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RESEARCH

Science Advancements Key to Increasing Management Value of Life Stage Monitoring Networks for Endangered Sacramento River Winter-Run Chinook Salmon in California

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ABSTRACT

A robust monitoring network that provides quantitative information about the status of imperiled species at key life stages and geographic locations over time is fundamental for sustainable management of fisheries resources. For anadromous species, management actions in one geographic domain can substantially affect abundance of subsequent life stages that span broad geographic regions. Quantitative metrics (e.g., abundance, movement, survival, life history diversity, and condition) at multiple life stages are needed to inform how management actions (e.g., hatcheries, harvest, hydrology, and habitat restoration) influence salmon population dynamics. The existing monitoring network for endangered Sacramento River winter-run Chinook Salmon (SRWRC, *Oncorhynchus tshawytscha*) in California's Central Valley was compared to conceptual models developed for each life stage and geographic region of the life cycle to identify relevant SRWRC metrics. We concluded that the current monitoring network was insufficient to diagnose when (life stage) and where (geographic domain) chronic or episodic reductions in SRWRC cohorts occur, precluding within- and among-year comparisons. The strongest quantitative data exist in the Upper Sacramento River, where abundance estimates are generated for adult spawners and emigrating juveniles. However, once SRWRC leave the upper river, our knowledge of their identity, abundance, and condition diminishes, despite the juvenile monitoring enterprise. We identified six system-wide recommended actions to strengthen the value of data generated from the existing monitoring network to assess resource management actions: (1) incorporate genetic run identification; (2) develop juvenile abundance estimates; (3) collect data for life history diversity metrics at multiple life stages; (4) expand and enhance real-time fish survival and movement monitoring; (5) collect fish condition data; and (6) provide timely public access to monitoring data in open data formats. To illustrate how updated technologies can enhance the existing monitoring to provide quantitative data on SRWRC, we provide examples of how each recommendation can address specific management issues.

KEY WORDS

Chinook Salmon, monitoring, conceptual models, life stage survival, migration, diversity

INTRODUCTION

California's Central Valley (the Central Valley) experiences extreme variation in precipitation compared to other regions in the United States (Dettinger et al. 2011). Floods and droughts occurred historically, and a diversity of native cold-water fishes evolved with this variation in hydroclimatic regimes (Moyle 2002). Indeed, the Central Valley supports the co-existence of four runs of Chinook Salmon (*Oncorhynchus tshawytscha*) that are adapted to exploit different ecological and physiological niches. Each has unique life history traits, such as the season they return to spawn, the duration of juvenile freshwater residence, and the timing and size of juvenile emigration (Yoshiyama et al. 1998). This life history diversity results in adult salmon and juveniles occupying the Central Valley year-round. Current and pre-historic climate variation also presents physiological constraints, which contribute to the existing patterns of habitat use (Cloern et al. 2011).

A series of landscape-scale changes have been overlain onto the historical habitat condition for Central Valley salmonids. The Sacramento–San Joaquin watershed and Delta are highly engineered with dams, reservoirs, levees, and water diversions to manage flooding risk and water supply reliability, given the extreme seasonal and annual climate variation. For example, numerous water storage facilities capture surface runoff. This reduces downstream flooding risk in wet years, and provides reliable water supply for 25 million people and irrigation for millions of hectares of farmland even in years with below-average precipitation. The timing and magnitude of flows released from the storage facilities is heavily regulated to meet multiple state-wide objectives, including water storage and supply, flood control, recreation, and fish and wildlife conservation.

There is growing concern that large-scale alterations to the landscape, such as dams, that block the majority (>70%) of historical spawning habitat for salmonids, stream channelization, reductions in habitat and habitat complexity, and the loss of >98% of tidal wetlands threaten the existence of salmon and will compromise their ability to respond and adapt to future climate change (Lindley et al. 2007; SFEI 2014; NMFS 2014). California recently experienced a 5-year drought (2012 to 2016) with its highest air and water temperatures on record, and anomalous warm ocean conditions. Examining how salmonid populations respond to climate variability will provide insights into the vulnerability of these species to new climate regimes across watershed–estuary–ocean ecosystems (Griffin and Anchukaitis 2014; Williams et al. 2015; Johnson and Lindley 2016).

Accurately monitoring the abundance of a species over time (e.g., status and trend) is fundamental to managing it. A measure of adult spawning abundance (stock) and survival of young to some specified point in time (recruits) are two key population parameters central in fisheries science (Beverton and Holt 1957; Ricker 1954). For salmonids listed as threatened or endangered under the Endangered Species Act (ESA), recommended status and trend monitoring also includes estimating other viability metrics, including diversity, spatial structure, and hatchery influence (et al. 2000; Lindley et al. 2007; Crawford and Rumsey 2011).

For Central Valley salmonids, a monitoring network is needed that allows fish population information to be obtained at key management-relevant locations, and that also allows freshwater effects to be disentangled from marine ecosystem effects on population dynamics. Sacramento River winter-run Chinook Salmon (SRWRC; *Oncorhynchus tshawytscha*) are currently displaced from their historical spawning habitat and relegated to a single population that depends on variable cold-water reserves from Shasta Reservoir for the survival of early life-stages. Unlike other Central Valley salmon runs, adult SRWRC spawn in the summer, when the average monthly mean air temperature is 37 °C, (98 °F; U.S. Climate Data 1981–2010). SRWRC are also spawned in the Livingston Stone National Fish Hatchery (LSNFH), which is a conservation hatchery that rears juveniles for release in February (CHSRG 2012). Most natural-origin SRWRC juveniles (i.e., predominantly fry < 46 mm) migrate downstream past Red Bluff Diversion Dam (RBDD) in the summer/fall, before the release of hatchery juveniles (LSNFH) to the upper Sacramento River in February (Poytress et al. 2014). Winter-run sized juveniles migrate past Knights Landing with increases in streamflow (>400 $m^3 s^{-1}$) or turbidity generally coincident with the first fall or winter storm events, and are thought to rear in the Delta for approximately 1 to 4 months before they enter the ocean (Martin et al. 2001; del Rosario et al. 2013; Poytress et al. 2014). The ocean is a critical environment for SRWRC, and that is where most of their growth occurs (MacFarlane 2010; Woodson et al. 2013; Wells et al. 2016). Finally, adults return in the winter to the upper Sacramento River and spawn predominantly as 3-year-olds in the following summer.

To assess the efficacy of the existing Central Valley monitoring network to monitor SRWRC status and trends at relevant scales, we employed three steps. First, we reviewed and modified existing conceptual models (CMs) to characterize specific environmental and management factors that drive SRWRC responses within discrete geographic domains and life stages (see CMs in Windell et al. 2017). Second, we compared the existing monitoring network to fish demographic responses in the CMs to identify deficiencies, which we interpreted as gaps in the existing network. The gaps prevent annual, quantitative population-level metrics from being developed that are needed to support water management, assess population viability, and prioritize population-recovery actions among geographic domains across the freshwater landscape. Third, we used the gaps to develop recommendations on ways to improve the scientific and management value of the current monitoring network.

CONCEPTUAL MODEL FRAMEWORK

Conceptual models are increasingly used in conservation biology as tools to understand and predict ecosystem function and species responses, as well as by decision-makers to manage critical resources (Heemskerk et al. 2003; IEP MAST 2015; Hendrix et al. 2014). Although the SRWRC life cycle is generally understood, CMs were recently developed that specify probable factors and management actions that affect the transition probabilities of a given cohort among life stages and between geographic regions (Windell et al. 2017). To assess the current monitoring network, Windell et al. (2017) used CMs for each major geographic region and life stage to characterize specific habitat attributes, environmental factors, and management actions that potentially drive fish responses within these discrete domains. The life stages and geographic domains are the same as those used in the National Marine Fisheries Service (NMFS) winter-run Chinook Salmon life cycle model, except that the Sacramento River was further delineated to separately identify the area above RBDD (Hendrix et al. 2014). The following geographic regions are delineated: upper Sacramento River (e.g., Keswick Dam to RBDD); middle Sacramento River (e.g., RBDD to the upper portion of the legal Delta in Sacramento); Bay–Delta (e.g., lower Sacramento River within the legal Delta, Yolo Bypass, San Francisco Estuary, North Bay, Central Bay, and South Bay); and the ocean (Figure 1). Life-stage transitions include: (1) egg to emerging fry; (2) rearing juvenile to migrating juvenile; (3) ocean juvenile to ocean adult; (4) migrating adults to holding adults; and 5) holding adults to spawning adults (Figure 2).

When we overlaid the CMs and structure onto existing monitoring programs, key unmeasured fish responses were revealed. Thus, the approach and framework we used highlighted opportunities to improve system-wide monitoring of key fish responses to assess specific habitat attributes, environmental drivers, and landscape attributes that

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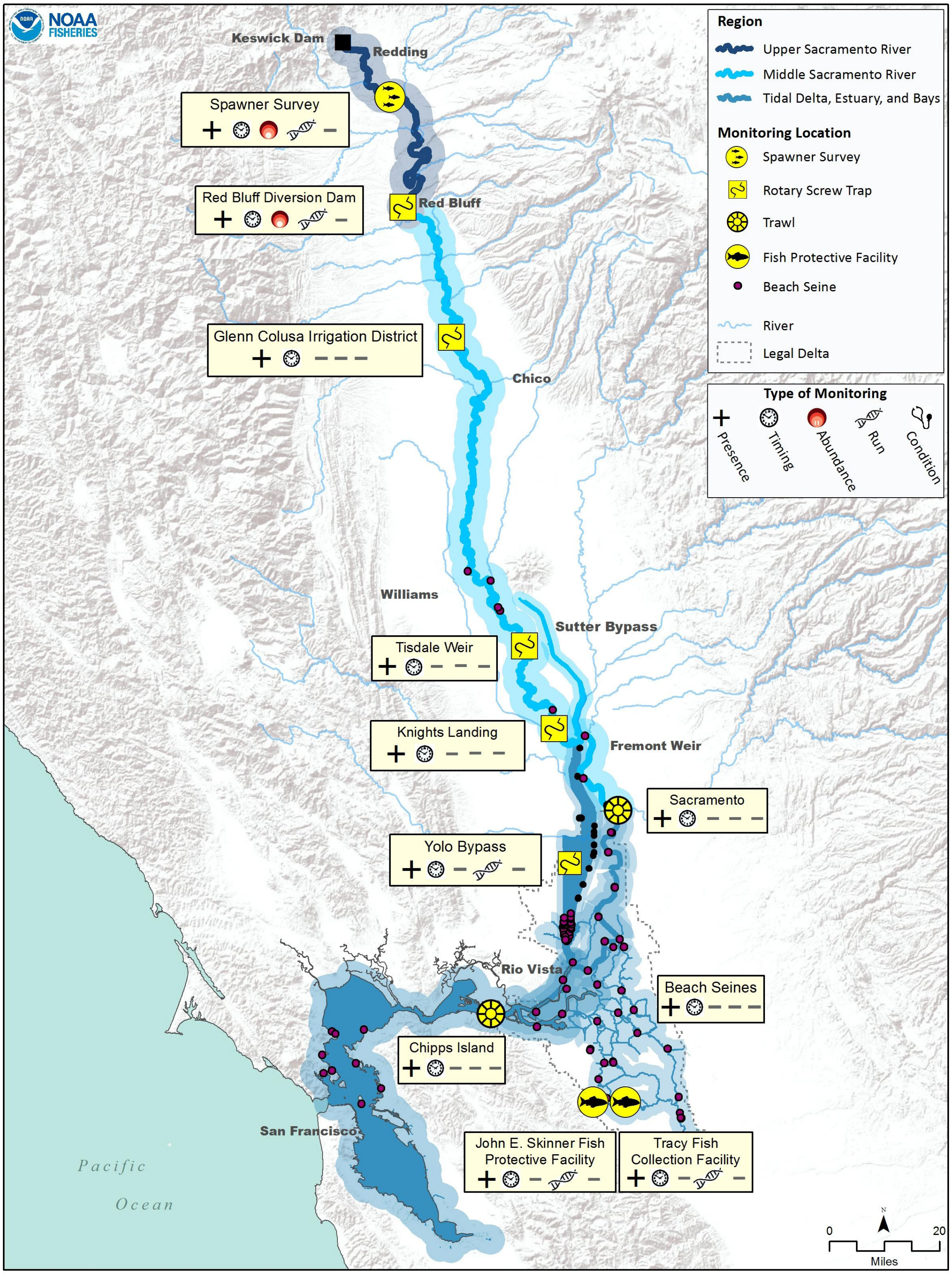

