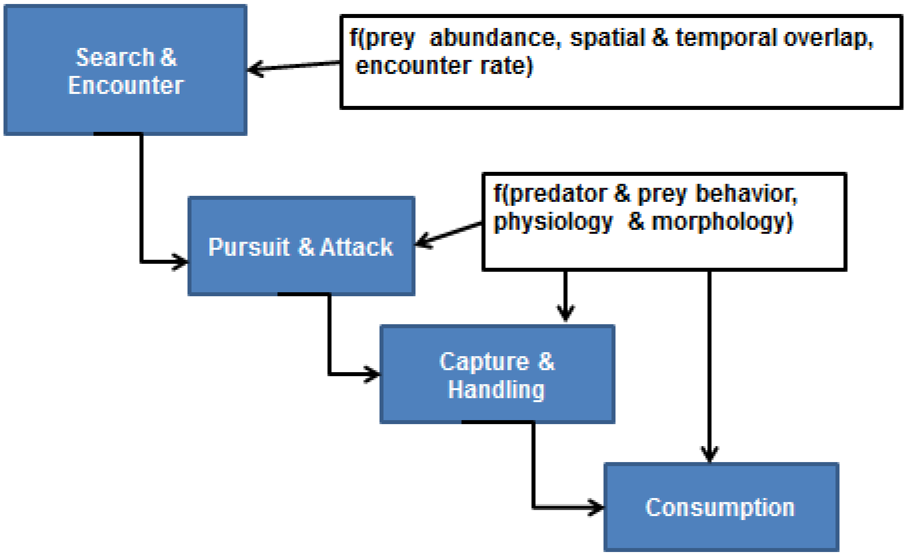

Fig. 2 A schematic depicting the components of the predation process.

Given that the majority of fish predators in the Delta are invasives, naïve salmonids may have a reduced ability to avoid predation. The predation process also is affected by temporal and spatial factors and behavioral data indicate that juvenile salmonids generally only spend weeks to months in the Delta co-occurring with fish predators. Nonetheless, significant predation effects on salmonid populations can occur if predation is localized but intense (Rieman et al. 1991; Wahl et al. 2007). This could occur for salmonids emigrating through the Delta especially in known "hot spots".

Ecological Uncertainty and Predator Effects in Aquatic Systems

Changes in predator abundance produced via removal, augmentation or invasion frequently produce unintended consequences (Polis and Strong 1996). The most common unanticipated shifts are indirect food web effects (Carpenter 1988) such as shifts from pelagic to benthic food webs or vice versa. Although not a predator, a local example of such a food web shift was produced by the small overbite clam *Corbula amurensis* within the San Francisco Bay ecosystem (Feyrer et al. 2003). When food webs are highly interconnected, predicting the consequence of a perturbation to even a single link in food web is nearly impossible (Yodzis 1998, 2000).

Nonetheless, prediction capacity is simplest when: 1) predators are specialists, 2) there is little omnivory, and 3) food webs are mostly linear (i.e., food chains), with little interspecific competition and few shared predators (Polis and Holt 1992, Strong 1992, Polis and Strong 1996, Borer, et al. 2005). Unfortunately these conditions describe neither the Delta food web nor the fish predator-salmonid prey interactions in the region. A second set of unintended consequences may arise via trait-mediated interactions, in which behavioral responses to predators outweigh direct consumptive effects (Preisser, et al. 2005, Schmitz, et al. 2004). In some cases the effects of a predator on prey growth and survival are much larger than that predicted from consumption rates alone. For example, cyprinid populations were nearly extirpated in northern Wisconsin lakes after introduction of largemouth bass, because cyprinids shifted to pelagic microhabitats with stressful high temperatures, low food abundance, and significant avian predation risk (Carpenter and Kitchell 1993). In other cases, behavioral avoidance of multiple predators may produce multiplicative effects, where the effect of one predator enhances the efficiency of a second predator (Hixon and Carr 1997).

Predicting the consequences of predator removal also requires insights into the functional and numerical responses of predators to prey. The functional response describes the per-capita feeding rate of predators, usually as a function of prey density. When the functional response becomes asymptotic as prey density increases (e.g. Type II functional response), the fraction of prey killed by predators increases as prey density declines, inducing depensatory mortality and strong population-level effects. When per-capita predator feeding rates are affected by predator abundance (e.g., interference competition) or when only a fraction of prey are vulnerable to predators, then fish predation rates may be relatively insensitive to fluctuations in predator abundance (numerical response, DeAngelis, et al. 1975, Ahrens, et al. 2012). For example, in the Baltic Sea, changes in juvenile herring abundance are not strongly related to changes in the abundance of their predator Atlantic cod (*Gadus morhua*) (Essington and Hansson 2004).

Much research demonstrates that predation is context dependent–meaning that the magnitude and importance of predation depends on many “local” factors. For example the presence/absence of structure and alternative prey in the environment typically have profound effects on fish predation rates (Mittelbach and Persson 1998). In addition predator: prey size ratios commonly influence predation rates (Ebenman and Persson 1988; Mittelbach and Persson 1998; Scharf, et al. 2000). Most predators are gape limited, and for salmonids this means that larger juvenile salmonids are exposed to fewer predators than smaller individuals. Hence, factors that affect the growth rates of prey such as water temperature, habitat quality, and food availability, also will affect their vulnerability to predators. Because predation only occurs when predator and prey overlap in space and time, large-scale processes (land use, hydro-climatological regimes, etc.) and innate behaviors (e.g., migration, territoriality) also may affect prey distributions and hence, predation rates by fish predators. Predator foraging tactics also may change depending on prey availability, either enhancing or diminishing vulnerability of emigrating salmonids to predators. Consequently fish predator-prey interactions should not be viewed as static. Moreover, fish predation on salmonids in the Delta is specific to one particular life history stage. This and the context dependency of these predator-prey relationships, given the variable Delta environment, undoubtedly will make the population-level effects of fish predation on salmonid survivorship/adult returns challenging to detect.

Habitat Loss & Invasive Species

The primary factors responsible for the imperilment of native species in freshwater systems are anthropogenic habitat change and invasive species (Dudgeon et al. 2006). In the Bay-Delta ecosystem, habitat change has followed intensive development of water resources for human use, including dams, levees, channelization and redistribution of flows (Delta Stewardship Council 2013). The Bay-Delta ecosystem is also one of the most invaded estuaries in the world with more invasive than native species (Cohen and Carlton 1998). Habitat change and invasive species interact, because habitat change, especially degradation, may favor invasives and thus intensify interspecific competition and predation (Meffe and Carroll 1994; Moyle and Light 1996; Bunn and Arthington 2002). Focusing on habitat change or invasive species alone is not adequate for recovery of native salmonids in the Bay-Delta. Rather, both of these ecosystem stressors must be addressed in a coordinated fashion. The importance of a natural flow regime (Grossman et al 1982; Poff et al. 1997) to the native flora and fauna, function, and resilience of lotic ecosystems is widely accepted. Restoration of natural hydrologic regimes is a large component of many regulated river rehabilitation programs (Richter and Thomas 2007) including the Colorado River Basin (Muth et al. 2000; McAda 2003; USBR 2011). However, in some cases restoration of natural hydrologic cycles alone is unlikely to benefit native fishes without concurrent management of invasives, especially predators (Tyus and Saunders 2000; Propst et al. 2008). Invasive predator management is now occurring in conjunction with flow restoration in both the Upper and Lower basins (Mueller 2005; Coggins et al. 2011) of the Colorado River. Salmonid conservation efforts in the Delta cannot focus on habitat restoration alone because 1) the physical structure of the system is highly constrained by domestic and agricultural water demands, and 2) invasive species, including predators, will continue to pose a threat to salmonid persistence. Nor is predator control likely to be effective on a broad scale without attention to the habitat conditions that make invasive predators successful, as the following case histories demonstrate.