Figure 1 Map of the Central Valley with key Sacramento River winter-run Chinook Salmon (SRWRC) monitoring locations identified by geographic domain in the upper Sacramento River (dark blue) and middle Sacramento River (bright blue), and Sacramento–San Joaquin Delta (tidal Delta, Yolo Bypass, estuary, and bays; blue). Summary of the extent to which the core monitoring network measures key demographic indicators such as presence, timing, abundance, run, and condition by life stage is displayed. Metrics that are not monitored are denoted by (–). Note that run identification in the upper Sacramento River is based on the absence of other potential runs during the SRWRC sampling period, not on genetic sampling.

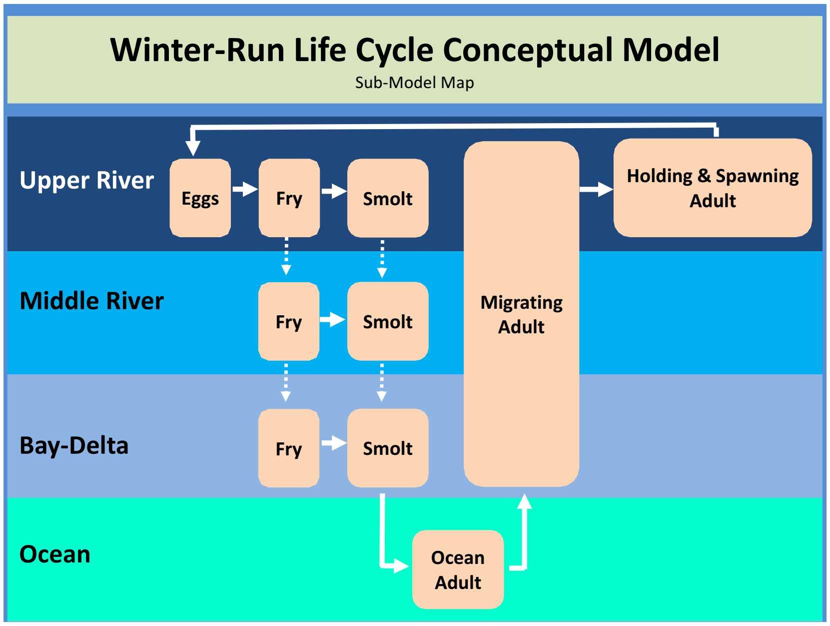

Figure 2 Depiction of the different life-stage and geographic domains developed into sub-models for Sacramento River winter-Run Chinook (SRWRC) (Windell et al. 2017). Solid arrows represent life-stage transitions, and broken arrows represent movement into different geographic domains. The geographic domains are referenced by color and label to the map in Figure 1.

potentially drive population dynamics (Windell et al. 2017). Specifically, we evaluated the extent to which existing monitoring efforts for each life stage and geographic domain provide information on the following fundamental demographic responses and vital rates for SRWRC: presence, timing, abundance, run identity, life-history diversity, and condition.

EVALUATION OF CURRENT LIFE-STAGE MONITORING NETWORK AND ADVANCEMENTS[1]

A salmon monitoring network needs to provide quantitative estimates of life-stage abundance across geographic domains to identify factors influencing survival as cohorts move over the landscape (Windell et al. 2017). Based on our review, although several monitoring locations exist for juvenile SRWRC, only one provides a population abundance estimate: the RBDD rotary screw trap (RST; Figure 1). Three key limitations to the current monitoring prohibit the generation of reliable estimates of juvenile SRWRC abundance downstream of RBDD. First, the lack of reliable run identification. Second, a lack of SRWRC sample gear efficiency estimates at in-river and Delta locations, which are needed to expand sample catch into robust population estimates (Table 1). Third, much of the monitoring data are not publicly available, limiting their access and use for monitoring the effects of management decisions in a timely manner (Table 2).

The most reliable measurements of the annual status of SRWRC are based on adult SRWRC counted that pass RBDD, and, more recently, from carcass surveys of adult spawners (Figure 3) and the resulting number of progeny that pass RBDD (Figure 4), from which an annual egg-to-fry survival estimate is calculated (Figure 5). For example, in 2014 and 2015, SRWRC experienced high mortality between the egg and fry life stages, which resulted in only 5.9% and 4.5% survival in those years, respectively, compared to the long-term average egg-to-fry survival of 26% (standard deviation [SD] = 10%; Poytress 2016; Figure 5). Confidence that survival in 2014 and 2015 was exceptionally low is based on the RSTs at RBDD sampling a high portion of Sacramento River flow, and on calibrated trap efficiencies under varying flow conditions (Poytress 2016). Thus, SRWRC captures at RBDD can be expanded into annual population-level abundancies of juveniles migrating downstream at that location with relatively high precision (±35%; 90% confidence intervals) (Poytress et al. 2014). However, once SRWRC leave the Upper Sacramento River, they mix with other

1 Recommendations to modify existing monitoring are based on our review of scientific information and assessments of the information gaps necessary to improve water- and resource-management decisions; we did not consider cost and permitting requirements as part of this review.

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Table 1 Summary of Sacramento River winter-run Chinook Salmon (SRWC) monitoring surveys, protocols, and precisions

Life stage	Location	Agency	Protocol	Level of precision	Protocol citation
Upper river					
Adults	Upper river	CDFW	Carcass mark–recapture; McCormick Jolly Seber	Abundance 90% CI = 10%	Bergman et al. 2012
Juveniles	RBDD	USFWS	Mark–recapture; gear efficiencies	Abundance 90% CI = 35%	Poytress et al. 2014
Middle river					
Juveniles	GCID	GCID	RST	Counts reported	
	Tisdale	CDFW	RST	Counts reported	
	Knights Landing	CDFW	RST	Counts reported	
	Yolo Bypass	DWR	RST; Beach seines	Counts reported	
Tidal estuary					
Juveniles	Sacramento	USFWS	Kodiak trawl	Counts reported	Honey et al. 2004
	Delta	USFWS	Beach seines	Counts reported	Honey et al. 2004
	Chipps Island	USFWS	Mid-water trawl	Abundance CV = 20–40%	Pyper et al. 2013
	Fish Protective Facility	USBR/ CDWR	Salvage; Loss estimate	Expanded counts per water volume	
Ocean					
Adults	Ocean fishery	NMFS	CWT recoveries; Cohort reconstruction	Not estimated for impact rates	O'Farrell et al. 2012
Multiple regions					
Hatchery juveniles	Multiple regions	NMFS	Reach-specific survival and movement rates; JSAT Acoustic Telemetry	Errors vary by reach	Michel et al. 2015
Adult migration	Flood bypasses	CDFW	Strandings and rescues	Counts reported	Purdy et al. 2015

juvenile salmon runs (spring and fall / late-fall). This mixing and the lack of another comparable sampling location downstream from RBDD compromises the ability to track the identity, abundance, life-history diversity, and condition of juvenile SRWRC until they return as adults to spawn and are counted in carcass surveys (Figure 1; Table 1). The current monitoring perpetuates the inability to disentangle freshwater from marine effects on SRWRC population dynamics. In addition, vital rates such as growth, energy reserves, and disease are not routinely monitored across any of the life stages of SRWRC (Figure 1).

Overall, we conclude that more focused monitoring is needed in the Central Valley to asses SRWRC status and trends. We developed the following six, system-wide improvements to provide the necessary quantitative metrics to better manage fish and water resources and support the life-cycle modeling necessary to inform the management, conservation, and recovery of SRWRC. The improvements address basic fish demographic metrics (e.g., run identity, abundance, life-history diversity, survival, condition) and technologies commonly implemented for salmon in other regions or in the Central Valley for other fish species (e.g., Delta Smelt, *Hypomesus transpacificus*) to track status and trends.

ADVANCEMENT 1: Incorporate Genetic Run Identification at Key Ecological and Management-Relevant Locations

Background

The timing of riverine and Delta water operations needed to protect salmon varies among the different runs (NMFS 2009). Yet, in most of the salmon monitoring network, it is unclear whether a juvenile salmon sampled at a location and point in time is from a stock that is listed as threatened or

Table 2 Summary of Sacramento River winter-run Chinook Salmon (SRWC) data availability and reporting. Note: Location abbreviations as in Figure 1.

Life stage	Location	Open data available via website	Data storage locations	On-line annual reports
Upper river				
Adults	Upper river	Yes[a,b]	CDFW Red Bluff	Yes[c]
Adults (broodstock)	Livingston Stone National Fish Hatchery (Keswick Dam)	No	USFWS Red Bluff	Yes
Juveniles	RBDD	Yes[d]	USFWS Red Bluff	Yes[e]
Middle river				
Juveniles	GCID	No[f]	GCID	No
	Tisdale	Yes[d,g]	CDFW Rancho Cordova	No
	Knights Landing	Yes[d,g]	CDFW Rancho Cordova	No
	Yolo Bypass	No[h]	CDWR West Sacramento	No
Tidal estuary				
Juveniles	Sacramento	Yes[d,i]	USFWS Lodi	No[j]
	Delta	Yes[d,j]	USFWS Lodi	No[k]
	Chipps Island	Yes[d,j]	USFWS Lodi	No[k]
	Fish Protective Facility	Yes[d,k]	CDFW Stockton	Yes[l]
Ocean				
Hatchery adults	Ocean fishery	Yes[m]	CDFW Santa Rosa	No[n]
Multiple regions				
Hatchery juveniles (survival)	Multiple regions (acoustic receivers)	No[o]	NMFS Santa Cruz	No
Migrating adults	Flood bypasses	No[p]	CDFW Sacramento	Yes[c]

a GrandTab available as pdf; *https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=84381&inline=1*
b Data available upon request; point of contact: *doug.killam@wildlife.ca.gov*
c *http://www.calfish.org/ProgramsData/ConservationandManagement/CDFWUpperSacRiverBasinSalmonidMonitoring.aspx*
d *http://www.cbr.washington.edu/sacramento/* and *http://www.baydeltalive.com/djfmp*
e *http://www.fws.gov/redbluff/MSJM%20Reports/RST/rbdd_jsmp_annual.html*
f Data available upon request; point of contact: *jloera@gcid.net*
g *http://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyJuvenileSalmonandSteelheadMonitoring.aspx*
h Data available upon request; point of contact: *Brian.Schreier@water.ca.gov*
i *https://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm*
j Biennial reports: *https://www.fws.gov/Lodi/juvenile_fish_monitoring_program/jfmp_reports.htm*
k CDFW Salvage FTP site; *ftp://ftp.dfg.ca.gov/salvage/*
l *ftp://ftp.dfg.ca.gov/salvage/Annual%20Salvage%20Reports/*
m Regional Mark Information System (RMIS); *http://www.rmpc.org/*
n Reports available upon request; Marine Region, Ocean Salmon Project, Santa Rosa, CA 95403
o Data available upon request; point of contact: *Arnold.Ammann@noaa.gov*
p Data available upon request; point of contact: *Colin.Purdy@wildlife.ca.gov*

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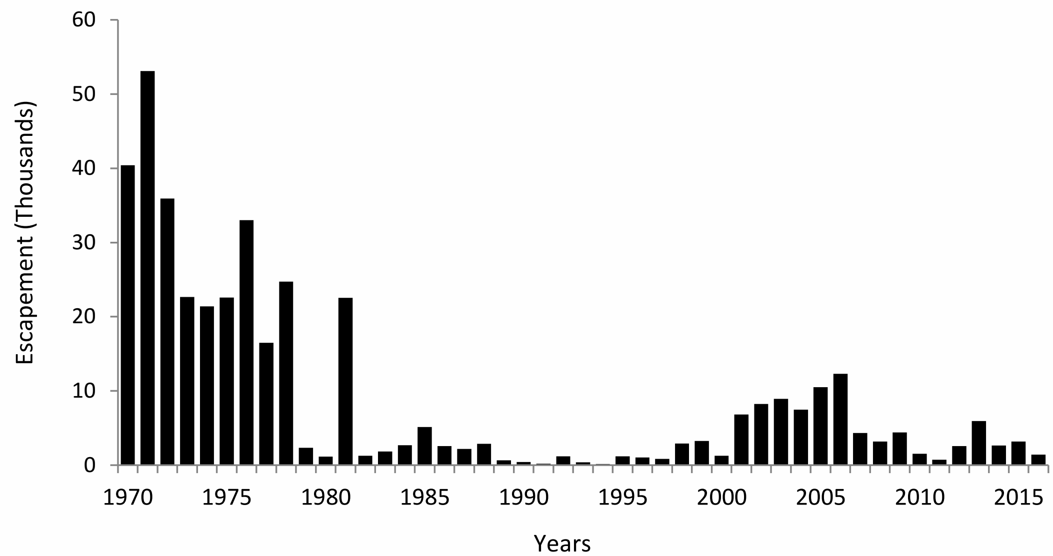

Figure 3 Time series of escapement for Sacramento River winter-run Chinook salmon (SRWRC) spawning in-river. Escapement is the average number of adults counted at Red Bluff Diversion Dam and the carcass survey mark–recapture estimates. SRWRC escapement is currently calculated from the carcass survey using a Cormack Jolly–Seber model (CJS). The CJS model allows the calculation of the confidence intervals necessary to robustly estimate significant changes in escapement over time (Crawford and Rumsey 2011; Bergman et al. 2012; Hendrix et al. 2014). Source: Figure modified from Johnson and Lindley (2016).

endangered under the state and federal endangered species acts (ESAs) (winter or spring runs) or is intended to contribute to commercial harvest as adults (fall/late-fall; Figure 1). For example, recent studies have identified that current length-at-date (LAD; Fisher 1992) methods for identifying juvenile SRWRC captured at monitoring sites in the Delta vary in accuracy within and among years compared to genetic identification (Harvey et al. 2014; Pyper et al. 2013a; Figure 6). Thus, the current monitoring network does not adequately meet this management need of assessing how management actions affect different runs.

Accuracy in LAD stock identification likely decreases with distance and time as salmon migrate from natal habitats throughout the Central Valley as a result of increased mixing of multiple runs along the migration corridor. Additionally, distinctions in size-at-date based on discrete run spawning dates are blurred by inter-annual shifts in spawn timing, variable temperatures, food availability, and juvenile distribution among variable habitats (Fisher 1992). Although most genetic SRWRC are largely classified as SRWRC by the current LAD method at the time they leave the Delta, some individuals fall into the LAD categories for spring, fall, and late-fall runs (Figure 6). In addition, the current LAD method misidentifies other more abundant salmon runs (i.e., fall and spring) as SRWRC. For example, winter run identified using the LAD at Chipps Island from 2008 through 2011 were genetically identified as fall (24%; SD = 0.05), spring (21%, SD = 0.05) and late-fall (12%, SD = 0.06). Thus, relying on LAD can result in two- to six-fold over-estimates in the true number of winter-run salmon (Figure 6). In 2016, only three of 44 LAD SRWRC collected at Chipps Island and genetically sampled were found to be genetic SRWRC (USFWS 2017, unreferenced, see "Notes"). This LAD inaccuracy leads to an over-estimate of SRWRC at Chipps Island, with the degree of over-estimation dependent on the relative population size of SRWRC. During the 2012 to 2016 drought, 159 winter-run-sized fish were observed at the water export facilities (i.e., Tracy Fish Collection and the John E Skinner Fish Protective Facilities; CDFW, unreferenced, see "Notes"). When fish that were identified as SRWRC based on LAD criteria were genetically analyzed (n = 155), only 41 were confirmed to be truly SRWRC (CDWR, unreferenced, see "Notes").

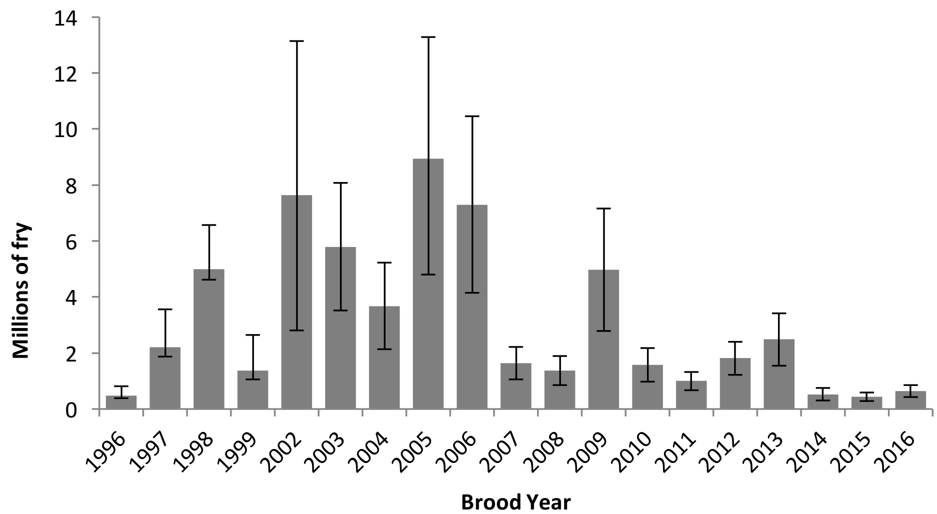

Figure 4 Abundance estimates (90% confidence intervals) of juvenile Sacramento River winter-run Chinook Salmon (SRWRC) passing Red Bluff Diversion Dam using calibrated trap efficiencies. Source: Estimates are generated using the fry-equivalent method and data described in Poytress et al. 2014.

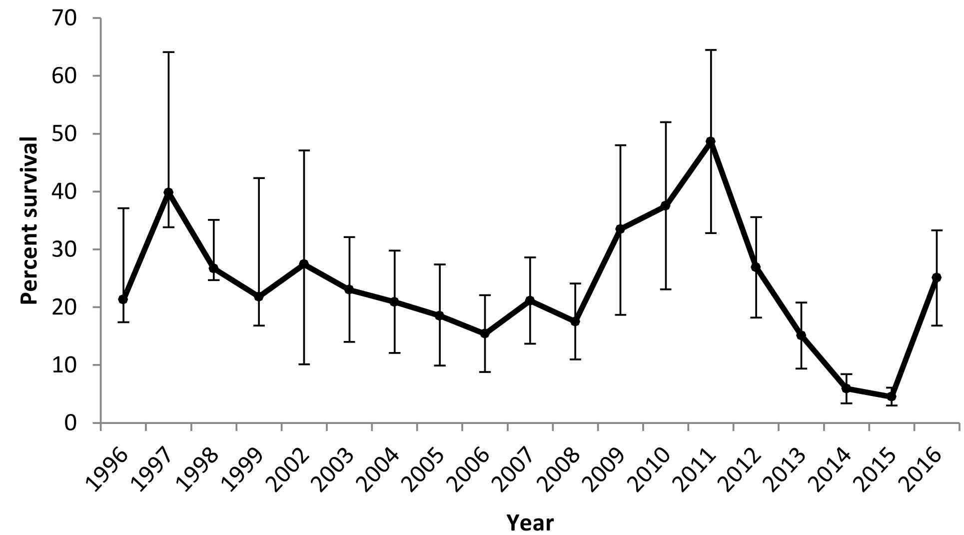

Figure 5 Egg-to-fry survival of Sacramento River winter-run Chinook Salmon (SRWRC). Egg estimates derived from the Coleman National Fish Hatchery average of 76 females spawned in 1995, for the years 1996 to 1999. Current population-level estimate of egg abundance is derived annually from the average numbers of eggs per natural-origin females spawned at the LSNFH (2002–2013) multiplied by the annual estimate from the carcass survey of females spawning in-river. The population-level abundance estimate of fry at RBDD is then used to generate the egg-to-fry survival metric. Errors on this estimate are 90% confidence intervals. Source: Data from Poytress 2016.

Therefore, the current LAD approach has limitations in generating precise abundance indices for true genetic SRWRC (Pyper et al. 2013a; Harvey et al. 2014) and belies how few genetic SRWRC may be emigrating from freshwater each year and exposed to various management actions. Inaccurate stock identification is problematic because it compromises the management value of the long-term data collected in monitoring programs (IEP SAG 2013) to inform water project operations and imply status and trends for salmon stocks.