Predator Control Case Studies

Control of undesired and invasive fishes is a common fishery management strategy (Kolar et al. 2010). Often, control of predatory fishes is proposed when more direct measures of remediating impacts to prey populations are economically or politically impractical (Beamesderfer 2000). For example, the proximate cause of juvenile mortality could be predation by fishes, but the ultimate cause could be water management schemes that degrade habitat and add stress to migrating juveniles, increasing their vulnerability to predators. Currently, large-scale predator removal programs are underway across North America to aid in the recovery of native and sport fish species, including salmonids. The following case studies illustrate the breadth of approaches and their efficacy to control predatory fishes.

Predator Control and Salmonid Species

Predatory fish control to benefit salmonid populations has been undertaken in both the eastern and western United States. One of the most widespread and effective predator control programs has been directed at sea lamprey *Petromyzon marinus* in the Great Lakes (Smith and Tibbles 1980; Larson et al. 2003). Application of the highly selective lampricide TFM (3-trifluoromethyl-4-nitrophenol) in rearing streams has been effective at reducing sea lamprey populations by 90% in most areas (GLFC 2013) at a cost of about $16M/yr (MDNR 2013). Lamprey control likely has been achieved because a vulnerable stage (ammocoetes) occupies a restricted habitat in which toxicant application is logistically feasible and effective. However, these conditions are not present in most predator removal situations. The Northern Pikeminnow (*Ptychocheilus oregonensis)* Sport-Reward Program began in 1991 in the Columbia River and is sponsored by Bonneville Power Administration. The program seeks to maintain 10-20% exploitation rate on northern pikeminnow throughout the Columbia River by paying anglers $4-$8 to harvest fish > 228 mm TL (Porter 2010). The program removed over 2.2 million fish during 1998-2009 and is believed to have reduced predation on juvenile salmonids, but positive effects on salmonid populations have been difficult to detect (Carey et al. 2012). Cumulative program cost in 2010 was $78.2 million (Porter 2010) but the reward system is still probably more cost-effective than if agencies performed the removal themselves (Carey et al. 2012). Lake trout have been widely introduced for sport fishing in western US lakes and reservoirs. In some systems these fish threaten native and introduced salmonid populations (Dux et al. 2011). Commercial fishing and anglers appear to have reduced lake trout abundance and allowed for kokanee recovery at Lake Pend Oreille, ID (Hansen et al. 2010). Angler incentives do not appear to have been effective at Flathead Lake, MT (BIA 2012), and although commercial-scale netting has removed over 450,000 lake trout at Yellowstone Lake, WY/MT the population continues to threaten native cutthroat trout (Syslo et al. 2011).

Predator Control and Non-salmonid Species

As part of the Upper Colorado River Endangered Fish Recovery Plan (U. S Fish and Wildlife Service 2012) invasive channel catfish, northern pike, smallmouth bass and others are being removed from critical habitat for ESA listed cyprinids and catostomids (Tyus and Sauders 2000; Johnson et al. 2008). Invasive fish control in the Upper Colorado River Basin is costing over $1 million annually (Mueller 2005). Demonstrating native fish response to invasive fish removal has been complicated by highly variable environmental conditions which affect predators and prey differentially. However, the available literature demonstrates that even in isolated reaches where removal efforts were intense, the positive responses of native fishes have been few (Bestgen et al. 2007; Skorupski et al. 2012).

In general, control of fish predators has not produced strong positive, population-level responses in prey species, be they small cyprinids or juvenile salmonids. These attempts are difficult logistically and costly, and the lack of success illustrates the challenges inherent in functionally eliminating wild fish populations in systems with complex dynamics. Eradication generally is unlikely, except in small, isolated systems where reinvasion can be prevented (Kolar et al. 2010). When eradication is impossible, suppression can sometimes be effective at reducing impacts to prey fish populations. However, removal effort must be intensive and sustained (Beamesderfer 2000), making suppression very expensive.

SECTION 2 – WHAT DO AVAILABLE DATA TELL US

2A – A Short Review of Available Data
2B – Appropriate Methods and Extant Data
  Biological and physical factors affecting salmonid predation
  Interactions among major factors
2C – Varying factors: Predation Hot Spots

2A – A Short Review of Available Data

The fish predator assemblage of the Delta is dominated by invasive predators, with the exception of the Sacramento pikeminnow (Table 1) (Brown & Michniuk 2007; Nobriga & Feyrer 2007, National Research Council 2010; Cavallo et al. 2012, National Research Council 2012, Larry Brown presentation). Abundance or relative abundance (e.g., catch-per-unit-effort) data exist for some predators at some locations and times, however fishery-independent population estimates of predator population sizes generally are lacking. Nonetheless, several predators such as striped bass and largemouth bass, appear to be abundant, based on both opportunistic (i.e., salvage data from water control projects) and targeted surveys (i.e., Nobriga et al. 2002; CDFW mid-water trawl surveys). However, there is little information on the spatial distribution and size/age structures of fish predator populations, or how these characteristics vary over time. This greatly limited the Panel’s ability to make quantitative inferences regarding the effects of fish predation on salmonids at the population level. Furthermore, populations of some fish predators (e.g., striped bass) have declined over time, but this decline has not coincided with concomitant increases in salmonid populations and there is uncertainty regarding variation in the abundance of sub-adult striped bass (Loboschefsky et al. 2012). With the exception of striped bass, there is little extant population-level information for fish predators including largemouth bass (e.g., Nobriga et al. 2002; Louise Conrad presentation) and Sacramento pikeminnow (Tucker et al.

1998) whereas there is even less information for smallmouth bass and white and channel catfish (Table 1). It is important to note that, in addition to predation by native and non-native fishes, there has been extensive modification of the hydrology, loss of tidal freshwater wetlands, increases in non-native submerged aquatic vegetation such as *Egeria densa*, and other effects of human population growth within the Delta (Brown & Michniuk 2007; National Research Council 2010, 2012), which also undoubtedly influence the survival of salmonids in the Delta.

Fish predation on juvenile salmon and steelhead obviously occurs within the Central Valley (Table 1, Stevens 1963, 1966; Thomas 1967; Tucker et al. 1998) and it is clear that all of the predators listed in Table 1 likely have the capacity to prey upon both healthy and stressed juvenile salmonids. Nonetheless significant additional information will be required to translate what little dietary data exist into robust estimates of fish predation rates or population-level effects for salmonids. The fish predator with the most complete data base is the striped bass, which also has received much attention because of the listing of several Central Valley Chinook salmon populations under the Endangered Species Act. The development of recovery plans for these populations requires the identification of mortality mechanisms and the identification of factors that will increase survival and population growth rates. Modeling studies indicate striped bass predation on salmonids has the potential to be high (Nobriga & Feyrer 2007; Loboschefsky et al. 2012); however, limited validation of modeling results has occurred because of a lack of required empirical data. For example, long-term abundance and dietary data for striped bass typically quantify abundance and diet of age classes 0-2 whereas significant predation likely occurs by adult fish. Even so, population data show conflicting results and some studies show adult striped bass (age-3+) declining in abundance since the 1960's (Lindley & Mohr 2003), whereas other studies show a long-term decline in age-0 fish, but a relatively stable adult population of approximately 1,000,000 since 1980 (Sommer et al 2011). The causal factors driving divergent trends in age-0 and adult striped bass abundance are unclear. In part, they may be due to a shift towards shallower habitats by age-0 fish, thereby reducing catches in the mid-water trawl survey (Sommer et al. 2011) which has used permanent sampling stations. Loboschefsky et al. (2012) provide additional evidence that age-0 abundance is likely underestimated and suggest that sub-adult abundance has increased since 1981, ranging from 3 to >12 million individuals. Overall, there is substantial uncertainty regarding abundance trends for juvenile and adult striped bass, and these uncertainties will have to be resolved before these data can be used with confidence to estimate impact of striped bass predation on salmonids.