Recommendation

To improve the management value of the existing monitoring data and reduce uncertainty in stock identification, we recommend applying well-established genetic stock identification methods (Sidebar 1) comprehensively to juveniles across the LAD size categories in the monitoring network. For SRWRC, a priority is genetic identification of individuals in the sub-yearling SRWRC LAD category, as well as juveniles over 1 year of age from all runs collected in the Sacramento and Chipps Island trawls. Collecting genetic information from salmon in the current monitoring program will provide robust

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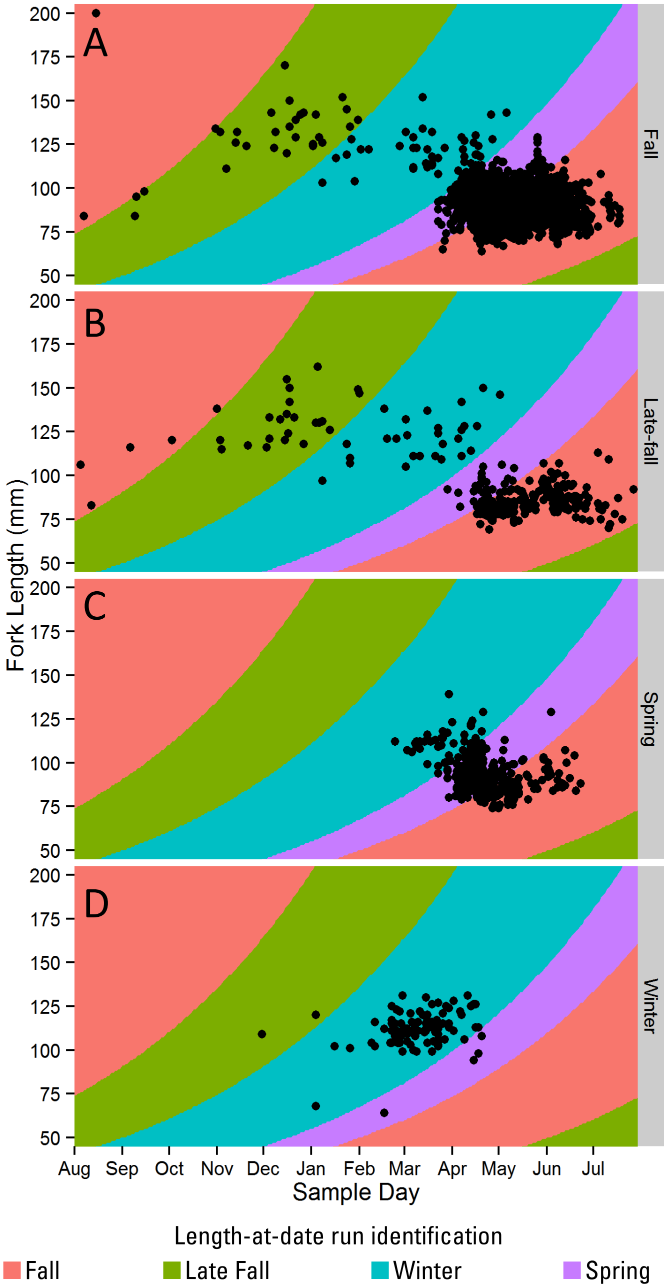

Figure 6 River Length-at-date (LAD) run identification curves (colored swaths) and true genetic identify of fish (separate panels **A–D**) for juvenile Chinook salmon collected at Chipps Island. Though most genetic Sacramento River winter-run Chinook Salmon (SRWRC) fall within the SWRC LAD category, many SRWRC-sized fish are genetically fall, spring, or late fall run. Note that genetic identification is broken into late-fall and fall panels, yet they are considered the same evolutionarily significant unit (ESU) and genetic reporting unit (Clemento et al. 2014). For accuracy, fall/late-fall should be combined in a single panel. Source: Figure from Pyper et al. 2013a.

SIDEBARS

Sidebars throughout this paper provide a quick reference for readers to understand what the tool is, how it may help improve the current monitoring network, and where it is used both within and outside the Central Valley. References regarding tool application are not intended to be exhaustive; instead they serve to illustrate that these tools are used for science or management benefit elsewhere, and are already starting to be used for SRWRC.

Sidebars include:

- **Genetic stock identification (GSI)**
- **Parental-based tagging (PBT)**
- **Passive Integrated Transponder (PIT) tags**
- **Acoustic Tags (AT) and real-time receivers**
- **Otoliths**
- **Condition monitoring**
- **Pathogen monitoring**

SIDEBAR 1

Tools for Enhanced Monitoring: Genetic Stock Identification (GSI)

- A DNA-based method of determining Chinook salmon stock (geographic) or run (winter, spring, fall/late-fall) with genetic baselines developed for Central Valley salmon stocks using microsatellites (Banks et al. 2014), single-nucleotide polymorphisms, or sequencing (Clemento et al. 2014; Meek et al. 2014, 2016; Satterthwaite et al. 2015; Johnson et al. 2016).

Key Benefits

- High degree of accuracy compared to current length-at-date method
- Improves accuracy of SRWRC abundance estimates at key monitoring locations
- Non-lethal sampling
- Results available in near real-time (<48 hours)

Application Examples

- Management of ocean harvest quotas in real-time for mixed-stock fisheries (Beacham et al. 2004)
- Used in the tidal Delta (Yolo Bypass and fish salvage facilities; Figure 1) to distinguish runs (Harvey et al. 2014)

information relevant for identifying the movement and distribution of juvenile salmon from distinct runs, and will reveal how distributions vary over time and with environmental and hydrological conditions. This is also a critical first step in generating run-specific abundance estimates (see Advancement 2).

Discussion

Sacramento and Chipps Island trawls are considered two high-priority locations for genetic monitoring of SRWRC for four reasons: (1) the majority of SRWRC are thought to spend several months rearing in the Delta before they migrate seaward, based on entry (at Knights Landing or Sacramento) and exit (Chipps Island) timing of wild SRWRC-sized salmon (del Rosario et al. 2013); (2) stressors and management actions in the Upper and Middle Sacramento River can be notably different than in the Delta, and thus knowledge of the abundance and timing of Delta entrance and freshwater exit provide important information on the role of the Delta in setting cohort strength and on how to prioritize actions among regions; (3) trawls at these two locations can generate population abundance estimates (see Advancement 2); and (4) all emigrating SRWRC salmon (as well as all salmon runs from Sacramento River tributaries) must pass these two trawl locations, unless the Freemont weir is spilling water into the Yolo Bypass. Therefore, these two locations can generate run-specific abundance estimates for all salmon runs that emerge from Sacramento River tributaries. For example, focusing efforts farther upstream of Sacramento, such as at Knights Landing, would not sample SRWRC that use the Sutter Bypass, nor other salmon runs from the Feather and American rivers.

Although this monitoring review focuses primarily on advances for SRWRC, the resolution of the current genetic baseline provides high-precision identification of both ESA-listed salmon runs in the Central Valley (i.e., SRWRC and wild spring-run Chinook from Deer, Mill, and Butte creeks; Banks et al. 2000; Seeb et al. 2007; Anderson et al. 2008; Banks et al. 2014; Clemento et al. 2014). However, there are challenges in distinguishing the late-fall run from fall run, and in identifying wild Feather River spring-run Chinook Salmon, because of introgression with fall-run Chinook Salmon (Clemento et al. 2014). Given the recent advancements in rapid genome assay technologies that can track parental lineages (parentage-based tags [PBTs]; Sidebar 2), adult and juvenile tissue libraries and collections may soon provide greater insights into the reproductive success of individuals as a function of ambient environmental conditions, water project operations, spawn timing, habitat carrying capacities, and hatchery release strategies. Thus, PBTs should be incorporated into juvenile and adult surveys (Ali et al. 2016; see Advancement 4). Advancements in the use of mucus swabs, as opposed to removing fish tissues (e.g., fin clips), may provide a less invasive sampling approach for future consideration (Le Vin et al. 2011). To develop a robust monitoring program for the multiple salmon runs and to explore opportunities for refined statistical models for LAD run identification, a system-wide tissue sampling strategy for Chinook

SIDEBAR 2

Tools for Enhanced Monitoring: Parentage Based Tags (PBT)

- A DNA-based method to link parents and offspring over multiple generations
- Requires annual tissue collection to develop reference library of parents (e.g., hatchery broodstock) or other adult monitoring stations (e.g., carcass survey)
- Utilizes single-nucleotide polymorphisms (Clemento et al. 2014)

Key Benefits

- Estimates effective population size
- Provides reproductive success of individual spawners
- Reduces inbreeding or (hybridization between runs) during controlled breeding
- Non-lethal sampling
- Results can be available in near real-time (< 48 hours)

Example Applications

- Monitoring tool to detect fitness effects of hatchery practices (Araki et al. 2007)
- Used to reduce hybridization between Feather River Hatchery spring and fall runs in broodstock (CHSRG 2012)

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Salmon is required that includes all sizes of Chinook Salmon encountered at all monitoring locations that can provide quantitative abundance estimates.

ADVANCEMENT 2: Bolster Estimates of Juvenile Abundance and Cohort Strength Across the Freshwater Landscape

Background

Abundance estimates at key checkpoints in the life history of salmon are crucial to monitor run status and understand variation in survival throughout the life cycle. SRWRC adult and juvenile abundances in the Upper Sacramento River are reported annually with relatively high precision (Poytress 2016). These estimates indicate population status and inform factors that affect survival during two life-stage transitions: (1) from spawners to fry emigrating past RBDD (where juvenile abundance is estimated); and (2) from fry at RBDD to spawners returning predominantly as 3-year-old adults (Windell et al. 2017, CMs 2 – CM 7; Figures 3–5). Juvenile abundance estimates at RBDD bracket a relatively short time-period and narrow spatial extent in the life history of SRWRC, which has allowed researchers to identify key factors that affect egg-to-fry survival (Martin et al. 2017). However, the second life-stage transition, from juveniles at RBDD to spawners, encompasses multiple years and hundreds of kilometers of the Sacramento River, Delta, San Francisco Bay, and Pacific Ocean. Consequently, resource managers have little information about run status or factors that affect survival between the time when fry pass RBDD and when they return as adults. Furthermore, when fitting life-cycle models or estimating survival for this life-stage transition, it is currently impossible to disentangle effects in the freshwater environment from those in the estuary or ocean. The scientific and management communities view estimating the population size of SRWRC that enter and exit the Delta as a critical element for informing freshwater and Delta water management actions (IEP SAG 2013).

Estimating fish abundance at key locations requires estimating the efficiency of sampling gear (e.g., RSTs or trawls), which has a long history in fisheries science (reviewed in Arreguin–Sanchez 1996). Generating reliable gear efficiency estimates amidst different environmental conditions allows raw catch data to be expanded into abundance estimates that can be compared within and between years and sites. Currently, the juvenile salmon monitoring network downstream of RBDD reports information on the presence and timing of winter-run-sized SRWRC (Figure 1) but not on annual population–level abundance estimates for SRWRC or the other salmon runs (Figure 1; Table 1 and Table 2). Raw catch cannot be used as an index of abundance because variation in catch is confounded with variation in gear efficiency. Thus, catch data from the current monitoring network downstream of RBDD is of limited utility for understanding inter-annual variation in abundance and survival, and for informing life-cycle model development or management actions.

Estimating gear efficiency is difficult, often requiring a long time-series of mark–recapture trials throughout a range of conditions to develop global efficiency models that can be reliably used to expand catches to abundance (Zeug et al. 2014; Poytress et al. 2014). Estimating abundance of SRWRC at the entrance (Sacramento) and exit (Chipps Island) to the Delta, where trawls are used to monitor juvenile salmon populations, necessitates estimating the efficiency of the trawls. Recent efforts investigated whether the long-time series of historical data from coded-wire tag (CWT) survival studies could be used to estimate trawl efficiency (Pyper et al. 2013a) and abundance based on DNA run assignments at Chipps Island (Pyper et al. 2013b). By using paired releases of CWT fish released upstream and downstream of Chipps Island, Pyper et al. (2013a) estimated the survival of each release group to Chipps Island, and trawl efficiency, here defined as the probability of capture during trawl sampling. They identified considerable variation in trawl efficiencies that could not be explained by covariates that would otherwise be expected to influence trawl efficiencies. The paired release design makes the critical assumption that downstream control groups survive at the same rate as upstream groups, beyond the downstream release point. Therefore, the authors suspected that violation of this assumption led to bias in the estimates of survival and efficiency, which drove large release-to-release variation in the apparent trawl efficiency. Given the findings of Pyper et al. (2013a), and the fact that historical CWT experiments were not designed to estimate gear efficiency, study designs that estimate trawl efficiency are needed to expand catch data into estimates of abundance at the entrance and exit of the Delta.