Although it is evident that striped bass consume juvenile salmonids (Stevens 1963, 1966; Thomas 1967; Tucker et al. 1998), the population-level impacts of that predation are less clear. Previous analyses attempted to estimate the linkage between striped bass abundance and stage-specific survivorship and subsequent population-level effects on salmonid populations (Lindley & Mohr 2003; Hendrix et al. presentation). Both Lindley & Mohr (2003) and Loboschefsky et al. (2012) found that significant proportions of the Delta salmonid population could be consumed by striped bass (approximately 9% of the Central Valley winter-run Chinook salmon for the former assuming a striped bass population of 1,000,000 adults; and 5 to >30 million kg/year for the latter). Although these studies demonstrate the capacity of adult striped bass to essentially consume all salmon juveniles emigrating from the Central Valley (i.e., 30-60 million salmon juveniles at a mean mass of 10-30 g per individual), it is obvious that salmonids have persisted in the presence of striped bass, perhaps because, juvenile salmon are only present in the Delta for relatively restricted time periods. More recently, Hendrix et al. (presentation) evaluated factors related to the survival of Butte Creek spring Chinook salmon and found that spring-run escapement from 1970-2007 was negatively associated with the catch of adult striped bass in two of the top three models. However, Hendrix et al. also determined that the escapement of winter-run Chinook salmon (1967-2008) was only weakly related to striped bass catches (or estimated abundance). The authors suggest that these somewhat contradictory results may be related to the asynchronous emigration of winter-run compared with spring- and fall-run juvenile Chinook salmon. It is possible that synchronous emigration evolved as a “predator swamping” adaptation (Ims 1990; Wrona and Dixon 1999), however, this would not explain the weak relationship between asynchronous winter-run Chinook salmon and striped bass abundance. These contradictory results typify the problems inherent in the existing fish predation data base for the Delta and highlight the need for direct measures of this process.

Table 1. Summary of available information on fish predators that consume juvenile salmonids in Sacramento – San Joaquin Valley waters. Reference numbers are identified below.

Species	**Abundance (trend)**	**Distribution**	**Age/size structure**	**Diet**
Striped bass *Morone saxatilis*	1,7,8,11 (↓ age-0 in pelagic surveys, ↑ or stable for sub-adults, ↓ for adults)	8,9	1,7,8,11	4,5,6,7, 8,9
Largemouth bass *Micropterus salmoides*	2,7,8,11, 12, 13 (↑)	8,9	1,2,3,5	7,8,9, 13
Smallmouth bass *Micropterus dolomieu*	(?)			7
White catfish *Ictalurus catus*	(?)			
Channel catfish *Ictalurus punctatus*	(?)			
Sacramento pikeminnow *Ptychocheilus grandis*	7,8 (?)		7,8	6,7,8
Hatchery-origin salmonids	↑ (?)			10

[1] CDFW Fall Midwater Trawl samples pelagic habitat monthly from September to December at 116 fixed stations throughout the northern region of the estuary. An additional 35 fixed stations sampled from San Francisco Bay through San Pablo and Suisun bays and into the Sacramento–San Joaquin Delta approx. monthly since 1980 using midwater and otter trawls (http://www.delta.dfg.ca.gov/data/mwt/).

[2] Salvage data from the State Water Project and Central Valley Project in the Sacramento-San Joaquin Delta (http://www.delta.dfg.ca.gov/Data/Salvage/).

[3] The CDFW adult striped bass (age 3+) survey during the spring spawning migration (April and May).

[4] Stevens 1963, 1966. Sacramento River. Approximately 600 striped bass diets.

[5] Thomas 1967. Relative comprehensive spatially throughout the year. 4500 striped bass (age 1-3+) diets from 1957-1961.

[6] Tucker et al. 1998. Sacramento River, April 1994-July 1996.

[7] FishBio. 2013. Lower Tuolumne River in 2012.

[8] Nobriga & Feyrer 2007. Decker, Medford, Sherman, Liberty, and Mildred Islands in 2001 & 2003.

[9] Nobriga et al. 2002. Decker, Medford, Sherman, Liberty, and Mildred Islands in 2000 & 2001.

[10] Sholes and Hallock 1979

[11] Cavallo et al. 2013. N. F. Mokelumne River. May 2011

[12] Brown & Michniuk 2007. 1980-83, 2001-2003

[13] Conrad et al., presentation. 2008-2010.

Salmonid Movement and Mortality

Estimates of survivorship on both regional and Delta-wide scales exist, Although it is difficult to calculate system-wide estimates of salmonid survivorship, tagging studies indicate that survivorship of all runs of Sacramento River Chinook salmon (i.e., fall, late-fall, winter, and spring) is variable (Lindley et al. presentation). Previous tagging studies, Perry et al. (2013) found that Chinook salmon have equal survival rates regardless of whether they transited Region1 either through the Sutter/Steamboat/Miner slough route or the main stem Sacramento River. When compared to extant data from the remainder of the Delta, it is clear that transiting the North Delta yields the highest survival rates for salmonids. Extant tagging studies of salmonid movement and mortality from the southern Delta indicate that recent (2008-2011) survivorship of juvenile Chinook salmon (mean size 95-111 mm FL) is low through the southern Delta to Chipps Island (0.02-0.05) and moderate (0.54) for larger steelhead (mean size = 277 mm FL) (Buchanan et al. 2013; Buchanan et al. presentation). These low survival rates occurred across ~90 river kilometers (rkm) though juveniles rarely appear to make a rapid, unidirectional transit through the South Delta. Although not well-integrated into estimates of overall survival from juvenile-to-adulthood, such low survival rates for Chinook salmon are unlikely to maintain populations given observed ocean survival rates (Welch et al. 2008; Scheuerell et al. 2009; Rechisky et al. 2013). Attempts to estimate system-wide survivorship indicate that juvenile Chinook salmon survival to the Golden Gate Bridge ranged from 3-16% for all runs in studies using either VEMCO or JSATS tags (2007-2011 for fall run, 2012 for spring and fall runs, and 2013 for winter run). These rates are quite low; however, they encompass a longer transit distance (~540 rkm) than studies from the southern Delta. Furthermore, estimates of survivorship down the Sacramento River from Battle Creek to Freeport (~365 rkm) are comparable to survivorship from other mainstem systems, such as the upper Columbia River (to the lowest mainstem dam ~460 rkm, 0.56 vs. 0.40-0.60, respectively; Michel 2010; Tuomikoski 2011; Rechisky et al. 2013; Wargo-Rub 2011). Nonetheless, it is difficult to derive conclusions regarding population-level survivorship for salmonids in the Delta because data: 1) are very recent (2010-present) and have not yet been published in peer-reviewed journals, 2) have limited spatial scales, 3) employed differing methodologies, especially tags and tagging procedures, and (4) generally cannot unambiguously tie tag loss or mortality to predation. Because most survivorship data are derived from acoustic tagging studies, it is essential to understand the biases associated with this technique, including: 1) the difficulty of linking mortality events to predation, 2) stresses imposed by tagging (i.e., handling stress and physiological and behavioral changes induced by the tag itself), and 3) the necessary use of larger, typically hatchery-reared fish to accommodate acoustic tags (Wargo-Rub et al. 2011, Buchanan et al. 2013). All of these potential biases may affect survivorship estimates (Wargo-Rub et al. 2011; Buchanan et al. 2013).

In examining the information presented to the Panel (Appendices 1-2), we did not find a source containing a comprehensive analysis detailing the relationships between present survivorship estimates and environmental and water management data. For example, although some data suggest that survivorship is higher under high flow conditions the mechanism producing this relationship is unknown. Is it due to reduced mortality from predators, dilution of toxicants, lower water temperatures or a combination of all three mechanisms? A comprehensive synthesis of survivorship data encompassing ecologically relevant spatial and temporal scales will be important for understanding patterns of salmonid mortality including that due to fish predation.

2B – Appropriate Methods and Extant Data

Biological and physical factors affecting salmonid predation

Interactions among major factors

Predation rates by fish predators and their concomitant effects on salmonid populations may be estimated in a variety of ways. Here we evaluate the primary ways that predation rates are commonly estimated, describe data requirements, and benefits and limitations of each method. However, as with all scientific endeavors, the first step is to precisely define what is meant by "population-level" effects, especially given that this term may mean different things to basic scientists, regulators and managers. This is a critical step, not only for clarity of results, but also because not all definitions will yield information useful for policy making. For example, population-level effects could be expressed as the per capita effect of a predator on the population growth rate of a prey species, or it could be expressed as the total number of juveniles removed from the prey population. However, these definitions may not directly translate into useful information for managers. Instead, managers may need a more specific definition such as what level of reduction in fish predation would create a doubling of the adult population. Given that our task is to evaluate the impact of fish predation on salmonids in the Delta, we have considered a population-level effect to be one that results in a change in salmonid: 1) abundance, 2) survivorship, or 3) production.

Statistical, Mathematical and Theoretical Modeling

The detection of predation effects using statistical or mathematical methods may be as simple as univariate correlation analyses between time series of predator and prey to more complex analyses based on population or individual-based modeling that fits parameters describing the effects of predation mortality on survivorship. These approaches may be based on a variety of population end points including salmonid production, survivorship, escapement, or harvest. Examples of the use of modeling to estimate the effects of fish predators on salmonids in the Delta are provided by Lindley and Mohr (2003) and Hendrix and colleagues (the OBAN model). Neither analysis indicated strong effects of striped bass predation on winter-run Chinook salmon survivorship. However, the results of these studies were inconclusive with respect to determination of population level effects for several reasons discussed below.

As with all statistical analyses, the strength of the results depends on the quality of the data used in the analysis. Unfortunately, abundance data for all potential piscine salmonid predators in the Delta are lacking, and therefore results from any statistical analysis will have questionable accuracy (see Future Research Needs). In addition, estimation of Chinook salmon and steelhead abundances are complicated by the presence of both hatchery and wild fish. Chinook salmon and steelhead escapement is extensively monitored (Adams, et al. 2011) but may not be collected in a way to distinguish the relative contributions of wild runs and hatchery fish. A variety of methods are used to estimate the population size of striped bass, however population estimates for other predators such as largemouth bass, catfish species, and Sacramento pikeminnow apparently are not available. Even when population data have been collected they possess limitations with respect to their use to estimate predation pressure. For example, mark-recapture methods are used to estimate the population of stripers age 3+ and older (Loboshefsky, et al. 2012); however, 0+ juvenile abundance is quantified via mid-water trawling (Kimmerer, et al. 2000) and unfortunately, the long-term patterns of the two time series are not similar (Kimmerer, et al. 2000). Finally, it appears that present modeling efforts are limited to winter-run Chinook salmon rather than extend to other runs of Chinook or steelhead.

Statistical and modeling approaches have inherent limitations in that they approach conclusions regarding causation via correlation (although mechanistic data may be included in models to simulate the predation process) and at best, produce a result that is ***consistent*** with a given mechanistic hypothesis. Unless alternative mechanisms are explored via the same techniques, the conclusions are always subject to the criticism that some other factor correlated with predator abundance is the true causal mechanism (e.g., predation is just a surrogate for physiological stress). Certainly there is no reason modeling cannot be used to test alternative mechanisms and this should be encouraged as should be the use of sensitivity analyses and model validation using independent data sets. In addition, statistical techniques such as information theoretic (Burnham and Anderson 2002; Grossman et al. 2006) and mixed modeling approaches (Hazelton and Grossman 2009) allow one to estimate the weight of evidence (and relative magnitude of effects) in support of multiple hypothesized causal factors, which is the most realistic approach for processes that undoubtedly are affected by many factors. Finally, modeling and statistical approaches generally assume that the per-capita effect of fish predators is constant through time. However we know that important environmental changes that likely affect predation rates have occurred in the Delta over the last 40 years (e.g. water quality, food web shifts, species invasions and displacement of native prey, increases in invasive submerged aquatic vegetation; Brown and Michniuk 2007), so this assumption likely is unwarranted. Furthermore, changes in environmental factors (e.g., oceanic conditions) or management/hatchery practices outside of the Delta also may limit the power of fish predation analyses using historical data, especially if these factors covary.

Anderson et al. (2005) describe a generalized theoretical approach to estimating predation vulnerability of a prey moving through predator-containing habitats. This method applies concepts from kinetic theory, to identify the key processes that dictate predator-prey encounters at varying temporal and spatial scales. The panel understands that at least some of the salmon life cycle models will use this approach in deriving plausible parameter estimates for emigrating juveniles (Lindley, presentation). We note that this model has not been validated for salmon in the Sacramento-San Joaquin Delta ecosystem. In conclusion, modeling and statistical approaches have the potential to contribute important insights, mainly through generation of plausible mechanistic hypotheses, to quantifying the effects of fish predators on population processes in Delta salmonids. Nonetheless, there are significant limitations in historical data sets from the Delta.

Estimates from energetics

Predation mortality may be measured directly by calculating the total mass or number of juveniles consumed by a predator population, and comparing that to the initial biomass or number of juveniles. In the simplest terms, total consumption of juveniles by a predator is a product of three things: predator population size, per-capita consumption rate, and the proportion of diet consisting of juveniles. This approach has been applied widely, often by using bioenergetics models to estimate per-capita consumption from growth and temperature data (Stewart, et al. 1981; Hansson, et al. 1996). However, bioenergetics models may not be appropriate if predation occurs over relatively brief time periods, because accurate quantification of growth under this circumstance requires frequent and intensive sampling. Furthermore, if fish predators have large home ranges then it may be difficult to link dietary habits and growth patterns to a specific location. Nonetheless, gastric evacuation models coupled with frequent sampling of predator stomach fullness may be used to provide estimates of consumption over short time intervals (Hansson, et al. 1996; Olson and Mullen 1986; Benkwitt, et al. 2009).

An ideal study design would quantify the number of salmon juveniles passing through a river segment over a defined time interval, and simultaneously measure the feeding of all main predators. If paired with an independent estimate of juvenile survivorship (e.g. through acoustic or PIT tags), then the fraction of total mortality due to each predator can be determined as long as dietary composition and population size of the various fish predators are known. Unfortunately there are few published studies that have data sufficient to derive reliable estimates of predation intensity using this method. Dietary studies that support bioenergetics work should ideally use unbiased methods, identify salmonid prey to race/run and origin (if possible), and estimate mass or energy content of the prey categories in the gut (Ahlbeck et al. 2012). Delta-wide estimates of consumptive demand by striped bass have been generated

(Loboshefsky, et al. 2012), but those rely on imprecise abundance estimates that may not be representative of Delta populations. Moreover, Loboshefsky, et al. (2012) estimated total annual consumption of striped bass and therefore did not quantify predation intensity on salmonids during emigration. In addition, there are few dietary data for fish predators in the Delta that are of the quality needed estimate fish predation effects via bioenergetic models. Specifically, there appears to be little evidence of frequent and consistent consumption of salmonids in the Delta by fish predators (FISHBIO 2013; Louise Conrad, presentation), but this does not mean that there is no population-level impact on the prey because salmonid availability may be temporally restricted and not well sampled. In addition, if prey populations are small, low levels of predation may still have a population-level impact. Because temperature is a factor that strongly influences bioenergetic processes in fishes, small scale (e.g., km) temperature monitoring throughout the Delta would facilitate future bioenergetics or gastric evacuation-based consumption studies. In conclusion, bioenergetic modeling coupled with accurate fish predator population size estimates are direct and useful methods for quantifying the effects of fish predators on salmonid populations. A final caveat is that unless bioenergetic modeling is coupled with prey population data, then it is possible that high mortality within the Delta could be compensated for by low oceanic mortality and relative stasis in adult population size.

Experimental Approaches

Controlled predator reduction experiments are one of the best methods for evaluating the effects of predation on survivorship of prey. Predator removal experiments with appropriate replication and suitable controls are the strongest method of determining the impacts of predators on prey populations. Nonetheless, like all methods, they are not free of logistical and interpretational limitations. Of necessity, predator removals can only be done over relatively restricted areas, and it is then difficult to “scale-up” results to a river or ecosystem. Maintaining an ecologically significant reduction in predator abundance within treatment sections also is challenging because of recolonization. In the one experiment conducted in the Delta region, predators were removed once and then again roughly one week later (Cavallo et al. 2012); however, recolonization was so extensive that it was unclear how long the actual “removal effect” was maintained. In addition, recolonization in many cases was by adults (i.e. potential predators) rather than by young and potentially inefficient predators (unpublished data). The complexity of conducting realistic predator removals in a system such as the Delta is daunting. Rather than rely on repeated removals, which also subject prey populations to stress, some investigators have relied on physical exclusion after removal (i.e. barriers to reinvasion), but these barriers also may alter environmental characteristics within experimental sites, including alteration of prey assemblages. In certain circumstances, semi-permeable excluders can be placed in smaller systems to exclude predators while letting prey pass through (Pearsons 1994).