Quantifying variability in trawl efficiency is critical to assess the expected precision of the abundance estimate, and, ultimately, to characterize the limitations in using trawls that sample dynamic environments. Factors that affect variation in estimated trawl efficiency are covariates that vary from trawl to trawl (e.g., tides, tow direction), from day to day (e.g., net outflow, turbidity), and from variation in the number of fish available to capture. Since the trawl sampling protocol in the Delta consists of ten, 20-minute trawls per day between 7 a.m. and 12 p.m., overall capture probabilities are low (and an order of magnitude lower than RSTs). The effects of low capture probability on statistical precision can be overcome by increasing the number of marked fish by an order of magnitude relative to release sizes for RST efficiency trials, which is feasible (e.g., tens or hundreds of thousands relative to thousands).

Recommendation

To estimate gear efficiency of the Sacramento and Chipps Island trawls, we recommend an innovative feasibility study that pairs releases of hatchery SRWRC tagged with CWT and acoustic tags (AT), as first suggested by Pyper et al. (2013a). Using the assumption that CWT and AT fish have equivalent survival rates and travel times from the release point to the trawl locations, the number of CWT fish available for capture (e.g., the number of fish expected to be present during trawling) can be estimated. Given estimates of the number of CWT fish available for capture, mean trawl efficiency for a given release group can be estimated as the fraction of CWT caught in the trawl out of the total number available for capture. The hybrid CWT–AT study design can quantify variability in trawl efficiency and how efficiency relates to covariates, which is needed to explore how these sources of variation contribute to the precision of the estimated abundance. This approach will provide the necessary information to determine the adequacy of using trawls to derive juvenile abundance estimates with precision to detect significant changes in abundance among years.

Discussion

Using the hybrid CWT–AT approach, the AT data will provide detailed information about the survival, daily passage, and diel passage behavior of the hatchery CWT fish that pass Sacramento and Chipps Island, allowing sources of variation and potential bias in trawl efficiency estimates to be assessed in detail. Notably, a given paired release of AT and CWT fish may pass the trawl site during several weeks, so it is important to estimate the number of fish available for capture by the trawl during a shorter time-period. Toward this end, a multi-state mark–recapture design can be used to estimate the joint probability of AT fish surviving and moving past the trawl site during shorter time-periods (e.g., 1 to 7 days, depending on release sizes of AT fish; Figure 7; Perry et al. 2012). This approach would estimate the number of CWT fish available to be captured during shorter time-periods, which would reduce the variation in estimated trawl efficiency that arises from daily variation in the number of fish available to capture. In addition, the AT data will help to quantify the time of day when fish pass the trawl site relative to the time of trawling, providing insights into the proportion of the population available for sampling between 7 a.m. and 12 p.m. – the period when trawl sampling traditionally occurs.

Quantifying trawl efficiency in this hybrid CWT–AT framework has several additional advantages. First, the data obtained from this feasibility study can be used in simulation studies to investigate optimal study designs that would maximize trawl efficiency and precision of abundance estimates, and reveal how violation of assumptions affect bias in abundance estimates. For example, given data and parameter estimates from the feasibility study, simulation studies can help us understand how increasing sampling frequency (number of sampling days), duration (hours per day), gear type (area of water column sampled), or time of sampling affect the precision of abundance estimates. Second, given multiple release groups and multiple efficiency estimates per release group, models can be developed – through repeated sampling throughout various seasons and environmental

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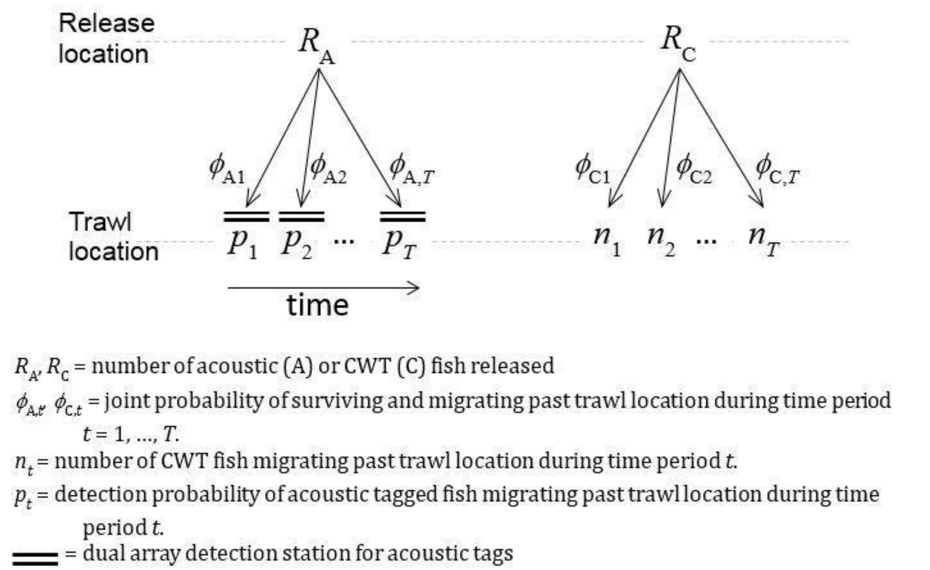

Figure 7 Schematic of multi-state model to estimate time-specific efficiency of juvenile salmon sampled by trawls. Joint movement–survival probabilities of acoustic tagged fish, $\phi_{A,t}$, can be estimated using a multi-state mark-–recapture model under which capture histories of individuals follow a multinomial distribution. The total survival from release site to the trawl site is simply the sum of $\phi_{A,t}$ over all T time-periods. Under the assumption that $\phi_{A,t} = \phi_{C,t}$, the expected number of coded wire tag (CWT) fish available to be sampled by trawls during time-period t is: $E(n_t) = R_C\phi_{A,t}$. Let r_t be the number of CWT fish captured by the trawl during-time period t, which has the expected value: $E(r_t) = R_C\phi_{A,t}E_tf_t$, where E_t is trawl efficiency and f_t is the fraction of time the trawl was sampling during time-period t. Solving for E yields an estimator of time-specific trawl efficiency: $E_t = r_t / (R_C\phi_{A,t}f_t)$.

conditions—to relate efficiency to environmental covariates. These models can then be used to predict trawl efficiency and estimate abundance of other populations during other times of the year. Lastly, modeling results will reveal whether covariates can predict sampling efficiency within a reasonable degree of accuracy, and may suggest strategic ways to modify sampling efforts to improve the precision of abundance estimates.

However, trawls may under-sample small-sized SRWRC that rear in littoral habitats near channel margins. To test for this, we compared the size distribution of fish caught at Delta Juvenile Fish Monitoring Program (DJFMP) beach seine sites near the Sacramento Trawl location against those caught in the Kodiak Trawl (KT). We found that the median fork length of salmon in both sampling gears during October through March in 1998 to 2014 was 38 mm, with greater size variation caught by the KT, which is likely reflective of the larger number of samples from the same distribution, or the KT's ability to catch larger fish. Thus, the KT could capture the full range of salmon sizes caught at beach seines in the same location (Figure 8).

Given that the Delta is the nexus between freshwater and ocean environments, identifying novel techniques to monitor the population status of SRWRC when they enter and exit the Delta is important. A feasibility study using the hybrid AT–CWT design will provide the necessary data to resolve key uncertainties about a trawl-based monitoring program, inform recommendations on the value of implementing this approach as part of the long-term monitoring program and, if viable, determine the applicability of this approach to estimate abundance of other Central Valley salmon and steelhead and of SRWRC at other monitoring locations (e.g., Sacramento River mainstem RSTs; Figure 1). A robust estimate of the timing and abundance of SRWRC that leave freshwater at Chipps Island before they enter the ocean could be used to estimate the likely influence of ocean conditions on SRWRC survival (Wells et al. 2006, 2007, 2008a, 2008b, 2012). This would contribute to predictions of year-

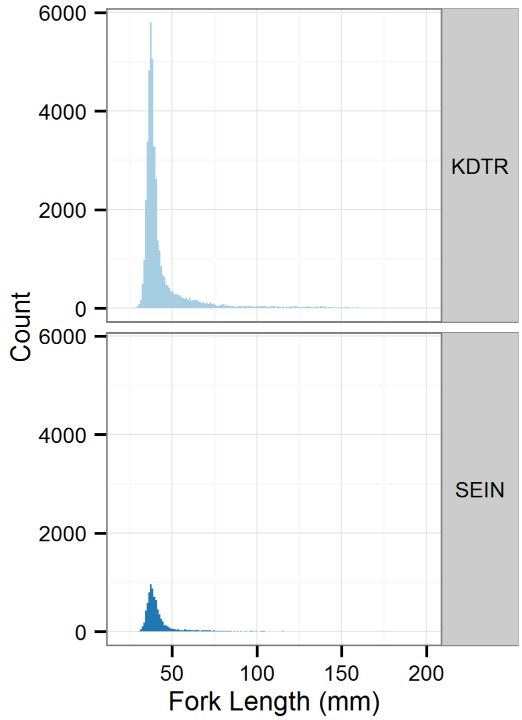

Figure 8 Fork length (mm) distributions of juvenile Chinook Salmon caught by the U.S. Fish and Wildlife Service's (USFWS; Dekar et al. 2013; Dekar 2014) in the (**A**) Kodiak trawl (KDTR) and (**B**) beach seines (SEIN) from Region 7 sites near Sacramento (sites SR062E, SR057E, and SR055E). KDTR and SEIN data includes October to March from 1998 to 2014. A midwater trawl, not included here, is used in late spring and summer, replacing the KDTR seasonally.

class strength for SRWRC in the ocean, a necessary step to move away from retrospective methods and toward prospective forecasts to improve the annual management of mixed-stock fisheries in the ocean.

ADVANCEMENT 3: Expand and Enhance Real-Time Fish Survival and Movement Monitoring

Background

The ongoing miniaturization of electronic tags has enabled the survival of salmon smolts to be measured and the timing and pathways of migration to be determined with unprecedented precision and detail. Effects from hydropower dams on salmon and steelhead in the Columbia River remained poorly quantified for decades until large-scale, electronic-tagging methods (e.g., passive integrated transponder (PIT) tags, Sidebar 3; and acoustic telemetry) allowed survival to be estimated with precision, and assessed relative to passage standards (>96% survival of spring migrating fish and >93% for summer migrants; Skalski et al. 2012, 2014). Today, more than 350 PIT tag detection systems have been installed in small streams (n = 320), on adult fish ladders (n = 29), and at hydroelectric dam juvenile fish bypass systems (n = 12) in the Columbia River basin (*http://www.psmfc.org/program/pit-tag-information-systems-ptagis*). The data produced address numerous key information needs regarding cohort strength, in-river survival of juvenile and adult salmonids, smolt-to-adult return rates, and water project operations (e.g., Zabel et al. 2008; ISAB 2016).

Although the water infrastructure in the Central Valley is engineered differently from the Columbia River system, a comparable investment in fish-tracking technologies along the salmon outmigration corridors specifically designed for the Sacramento–San Joaquin system is needed to better understand how hydrologic regime, water operations, and stressors in different geographic domains influence salmon cohort strength, smolt-to-adult return rates, migration rates, and reach-specific survival during outmigration. Results of acoustic tagging studies in the Sacramento and San Joaquin rivers have generated important insights into overall low survival, effects of flows and turbidity on survival, diversity in migration behaviors among races of Chinook Salmon, and variability in survival rates among different regions of the river, Delta, and bays (Buchanan et al. 2013; Singer et al. 2013; Cavallo et al. 2015; Michel et al. 2015; reviewed in Perry et al. 2016). However, most of these studies were conducted on hatchery-origin salmon from different runs, highlighting the need to expand this approach to gathering comparable information on salmon originating and migrating from Central Valley rivers.