If predation is an important regulator of salmonid survivorship, then survivorship in reaches with high predator densities would be expected to be lower than those with low predator densities. Thus, a comparative approach that combines independent estimates of predator abundance (or other variables that govern vulnerability to predators, such as flow, turbidity, structural habitat) and juvenile prey survival can provide insight into predation, although this approach assumes that all other factors are equal. Comparative approaches should attempt to control or account for differences in survival that are unrelated to predation so that spurious results are reduced. For example, low prey survival could occur in an area with low predator densities because of poor water quality and high survival could occur in areas with high predators because of good water quality. Existing tagging studies indicate high variation in survivorship across the Delta (Buchanan, et al. 2013), and this variability could be used to generate hypotheses about underlying mechanisms.

Tag and Release

Acoustic and other tags may be used to estimate survivorship and these data may then be used to generate hypotheses regarding predation mortality. If one assumes that all mortality is due to predation, the existing data collection programs (e.g. the VAMP, Michel 2010) can be used to map areas of high predation intensity and to generate estimates of total predation mortality. However, it is unlikely that this assumption is justified and it is difficult to control for the effects of handling and the physiological stress imposed by the tag. Similar to other methods this approach also typically cannot distinguish ultimate (e.g. physiological stress) vs. proximate (predation) mechanisms influencing survivorship. Most tagging studies have been conducted with hatchery fish which also may yield biased results. Hatchery origin fish may perform differently than natural origin fish because of differences in behavior, physiology or size.

Furthermore, the effects of tags on susceptibility to predation also must be considered (Wargo-Rub et al. 2011, 2012). Tagging also typically cannot yield information on mortality produced by different species of fish predators, although habitat data might aid in inferences of this type. However, tagging may be one of the better methods for identification of spatial variation in survivorship.

Estimating Population-level Effects

The statistical approach used by Lindley and Mohr (2003) and also by Hendrix and colleagues provides the most direct way to assess how salmonid production has historically varied with population abundance. By estimating parameters from historical data, the consequences of future actions that change predator densities can be forecasted. As noted above, this approach works best when the predator-prey system is stationary, i.e., the vulnerability of salmonids to predators has been unchanged over the historical data record. One of the benefits of this technique is that it has the potential to span the entire life-cycle of salmon; hence, it is capable of incorporating compensatory survivorship that occurs after the juvenile stage.

An alternative to statistical approaches is an exploratory stage-based population model that captures the main demographic processes across salmonid life histories. The Panel recognizes that these models may be used to estimate the percentage increase in emigration survivorship that may be reliably detected at the population level, given presumed levels of variability in other stage-specific parameters. Alternatively, the Panel sees opportunities to use these models to define the levels of mortality in post-juvenile stages that are needed to produce a positive population growth rate given current estimates of emigration survivorship (derived from tagging or other studies). If these levels are not biologically realistic, it implies that some component of the delta salmonid population biology is poorly understood and therefore warrants investigation. There is likely ample data available that can be used to parameterize an exploratory model of this type.

Finally, a more comprehensive food web modeling approach could be used to assess the role of predation on populations. It is quite likely that any food web model will quickly find limitations in data inputs needed for parameterization. Regardless, modeling workshops–where the goal is to synthesize existing data and to flag key uncertainties (Walters 1986)–may be used to generate hypotheses about the importance of functional responses, migration times, and how those might be affected by flow regime, turbidity, SAV, predator density and type. This can also be used to identify unexpected indirect effects of predators that might induce population level effects that are opposite from that expected when only considering a single predator and a single prey species. Qualitative models can be used specifically to capture key feedback processes without the need to specific parameter estimates (Dambacher, et al. 2009; Dambacher and Ramos-Jiliberto 2007; Hosack, et al. 2008; Metcalf, et al. 2008)

In summary, we find that for each method some data are available, but in no case are all data available. That said, a combination of approaches might be useful for bracketing plausible ranges of predation mortality rates imposed by fish and other predators. Furthermore, a combination of approaches may allow for addressing weaknesses in any particular method, thereby allowing stronger conclusions.

2C – Regionally Varying factors: Predation Hot Spots

The literature, presentations and published information (Appendices 1-2) a make it clear that a number of key locations within the Delta are predation "hot spots" where substantial mortality, presumably predation, consistently occurs (Gingras 1997; Michel 2010; Buchanan et al. 2013, presentation; FISHBIO 2013; San Joaquin River Group 2013). A list of these hotspots is presented in Table 2 and it is clear that they are most often located near artificial structures. By region the hotspots are as follows:

Region 1 - If the Sacramento River DCC gates are opened during the salmonid migration period there is a possibility of juvenile salmonids being diverted into the Central Delta (Region 4) and experiencing high mortality. In general, the DCC is managed so that gates are closed when salmon are in the region. However, closing the DCC gates reduces the input of higher quality Sacramento River source water into the Mokelumne (Region 3) and Central Delta (Region 4). Historically, however, there have been cases where water quality issues in the Central Delta (Region 4) have resulted in DCC gate openings even when salmonids are in the area. In these cases, the DCC gates were opened for short periods, but nonetheless, salmonids could be transported into inhospitable areas with increased fish predator abundance (i.e., Georgiana Slough or Region 4).

Region 2 – There was no evidence of significant fish predation hotspots in this Region.

Region 3 - It is unclear whether Georgiana Slough is considered a hot spot because it is a transport channel to regions with low salmonid survivorship or if the channel itself is an area of high predation. The channel is narrow (50-150 m) with rip-rapped levees on either side and no side channels. Nonetheless, this location has been identified as a mortality “hot spot” (BDCP CM15 2013).

Region 4 - Franks Tract has been identified as a predation hot spot in BDCP Conservation Measure 15. However, neither the Panel literature nor the presentations addressed predation in this location. In addition, the modeling presentations did not include Franks Tract in their simulations. Given that the levee between Franks Tract and Old River has eroded significantly, it is unlikely that modeling simulations are representing water exchange in this region properly and may minimize the importance of Franks Tract. Studies of phytoplankton dynamics in Franks Tract demonstrated that tidal exchange between this shallow water habitat and the adjacent channels is an important mechanism controlling phytoplankton concentrations in this region (Lopez et al. 2006, Lucas et al. 2002). This shallow water habitat also influences turbidity, a key environmental factor for predation.

The Stockton Ship Channel has been identified as a predation hot spot based on mortality rates of tagged salmonids (Vogel 2011), although there was no direct evidence that the fish were killed by predation or whether salmonids were stressed by low dissolved oxygen levels (or a combination of both mechanisms), sometimes present in that habitat.

Region 5 – The readings and presentations indicate there are multiple predation hot spots in Region 5. Clifton Court Forebay (CCFB) has been identified by multiple sources as an inhospitable location for salmonids. Within CCFB several areas are particularly hazardous including: 1) the deep scour hole just inside CCFB by the radial gates; 2) the trash gates in front

Table 2 Identified hotspots for fish predation on salmonids in the Delta.