Recommendation

The current acoustic tagging program should be expanded to create a system-wide, real-time, core acoustic array aimed at improving our understanding of survival, distribution, and migration timing of SRWRC and other fishes (e.g, spring, fall, and late-fall

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SIDEBAR 3

Tools for Enhanced Monitoring: Passive Integrated Transponder (PIT) Tags

- Small (8- to 23-mm) tags (microchip and antennae) with unique alpha-numeric codes that are inserted into the peritoneal cavity and remain dormant until within range of a reader, which uses radio frequency identification to activate and read the tag code (Gibbons and Andrews 2004)

Key Benefits

- Individual-level tracking through adult life stage (no battery limitations) with repeat sampling of the same individual non-lethally.
- Fish as small as 40-mm fork length can be tagged, compared to 80 mm for the smallest acoustic tags
- Provides capability to monitor behavior, habitat use, growth, status, migration behavior, and survival through full life cycle

Application Examples

- Columbia River watershed: 35 million fish tagged over throughout 25-plus+ years Detection data feeds into regional databases—Data Access in Real Time (DART, *http://www.cbr.washington.edu/dart*) and PIT Tag Information Systems (PTAGIS, *http://www.ptagis.org/*)—used to synthesize adult return and juvenile movement data
- Useful for growth, habitat use, and life-history studies (Connor et al. 2011,Connor and Tiffan 2012; McNatt et al. 2016)

Chinook Salmon; steelhead, *O. mykiss*; and sturgeon, *Acipenser medirostris* and *A. transmontanus*). This would require long-term funding for tags, receivers, infrastructure maintenance, database quality assurance / quality control and management, and statistical analyses and support. Systematic and representative tagging of all salmon populations of interest annually will result in a time-series database that can be used to evaluate environmental and hydrological covariates and management actions. Installing additional real-time receivers co-located with existing water-quality monitoring stations – initially placed for restoration, levee repair, and hydrodynamic relevance – would leverage and integrate these different datasets (USGS 2016). The data generated from this program will improve our understanding of how hydrologic variation, water project operations, and habitat restoration influence salmon survival, and will support in-season water management for multiple purposes (e.g., including fish protection).

Discussion

Given the complexity of the role that water project operations may play in influencing environmental drivers, habitat attributes, and fish behavior (Windell et al. 2017, CMs 2–4), reach-specific and through-Delta salmon survival estimates are a critical biological response metric. For example, estimating through-Delta survival for different salmon runs as a function of water project operations is the goal of several developed and emerging scientific evaluation tools (e.g., the Interactive Object-oriented Salmon [IOS] simulation model, Zeug and Cavallo 2014; unTRIM–FISH PTM model, Gross et al. 2014, unreferenced, see "Notes"; enhanced Particle Tracking Model, Jackson et al. unpublished, see "Notes"; Sridharan et al. unpublished, see "Notes"; Sal–Sim, Salmon Simulator San Joaquin River fall-run Chinook Salmon population model, CDFW 2013; and the SRWRC life-cycle model, Hendrix et al. 2014). Empirical data on relationships among flow, survival, routing, and migration rates generated primarily from AT studies have been seminal in the development of these analytical tools, and are required to test the predictions generated from these and other models. Reach-specific or through-Delta survival of different release groups provides a population-level response metric that could be incorporated as the response variable in mechanistic studies and flow-manipulation experiments, or to test model predictions.

The use of real-time acoustic receivers that immediately transmit AT fish detections needs to be included in the expanded network. These provide multiple benefits compared to autonomous receives, which need to be physically retrieved to download fish movement data (Sidebar 4). Real-time receivers transmit the status information needed to identify failures so field crews can be alerted to the need to repair or replace faulty or lost receivers. Real-time acoustic detection data support in-season management decisions. For example, during 2014 and 2015, real-time receivers located upstream of the Delta Cross Channel (DCC) provided valuable information on the timing and movements of acoustically-tagged SRWRC from the conservation hatchery (Klimley et al. 2017), and information on the potential vulnerability of the hatchery-origin SRWRC to the opening of the DCC during the drought, which could route fish into the interior Delta, a route with lower survival, as reviewed in Perry et al. 2016. In-season survival estimates associated with testing experimental pulse flows from tributaries can be of significant value to scientists and managers. For example, one such experiment conducted on the Feather River in 2014 where increases in flows showed a measurable increase in fish detections. This approach can provide tangible information linked to management actions foundational to adaptive management of water resources.

Recent work by the California Department of Water Resources highlights the value of integrating survival monitoring with water-quality measurements in the Delta. For example, they found that juvenile hatchery salmon survival was lower when flows at Freeport, CA were low, water temperatures were high, and turbidity was low, regardless of the route taken to Chipps Island (Figure 9; CDWR 2016). However, it is unclear which of these inter-correlated habitat attributes directly (e.g., water temperature) or indirectly (e.g., temperature or turbidity modification of predation rates) influenced survival more. This emphasizes the importance of monitoring salmon survival and water-quality metrics at the appropriate spatial and temporal scales, and conducting studies targeting how different hypotheses identified in CMs influence fish responses in the Bay–Delta (Windell et al. 2017, CM4). Establishing a core receiver infrastructure is needed to support mechanistic studies and experimental manipulations to understand and improve salmon survival, including, for example, changes in survival from predator removal, habitat restoration, or manipulations of water project operations and Delta hydrodynamics.

SIDEBAR 4

Tools for Enhanced Monitoring: Acoustic Telemetry (AT) Tags and Real-time Receivers

- Small (0.22-0.30 g) battery-powered tags which transmit a unique coded signal that are inserted into the peritoneal cavity

Key Benefits

- Individual-level tracking through outmigration with repeat sampling of the same individual without having to physically recapture individuals
- Much longer detection range to receivers (up to 300 m) compared to PIT tags
- Fine-scale habitat use and swimming behavior with 2-D and 3-D receiver systems
- Provides capability to monitor behavior, habitat use, movement and survival
- Real-time receivers reduce vulnerability to data loss over autonomous receivers

Application Examples

- Current and previous Central Valley AT tagging programs have provided important new insights into migration rates, reach-specific survival estimates, behaviors at junctions, and survival related to environmental co-variates (reviewed in Perry et al. 2016)
- Extensively used in Columbia River Basin to estimate survival of juvenile salmon through dams (McMichael et al. 2010)
- Real-time receivers can provide in-season detections and fish distribution and movement data, and with modeling support can be used to monitor in-season survival standards

ADVANCEMENT 4: Develop and Collect Life History Diversity Metrics at Multiple Life Stages

Background

Maintaining genetic and behavioral diversity is critical for supporting resilient salmon populations, yet it proves to be one of the most challenging metrics to monitor in salmon recovery plans (Lindley et al. 2007; Ruckelshaus et al. 2002). In regulated rivers, there is a high likelihood to select for a constrained set of life history traits and behaviors over time, which reduces the ability of salmon stocks to withstand stochastic events and changing climate conditions, and makes them more vulnerable to extinction (Moore et al. 2010; Carlson and Satterthwaite 2011; Satterthwaite et al. 2014; Huber and Carlson 2015; Satterthwaite and Carlson 2015).

Genetic Diversity. Maintaining the current level of genetic diversity in SRWRC is fundamental to their

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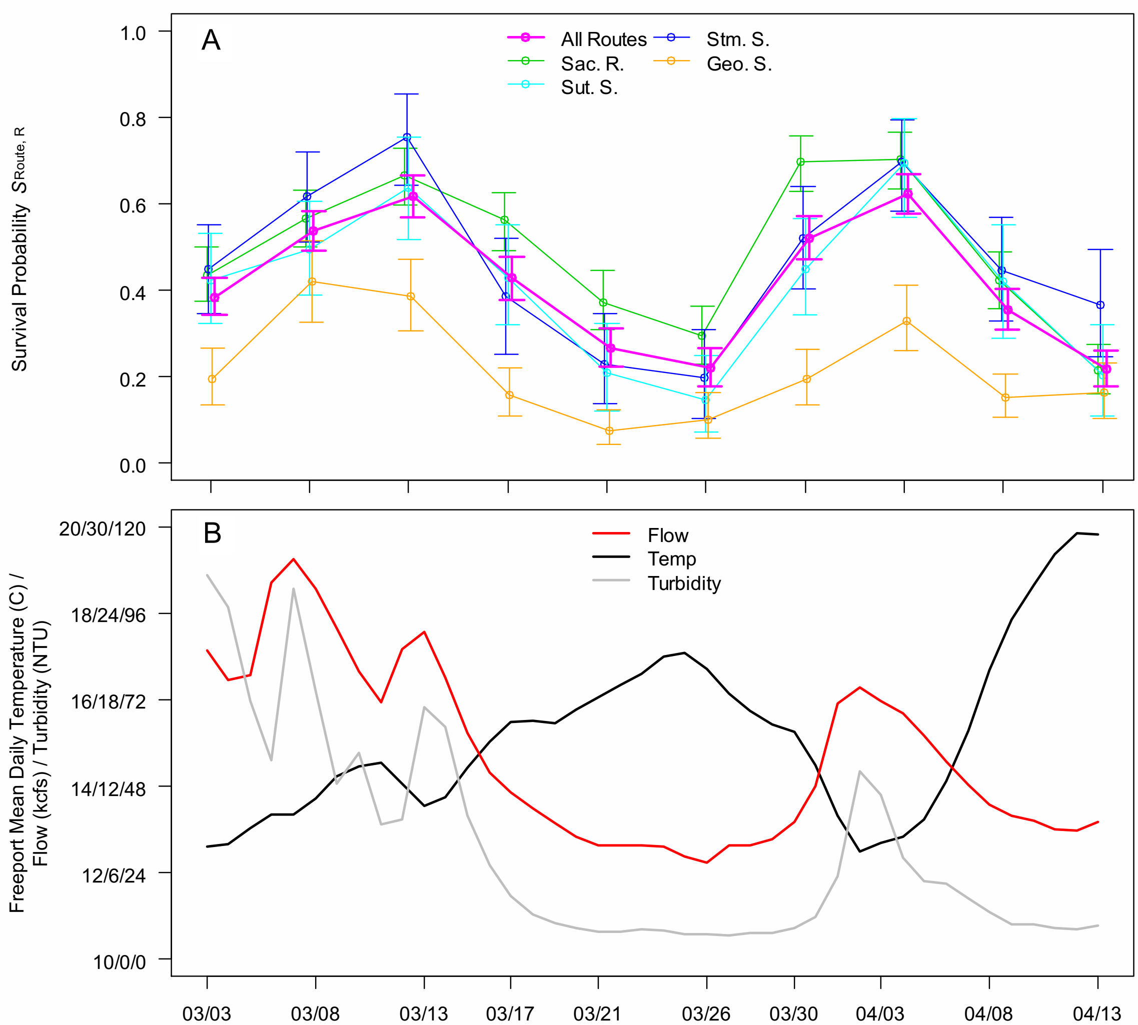

Figure 9 (**A**) Route-specific and Delta-wide survival estimates (posterior medians with 95% credible intervals) from Freeport to Chipps Island for acoustically-tagged juvenile late-fall Chinook Salmon released in 50-day groups during 2014, and (**B**) mean daily temperature, flow, and turbidity at Freeport. Source: CDWR (2016).

long-term viability, especially given their recent population bottlenecks and low genetic diversity (Banks et al. 2000; Lindley et al. 2007). Monitoring within-population genetic diversity, effective population size, relative reproductive success of individuals as a function of origin (hatchery versus wild), and spawning behavior (timing and location) provide important insights into how management actions (e.g., hatchery broodstock management) and water project operations (e.g., water temperature, flow timing, and the magnitude of flow releases) may influence the population's long-term genetic integrity.