Hot Spots	Region	References
Painterville Bridge (Junction of Sacramento and Sutter Slough)	Region 1	BDCP CM15
Georgiana Slough	Region 1 Region 3	BDCP CM15
Delta Cross Channel	Region 1 Region3	Perry et al. 2010
Franks Tract	Region 4	BDCP CM15
Mildred Island	Region 4	Nobriga and Feyrer 2007
Stockton Ship Channel	Region 4	Vogel 2011
Clifton Court Forebay 1) deep scour hole by radial gates 2) trash gates@ Tracy Fish Collection Facility 3) Old River adjacent to the radial gates	Region 5	BDCP CM15, California F&G 2011 Vogel 2010 Vogel 2010 Gingras 1997
Borden Highway Bridge (Old River and Hwy 4)	Region 5	Vogel 2011
Seasonal South Delta Physical Barrier 1) Head of Old River Barrier 2) Old River near Tracy	Region 5	Bowen et al. 2009 BDCP CM15 Vogel 2010
Scour hole directly downstream of the head of Old River	Region 5	Vogel 2010
salvage release sites	Region 6	BDCP CM15
Red Bluff Diversion	North of Delta Sacramento	Tucker et al. 1998

of the Tracy Fish Collection Facility; and 3) section of Old River adjacent to the radial gates. The bridge passing over Old River directly downstream of the CCFB complex also is known to have significant predator abundances. The seasonal temporary barriers (Middle River, Old River and Grant Line Canal) also are hot spots, with predators patrolling culverts or notches that allow water circulation. Fish predators are known to frequent the deep hole directly downstream of the HORB. When the HORB is inactive and the water tidal in the region, prey could potentially be tidally washed in and out of the deep hole below the HORB.

Region 6 - Current information, though not extensive, suggests that fish predation is not significant in this region except at release locations of fish transported by truck from the State Water Facilities.

In conclusion, available data and analyses have generated valuable information regarding aspects of the predation process in the Delta but do not provide unambiguous and comprehensive estimates of fish predation rates on juvenile salmon or steelhead nor on population-level effects for these species in the Delta. Recent survival studies are based on acoustic tagging of larger hatchery-raised fish from ~95 to >250 mm FL. Although it is assumed that much of the short-term (<30 d) mortality experienced by these fish is likely due to predation, there are few data establishing this relationship. Juvenile salmon are clearly consumed by fish predators and several studies indicate that the population of predators is large enough to effectively consume all juvenile salmon production. However, given extensive flow modification, altered habitat conditions, native and non-native fish and avian predators, temperature and dissolved oxygen limitations, and overall reduction in historical salmon population size, it is not clear what proportion of juvenile mortality can be directly attributed to fish predation. Fish predation may serve as the proximate mechanism of mortality in a large proportion of the population but the ultimate causes of mortality and declines in productivity are less clear. For example, stress caused by harsh environmental conditions or toxicants will render fish more susceptible to all sources of mortality including predation, disease or physiological stress. This point was stressed in a recent report by the National Academy of Sciences on the Delta environment “Nobody disagrees that engineering changes; the introduction of many exotic species, the addition of contaminants to the system, and the general effects of an increasing human population have contributed to the fishes' declines. There are, however, disagreements about the relative contributions of those factors and the appropriate remedies for them."

Section 3 Research Needs and Study Design

In this section we give general advice regarding study design and identify both high and lower priority research needs, based on the readings and presentations. The appropriate study design depends entirely on the questions and/or hypotheses being addressed, and hence a clear articulation of hypotheses is necessary for meaningful research (Fowler & Hobbs 2009). In its review of past research the Panel noted a lack of consistent methodologies used even among similar studies, making comparisons and syntheses difficult. Some studies failed to state clear objectives/hypotheses or place the study within an overarching research framework. In addition, multiple studies failed to provide adequate detail on environmental conditions (flow levels, temperatures, etc.) rendering both the interpretation and representativeness of results open to question. Frequently, important methodological issues were not thoroughly described and resulting data presented without quantification of variance or other measures of statistical uncertainty. These issues made it difficult for the Panel to evaluate the reliability and generality of conclusions from past work.

It is obvious that research in the Delta is conducted by a complex of federal, state, local and non-governmental organizations who either use their own personnel (with various levels of training) or subcontract work to private firms or academic institutions. As might be expected, this produces a situation where different investigators use different methodologies, sometimes for even the same research question. The lack of common research methodologies and coordination of research projects certainly has inhibited the abilities of researchers and managers to build on previous studies and maximize the productivity of sequential/long-term research projects, which are necessary for scientific management of the Delta. We recommend development of a set of standard methodologies, developed and agreed upon by researchers, for ecological studies in the Delta and not restricted to those linked to predation. The National Ecological Observatory Network has recently gone through this process and established, via expert opinion, sampling methodologies for fish population sampling in streams and lakes on Observatory sites. Standardized approaches are also being applied and advanced among multiple organizations in the Columbia River Basin. Agreement upon standardized methods will improve research coordination and reduce the need for duplication of studies, and such efforts are already underway (Johnson et al. 2007). Mainly, however, it will ensure that the research studies build on each other to advance our knowledge and ability to manage the Delta in the most efficient manner possible. Investigators should be free to design studies using the best available methods; however, to maximize the utility of new data future research should adhere to several general principles. It is possible that the development of standardized methods could be undertaken through funded workshops of experts and their use incentivized via "use agreements" in future funding. A set of proposed methodological guidelines follows:

1) Studies need clearly articulated questions and objectives that relate to data gaps in conceptual models of the system (Brown and Guy 2007). Hypotheses should be falsifiable and specific to time and space and representativeness of both mean and variances in environmental conditions (i.e. conducted during high flow years, low flow years etc.)
2) Regardless of the scale and duration of the study, research should be conducted to meet standards of scientific peer review.
3) Sampling methods need to be operationally defined, appropriate, and standardized (Johnson et al. 2007; Bonar et al. 2009; Zale et al. 2012).
4) Empirical studies should adhere to fundamental principles of sampling/experimental design including randomization, quantitative assessment of sample size adequacy and power analysis (Hansen et al. 2007).
5) Modeling studies should state and justify assumptions, have clearly stated objectives that motivate model development, consider alternative conceptualizations of model states and conditions, include error/sensitivity analysis, and whenever possible, employ independent data for validation (Hilborn and Walters 1992; Anderson 2008).
6) Sampling, experimentation and modeling are most synergistic when performed in a coordinated fashion: models and experiments should produce testable predictions that can be addressed with future empirical studies. Modelers and empiricists should work together to further refine the precision and accuracy of models, especially those used for management.

It also is clear that both current research and management are limited by the lack of a centralized "data repository" with perhaps a relational data base and an integrated, publically accessible, GIS for the San Francisco Bay Delta ecosystem. The lack of a data repository, similar to that used by the National Science Foundation Long-Term Ecological Research Program, makes it difficult for researchers and the public to know which data have been collected, where data are located and how data can be accessed, even when they exist. This should be a future priority from both a policy and research management standpoint.

An additional focus of future funding should be the development of a system-wide GIS with funds provided for both extant and future data to be entered in such a system. Although far from an exhaustive list, the GIS should include layers for water temperature, air temperature, cloud cover, turbidity, salinity, conductivity, and other water quality measures, temporal and spatial distributional and abundance data for flora and fauna, distribution of engineered structures influencing flow, flow direction, magnitude and velocity, water depth, operating conditions at all monitored water projects, and other relevant data should be included. At least some of these data currently are being collected via the California Department of Water Resources (e.g. CDEC) and the U.S. Geological Survey (flow and sediment data), although many lie in the hands of individual investigators. All data that are provided on web databases should go through quality control to be reliably used in future investigations. In addition, funding for the existing network of environmental monitoring sites (e.g. stage, flow, sediment, temperature, salinity, and meteorological data) throughout the Delta should be continued into the future. This basic information is essential for all research in the Delta. Additional environmental monitoring sites in Clifton Court Forebay and Franks Tract should be established. Finally, it is our understanding that much of the flow modeling is proprietary and not readily available to many investigators. Efforts should be made to develop non-proprietary models or to establish cost-effective agreements with proprietary data holders to make models widely available.

Primary future research

We have divided future research into two types: primary and secondary. Primary research is essential to evaluating predation risk and secondary research provides important complementary information that helps to evaluate predation risk:

1) It will be essential to obtain spatially and temporally explicit, Delta-wide estimates of predation risk for juvenile salmonids. Of particular value would be studies that quantify the percent of the prey population (by species and origin) consumed by predators. This might be done in areas that are hypothesized “hotspots” as well as in “normal locations”. Estimation of predation risk and exploitation rates by predators will require accurate estimates of both predator and prey abundance.

2) Given that higher predation rates appear to be a function of specific locations with atypical characteristics such as Clifton Court Forebay, Red Bluff Diversion Dam and some domestic water intakes, it seems likely that predation estimates from these structures are not representative of the Delta as a whole. Perhaps juvenile salmonids only are susceptible to predation in unusual conditions and efforts should then be focused on making conditions in these localities more conducive to juvenile salmonid survival. To this end, it also is clear that Clifton Court Forebay is a predation hotspot and that both predators and salmonids may move in and out of this habitat. However, little is known about the hydrology around the radial gates that may attract or repel fishes. A better understanding of the hydrological processes and their effects on fish behavior around this and other predation hotspots could yield insights into flow/structure-based management changes that could reduce levels of salmonid predation mortality.

3) There is a need for fishery-independent, Delta-wide estimates of population size for fish predators of salmonids including estimates of precision and bias. These estimates should encompass both the spatial and temporal variation present in environmental characteristics of the Delta. Potential species include striped bass, largemouth bass, Sacramento pikeminnow, large sunfish and catfish. These estimates should be size-

specific because YOY/1+ fish predators are unlikely to consume juvenile salmonids yet they form the basis of much of the historic population data base. It is important that these estimates be derived in ways that are based on well-established methods so that the uncertainties in the estimates can be reliably determined. Furthermore, it is important that abundance is estimated during times when predation is thought to be highest (e.g., times of spatial overlap with prey) so that the abundance information is relevant to the question of predation. In addition, there is little information on population sizes of salmonids as they remain or transit the Delta.

4) Additional BACI-design predator removal experiments are needed, conducted in various Delta regions. Although logistically difficult, these studies like are the most direct way to answer questions regarding the effects of fish predation on juvenile salmonids. Nonetheless, the data from the one predator removal experiment that has been conducted indicated that recolonization was rapid and mean sizes of colonists did not differ for abundant species from that of the original inhabitants. Consequently, predator removal may merely end up in compensatory recolonization or increases in predation by other predators such as sea birds. Thus, these experiments need to be conducted at relatively large time- and space scales and with adequate replication to provide results that are meaningful. Active adaptive management can be applied to create these large-scale manipulations.

5) A better understanding is needed of the mechanics of the predation process for fish predators. Studies should be conducted on functional responses, handling times, meals/day, metabolic requirements, etc. to obtain potential predation pressure estimates per predator species which, when combined with spatially explicit population estimates and bioenergetic and population modeling would lead to estimates of the percentage of the salmonid populations consumed by each predator species. These studies need to include relevant environmental factors such as turbidity and temperature variation, for example. Concomitantly, these studies should be conducted with both natural and hatchery origin juvenile salmonids because natural origin fish may migrate at a smaller size and behave differently than hatchery origin fish. If a large proportion of juveniles

come from natural sources and smaller fish are subjected to higher predation rates than larger fish, then tagging studies with fish over 100mm FL may actually underestimate predation rates. Due to the specimen-size restrictions of tagging studies, it may be necessary to use modeling to address this question, with assumptions regarding higher mortality rates compared to known survivorship of different year classes. This latter question basically reduces to: do predation rates by piscivores on natural vs. hatchery origin fish differ? Isotopic analysis of muscle tissue and otoliths ($^{87}Sr/^{86}Sr$) may offer potential ways to identify the origin of fish too small to be tagged or larger fish that may have lost a tag, and can be performed on juvenile salmonids sampled from stomachs of predators, provided they are not too digested.

6) Both growth-based and meal-turnover bioenergetic models should be developed and validated for the dominant predator species. We are not aware of a bioenergetics model developed specifically for channel or white catfish, but well-accepted models exist for striped bass, largemouth bass and northern pikeminnow. Laboratory work to develop catfish bioenergetics models and to test the accuracy of sensitive parameters in the bass models would make this modeling approach more generally accepted and useful. It appears that recent bioenergetics modeling provided a wide scale but relatively low resolution analysis of striped bass consumptive demand in the Bay-Delta system. As more detailed information on predator abundance, distribution and diets become available, system-wide estimates of consumption of juveniles with bioenergetics models should be refined.

7) Estimates are needed for the cumulative effects of physical and chemical stressors during migration through the lower rivers and Delta, especially because these effects may be the true causal mechanism for mortality via predators. One option for future research is to quantify the effect of selected stressors on juvenile salmon (e.g., Thorstad et al. 2013). Such an experimental approach could provide a clearer indication of the role environmental conditions play in the ability of juvenile salmon to evade predators during emigration.

8) The relationships between submerged aquatic vegetation, predator distributions, flow patterns and predation intensity needs to be established via experimental and descriptive studies. In particular, there apparently have been few studies that either sampled or focused on Franks Tract which is the largest shallow water habitat in the central Delta. Franks Tract historically has held large populations of adult striped bass and also has significant amounts of *Egeria* which affects both water clarity and flow patterns.

9) Managers would greatly benefit from development of a spatially explicit decision model that examines where restoration/anti-predator efforts can have the biggest impact on increasing juvenile production.

Secondary research

1) A better understanding is needed of the relationship between tag/fish loss and predation. Specifically, what percentage of tag/juvenile loss is due to predation and what percentage to other forms of mortality. Dr. Buchanan (presentation) had some excellent data on this.

2) Based on historical data, survivorship of juvenile salmonids decreased in the late 1990s and early 2000s, especially from the San Joaquin River. Biological, physical, and chemical data should be examined to determine what might have caused this decline and whether it could yield productive hypotheses regarding the mechanisms behind the current situation.

3) The effects of flow, especially when water is diverted along an artificial pathway (i.e., Sacramento River water to the Central Delta via the DCC) on olfactory cues that salmonids use for both upstream and downstream migrations should be evaluated.

4) A tremendous amount of money and effort has gone into telemetry studies but many of these were relatively small-scale in space and time. A meta-analysis of existing telemetry results could provide more general conclusions from the telemetry datasets.

Table 3 A summary of future research topics along with their advantages and shortcomings and methodological examples for these topics.

Research topic	Advantages	Shortcomings	Methodological examples
Primary			
1 & 3) Spatially explicit and comprehensive estimates of predation risk for juvenile salmonids.	Would generate empirical estimates of predator and prey population abundance, predation rates, and precision and bias.	Certain fish predators migrate. Stratified, randomized sampling designs can be labor-intensive & expensive. Limitations of fishery-dependent data. Need for fishery-independent data.	Beauchamp et al. 1999 Fritts and Pearsons 2004
2) Mortality hotspots and effects on prey behavior and predation rates.	Acquisition of site-specific, relevant information. Potentially identify linkages between hydrology, behavior and predation. Focuses on the areas that are likely responsible for a greater proportion of predation and may require greater sampling effort.	Logistically challenging. Experimental prey may be limited to hatchery fish.	McCormick et al 1998 Major et al 2005
3) Experimental predator removal – Before After Control Impact Design (BACI) and use of “control” reaches.	Experimental approach allows for more direct evaluation of mechanisms. Ability to compare with prior conditions (Before-After) as well as un-manipulated areas. Potential to have actual impact on survival rate in field at certain “hotspots”.	Logistically feasible only at smaller spatial scales and in certain locations. Challenges to scale up. May need multiple removals in same locations.	Bestgen et al. 2007
4) Bioenergetic approaches, lab approaches, estimation of functional responses.	Empirical estimates of potential consumption rates. Could assist in design of field studies, i.e., required sample sizes, generate specific expectations/hypotheses to guide field studies. Could explicitly incorporate variance in model parameters.	Requires experimentation under realistic variation in temperature, turbidity, prey density, alterative prey density, prey body size.	Model development: Keskinen et al. 2008
5 & 6) Bioenergetic approaches, field approaches, population-level estimates.	Can provide population-level estimates of consumption. Potentially more representative than laboratory studies. Can be coupled with lab studies.	Diel sampling required in multiple locations. Difficult to accurately incorporate full range of environmental variation. Difficult to translate to functional response.	Trudel & Rasmussen 2000 Ney 1990 Johnson et al. 2008
6) Differentiation between hatchery and natural production – individual vs. sample population level.	Would address whether origin influences predation. Easier to address at population-level with initiation of constant fractional marking approach.	Time consuming and costly but more informative. More limited inference if based on marking rates due to lack of individual information.	Barnett-Johnson et al. 2007 Zhang & Beamish 2000 Weber et al., 2002 Woodson et al. 2013 Lepak et al. 2012b