The decline of adult abundance and potential increased influences of hatchery production during the past decade (Figures 10 and 11) has placed the population at a greater risk of extinction (Johnson and Lindley 2016). PBT is commonly used in other salmonid systems to monitor how integrated hatchery practices affect the reproductive success of salmon that spawn in rivers. For example, this research tool has shown that when hatchery-origin steelhead spawn with natural-origin steelhead in the wild, the natural-origin fish can experience a 40% reduction in the number of progeny produced (Araki et al. 2007). Significant uncertainty remains about the potential

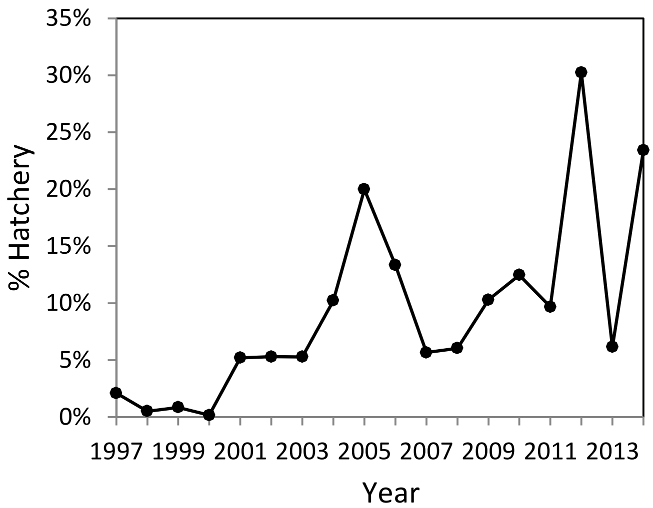

Figure 10 Percentage of Sacramento River winter-run Chinook Salmon (SRWRC) of hatchery origin spawning in-river from Johnson and Lindley 2016. Extinction risk is "moderate" when stray rates from hatcheries employing "best management practices" is >15% in a single generation. The average over four generations (most recent 12 years) is 13% (>5%), also placing the population at a "moderate" risk of extinction (Lindley et al. 2007; Johnson and Lindley 2016). These recent data demonstrate an emerging threat to SRWRC. Data sources: CDFW, D. Killam 2016.

trade-off between fitness effects from the three-fold increase in hatchery production of SRWRC during drought years when survival of natural juveniles from the Upper Sacramento River was exceptionally low, and the rescue role the hatchery may play in overall population abundance.

Meteorological conditions and reservoir operations, especially during drought conditions, likely play a role in influencing spawn timing and, ultimately, progeny success (Windell et al. 2017, CM 1 and CM 7). For example, in 2014, water temperatures downstream of Keswick Dam were elevated from September to November because of the depletion of accessible cold water stored in Shasta Reservoir—and lethal to SRWRC eggs and juveniles (>60 °F; SRTTG 2015; Martin et al. 2017). Thus, females that spawned later in the season and farther downstream likely produced fewer successful progeny because of lethal temperatures than those that spawned earlier and farther upstream (Figure 12). Given that spawn timing may in part be heritable (Carlson and Seamons 2008), this event and the entire drought series (2012 to 2016) may have

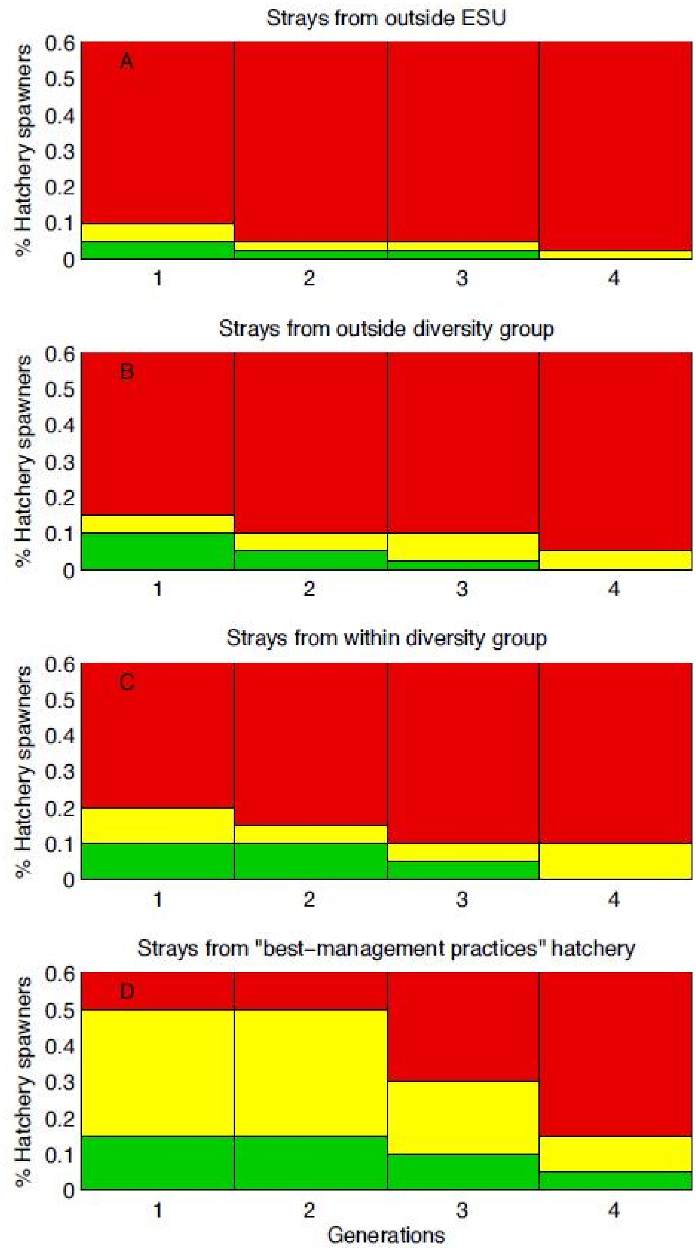

Figure 11 Percentage of hatchery-origin spawners and the resulting risk of extinction caused by hatchery introgression from different sources of strays (**A–C**) over multiple generations for Sacramento River winter-run Chinook salmon (SRWRC). Low (green), moderate (yellow), and high (red). Model using "best management practices" was used in the SRWRC assessment based on the breeding protocols at the Livingston Stone National Fish Hatchery (Johnson and Lindley 2016). Source: Figure reproduced from Lindley et al. 2007.

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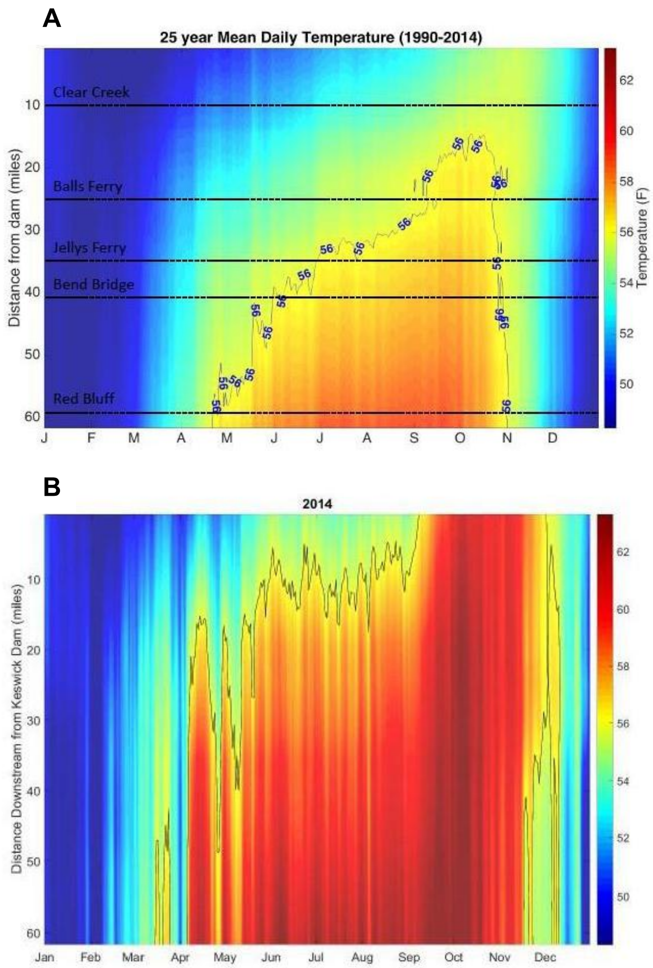

Figure 12 Temperature landscapes for the Sacramento River based on the River Assessment for Forecasting Temperature (RAFT) model (Pike et al. 2013). (**A**) Mean daily temperatures over the past 25 years. Blue line represents the location of the 56 °F compliance temperature. (**B**) Mean daily temperatures during the 2014 drought. Note the location of the 56 °F line (black solid line).

resulted in a reduction in effective population size (i.e., the estimated number of breeders).

Behavioral Diversity. Variability in juvenile size, timing and habitat use during downstream migration to the ocean ensures that some component of the population in dynamic environments experiences favorable riverine, estuarine, and ocean conditions (Beechie et al. 2006; Sattherthwaite et al. 2014). The extent to which fish have access to spatially diverse habitats influences their rate of growth, movement, and phenotypic diversity, and has been shown to stabilize inter-annual variation in juvenile production (Thorson et al. 2014). Movement of LAD SRWRC-size fish past monitoring locations in the Middle Sacramento River and into the tidal Delta typically occurs in the winter with the first large rain event (i.e., the first flush; Poytress et al. 2014) when flows at Wilkins Slough increase to 400 $m^3 s^{-1}$ (del Rosario et al. 2013; Windell et al. 2017, CM3). Comparison of times when SRWRC-sized juveniles enter and exit the Delta suggests relatively long residence times (41 to 117 days; del Rosario et al. 2013). However, the extent to which the individuals emigrating at Chipps Island represent early-migrant fry that successfully reared in the Delta, versus those that reared predominantly upstream of the Delta before quickly transiting it, is largely unknown. Recent otolith reconstructions on fall-run Chinook Salmon returns suggest that Delta rearing may be demographically important, especially in wet years (Miller et al. 2010; Sturrock et al. 2015). Understanding the survival of SRWRC rearing in the Delta was identified as one of the largest empirical data gaps in the development of the NMFS SRWRC life-cycle model (Hendrix et al. 2014; Perry et al. 2016).