7) Assessment of cumulative effects.	More comprehensive, ecosystem-based approach.	Need to identify a subset of testable parameters amongst a long list, i.e., temperature, dissolved oxygen, pesticides, etc.	Thorstad et al. 2007
8) Habitat-specific estimates of predation rates.	Allow for more accurate estimates of system-wide predation rates.	Requires logistically challenging, stratified, randomized sampling design.	Cartwright et al 1998 Harvey & Nakamoto 2013 Lawrence et al 2012
9) Spatially-explicit decision models.	Help identify knowledge/data gaps and develop clear, testable hypothesis relevant to management needs.	Requires “buy-in” by multiple stakeholders.	Shelton presentation
Secondary			
1) Tag effects, detection of tag loss, and identification of predation events associated with acoustic tags.	Improve accuracy of mortality estimates.		Wargo-Rub et al. 2012.
2) Meta-analysis of existing survival studies.	Synthesize results from disparate studies. Aid development of system-wide understanding and identify factors related to survival.	Different tag types, species, and experimental design inhibit robust comparisons.	Zelasko et al. 2010
3) Examine alternative hypothesis for high rates of juvenile mortality.	Employ method of multiple working hypotheses and enables an information-theoretic approach.		Chamberlin 1890 Elliot & Brook 2007 Anderson 2008
4) Influences of flow on juvenile & adult migratory behavior.	Necessary information for evaluating impacts of predation, in particular identification and evaluation of management options to decrease predation rates.	Logistically challenging, spatially limited.	McCormick et al 1998 Quinn et al 1997

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APPENDIX ONE

CHARGED READINGS FOR PREDATION WORKSHOP PANEL

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APPENDIX TWO

RESEARCH PRESENTATIONS AT THE PREDATION WORKSHOP

9:15	Introductory Remarks	Carl Wilcox, California Department of Fish and Wildlife; Peter Goodwin, Delta Science Program Lead Scientist; and Maria Rea, National Marine Fisheries Service
9:30	Panel Introduction	Panel
10:00	Bay Delta System Orientation (25 minutes each)	1. Hydrodynamics – John DeGeorge, RMA 2. Operations – Ron Milligan, USBR 3. Ecological Context – Larry Brown, USGS 4. State of Salmonids in the Delta – Carl Wilcox, CDFW
1:00	Salmonid Survival and Fish Predation Studies (25 minutes each)	**Fish Predation Studies** 1. CCF, Head of Old River, & Georgiana Slough - Jacob McQuirk, DWR Bay Delta Office 2. Largemouth Bass - Louise Conrad, DWR Division of Environmental Services 3. Striped Bass Migration - Cynthia LeDoux-Bloom **Salmonid Survival Studies** 1. Juvenile Salmon Survival – Steve Lindley, Sean Hayes, Cyril Michel, NMFS 2. San Joaquin Studies - Rebecca Buchanan, Univ. of Washington
3:45	Models (15 minutes each)	1. OBAN - Noble Hendrix, QEDA Consulting, LLC 2. NMFS Life Cycle Model - Steve Lindley, NMFS 3. Delta Passage Model - Brad Cavallo, Cramer Fish Sciences 4. SALSIM – John Shelton, CDFW, Region 4 5. Bioenergetics – Erik Loboschefsky, DWR, Suisun Marsh

		Planning Questions from panel to follow all the presentations.
5:15	Questions, Comments	Public (from Blue Cards)
5:50	Concluding Remarks, Next steps	Gregg Erickson, CDFW, IEP Manager

APPENDIX 3 – Summary of current hatchery releases in the Central Valley identified in the review by the California Hatchery Scientific Review Group (2012). Since the 2006 brood year, tagging programs for most Chinook salmon hatcheries in California consist of "constant fractional marking" programs in which a fixed proportion (25%) of all hatchery fish are externally marked by an adipose fin clip and internally tagged with a CWT. Chinook salmon (Fall, Spring) and steelhead (SH). The abbreviation fpp stands for "fish per pound"

Source	**Initial Year**	**Runs**	**Production**
Nimbus Fish Hatchery	1955	Fall Chinook, steelhead (SH)	**Fall:** Four million juveniles (≥60 fpp). Mark rate of 25% with an adipose fin-clip and coded wire tag (CWT) and released in San Pablo Bay between mid-May and mid-June. **SH:** 430,000 yearlings (4 fpp). Mark rate of 100% with an adipose fin clip. Fish are released from January to February above the confluence of the American and Sacramento rivers to reduce predation on natural-origin Chinook fry.
Mokelumne River Hatchery	1961	Fall Chinook, SH	**Fall:** Five million juveniles (≥60 fpp). Approximately two million additional juveniles raised to post-juveniles size (45 fpp) for ocean enhancement program. All enhancement production is released into San Pablo Bay or reared in coastal net pens. Remaining juveniles are released ~10 mi downstream of the hatchery between March and June. Mark rate of 25% with an adipose fin-clip and CWT. **SH:** 250,000 yearling steelhead (4 fpp). Experimental releases (< 2,000 fish) of two-year-olds using a "natures" rearing strategy. All production released from February to March with an adipose fin clip downstream from the confluence of the Mokelumne and Consumes rivers.
Merced River Hatchery	1970	Fall Chinook	Most releases are for experimental purposes. 960,000 juveniles and 330,000 yearlings. The yearling program was discontinued due to high mortality from proliferative kidney disease. One million juveniles (60 fpp) are adipose fin-clipped, CWT, and released between late April and mid-May. Remaining fish are marked at a 25% with an adipose fin-clip and CWT. Releases occur at the hatchery, at lower Merced River locations, and at various locations in the San Joaquin River and further downstream.
Feather River	1960s	Fall & spring	**Fall:** Production goal of six million fall-run juveniles (≥60 fpp). Up to two million additional fish may be for ocean

Hatchery		Chinook, SH	enhancement program (≥30 fpp). Majority of juveniles are released into the Carquinez Straits between April and June. Mark rate of 25% with an adipose fin-clip and coded wire tag (CWT). **Spring:** Mitigation and conservation production. Two million juveniles (60 fpp) released during April or May with a mark rate of 100% with an adipose fin-clip and coded wire tag (CWT), released into the Feather River south of Yuba City. **SH:** 450,000 yearling steelhead (3 fpp) released during late January or February. Mark rate of 100% with an adipose fin-clip and released into the Feather River south of Yuba City or at the confluence of the Feather and Sacramento rivers.
Coleman National Fish Hatchery	1943	Fall & late-fall Chinook and steelhead	**Fall:** Twelve million fall Chinook in April (90 fpp). Mark rate of 25% with an adipose fin-clip and coded wire tag (CWT), and released at the hatchery. Ninety percent are released at or near the hatchery in Battle Creek; 10% released into San Pablo Bay. **Late-fall:** One million late-fall Chinook released in December (13 fpp). Mark rate of 100% with an adipose fin-clip and coded wire tag (CWT), and released at the hatchery or near the hatchery in Battle Creek. **SH:** 600,000 steelhead in January (4 fpp). Mark rate of 100% with an adipose fin-clip released into the Sacramento River ~15 mi downstream of the Battle Creek confluence to reduce predation on emerging Chinook in the upper Sacramento River and Battle Creek.
Livingston Stone National Fish Hatchery	1997	Winter-run Chinook for population recovery.	**Winter-run:** Up to 250,000 winter-run Chinook salmon (≥60 fpp) released in late January or early February. Mark rate of 100% with an adipose fin-clip and coded wire tag (CWT), and released into the Sacramento River at Caldwell Park (RM 299), ~10 mi downstream of the hatchery.