Age Structure Diversity. Many salmonid stocks are thought to be buffered from demographic stochasticity through risk being spread across different cohorts that can mature and spawn in mixed-age classes (Greene et al. 2010; Schindler et al. 2010). In addition, the presence of a significant number of age-4 spawners could positively influence SRWRC productivity through increases in fecundity common to larger females (Beacham and Murray 1993). However, maturation rates and age structure diversity among the evolutionarily significant units (ESUs) of Central Valley salmon vary, with SRWRC expressing the lowest diversity (Fisher 1994; Satterthwaite et al. 2017). SRWRC tend to primarily comprise age-3 spawners, with very few age-2 or age-4 adults (O'Farrell et al. 2012; Satterthwaite et al. 2017). Cohort reconstructions applied to hatchery origin SRWRC estimate that maturation rates for age-3 SRWRC are 85% to 100%, with a mean of 95%. Thus, even in the absence of fishing, few fish would remain in the ocean to return as age-4 adults (O'Farrell et al. 2012). Therefore, it is important to know if natural origin maturation rates are similar to those for hatchery-origin fish, because, if this is the case, there are limited prospects for increased age-structure diversity in SRWRC through harvest management.

Recommendations

1. **Genetic Diversity.** Expand the current monitoring network to include genotyping adults and recovering their progeny (juveniles and adults) so genetic relatedness among individuals can be reconstructed using PBT. A comprehensive sampling design is needed to assess the effects of water-project operations and domestication selection on reproductive success in SRWRC, given the on-going challenges with water-temperature management during periods of drought and the recent increase in hatchery production. The PBT technology is routinely used to monitor salmonids in other systems, and it is used in broodstock management for spring-run Chinook Salmon in the Feather River Hatchery within the Central Valley (Araki et al. 2007; Chilcote et al. 2011; Steele et al. 2013; Christie et al. 2014; CDFW 2016). Tissue samples currently being collected during in-river carcass surveys for SRWRC and broodstock at LSNFH serve as a ready-made library of parental genotypes for natural-origin and hatchery populations.
2. **Behavioral Diversity.** To quantify survival and the relative contribution of different juvenile rearing strategies to population productivity, develop a time-series metric of juvenile life-history diversity, migration, and habitat use by annually collecting and analyzing the otoliths of SRWRC adults from the LSNFH broodstock and in-river spawners. SRWRC juvenile otoliths collected near the city of Sacramento and Chipps Island need to be analyzed to test predictions from the NMFS life-cycle model about the proportion of SRWRC fry that rear in the upper, middle, and lower Sacramento River, the Delta regions, and the Yolo Bypass, as a function of density-dependent processes and habitat carrying capacities.
3. **Age Structure Diversity.** To increase our understanding of how age structure promotes population stability, use scales collected as part of the salmon spawning survey to create a time series of age and maturation rates in natural-origin SRWRC.

Discussion

Genetic Diversity. PBT of adult spawners would allow progeny captured in monitoring locations (juvenile and adult) to be assigned to specific parents through genetic reconstructions. The information would be used to evaluate how spawn timing, location, and origin (hatchery or wild) influence SRWRC reproductive success. For example, capturing juveniles at RBDD and analyzing their genetic tissues to trace the identity of their parents would provide an estimate of the number of females producing progeny that survive to RBDD. This information on reproductive success could then be related to information about water operations, environmental conditions at the time and location of spawning, adult condition (see Advancement 5), and origin (identified by CWT) to assess how these variables influence reproductive success. Parental reconstruction with PBT has demonstrated that second-generation fish from LSNFH successfully spawned in-river, contributing to the effective size of the natural SRWRC population (McGlauflin et al. 2011; Smith et al. 2015). Thus, PBT is recommended to assess the extent to which fitness effects occur with hatchery SRWRC that spawn in the wild, and to inform the trade-offs associated with increased hatchery production during droughts or periods of low overall population abundance. Results from this previous reconstruction, in addition to recent advancements in rapid genome assays to identify parent–offspring linkages (with only a single parent sampled), highlight the feasibility of this tool to address these management-specific questions, as well as changes in within-population diversity (Ali et al. 2016).

Behavioral Diversity. To quantify survival and relative contribution of different juvenile rearing strategies to population productivity, an annual time-series metric of juvenile life-history diversity, migration, and habitat can be developed by collecting and analyzing the otoliths of SRWRC adults from the LSNFH broodstock and in-river spawners annually. These techniques are well established and widely used (Barnett–Johnson et al. 2005, 2008; Sturrock et al. 2015; Johnson et al. 2016; Figure 13). The chemical composition and the banding patterns in otoliths record the migration history (duration of time in different habitats) and condition (growth)

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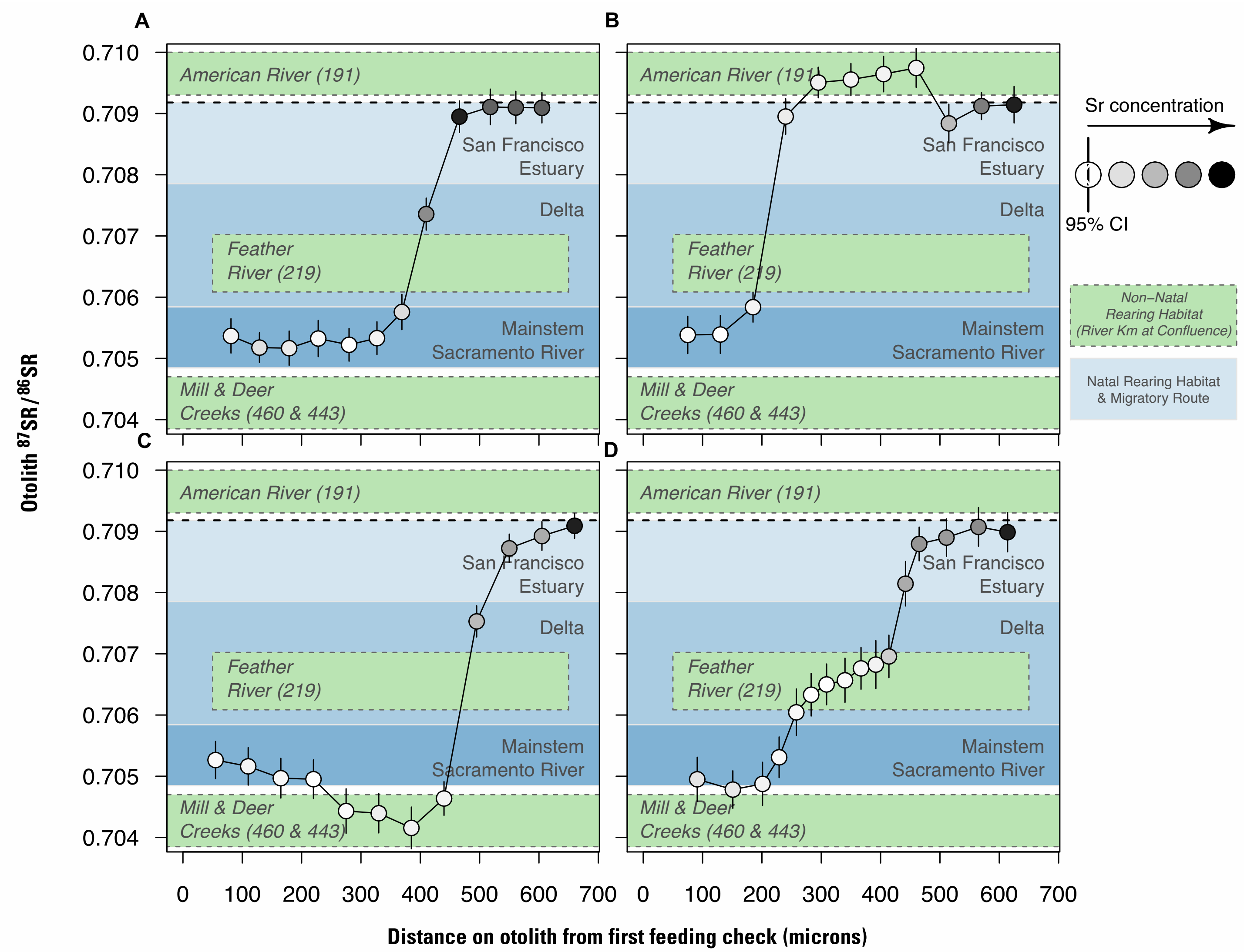

Figure 13 Examples of variation in juvenile rearing location of successful adult Sacramento River winter-run Chinook salmon (SRWRC) sampled during the 2008 and 2009 carcass surveys. $^{87}Sr/^{86}Sr$ is expressed as a function of distance from the first feeding check on the otolith, and records distinct environments the fish encounters during natal rearing and seaward migration. The average standard error on each spot measurement (60 µm diameter) is ± 0.00011. Otolith Sr concentration denoted by low (white circles), medium (grey circles), and high Sr (black circles) is used to distinguish locations with similar water $^{87}Sr/^{86}Sr$ but distinct Sr concentrations such as the American River (low Sr concentration) and the ocean (high Sr). Panels illustrate individuals that reared in (**A**) Sacramento River, (**B**) American River (**C**) Mill/Deer Creek, and (**D**) Feather River or Delta before seaward migration. Source: Phillis et al., submitted.

throughout the lifetime of a fish (Sidebar 5). Thus, archiving otoliths from adults ensures that a time-series of information can be reconstructed to reveal information about outmigration behavior and juvenile rearing success under different water year (WY) conditions. Otoliths offer a significant advantage compared to physical tags because they are not constrained to larger-sized fish and can be used to examine rearing patterns of fry that move downstream soon after emergence. The data gained on juvenile rearing strategies among years can then be related to information about water operations, environmental conditions at the time and location of rearing, and habitat carrying capacities to assess the influence of these variables on outmigration success, population productivity, and resiliency. For example,

SIDEBAR 5

Tools for Enhanced Monitoring: Otolith-based Analyses

- Calcium carbonate structure found in the inner ear of fishes used for balance, movement, orientation, and sound detection (Popper and Fay 1993; Oxman et al. 2007)

Key Benefits

- Permanent record of age, growth, diet, and chemical environment over fishes' lifetime
- Can be sampled from spawned carcasses (non-lethal sampling)
- Natural tag that records origin and movement patterns during young life stages too small to physically tag

Application Examples

- Chemical analyses used to reconstruct migration patterns (Sturrock et al., 2015), population of origin (Barnett–Johnson et al. 2008; Johnson et al. 2016), and diet (Weber et al. 2002)
- Alaska hatcheries "thermally mark" fish by varying temperatures in unique patterns visibly recorded in otoliths (Scott et al. 2001)
- Freshwater growth rates linked to higher ocean survival (Woodson et al. 2013)

it is unclear the extent to which drought conditions may have truncated diversity in outmigration behaviors (e.g., created limited suitable habitat options), or if rearing behavior or habitat types (e.g., tributary or Delta-rearing) may have provided critical refuges to salmon migrating downstream during the drought (Figure 13).

Comparison of adult otolith analyses with size and abundance estimates of juvenile SRWRC collected near the city of Sacramento and Chipps Island from that cohort (see Advancements 1 and 2) would be particularly useful to understand the fate of juveniles too small to be acoustically tagged, as is the case for most in-river-produced SRWRC that enter the Delta. In fact, the NMFS SRWRC life-cycle model predicts the proportion of SRWRC fry that rear in the upper, middle, and lower Sacramento River, the Yolo Bypass, and the Delta as a function of density-dependent processes and habitat carrying capacities, which vary with annual flows. These predictions could be tested, and the model refined, by analyzing otoliths of juveniles collected at Sacramento, CA or Chipps Island to reveal the duration of time spent rearing in habitats in these different geographic regions. In addition, comparing the abundance and size distributions of juvenile SRWRC that entering the Delta to their representation in the adult returns yields a survival estimate for fry-sized SRWRC that reared in the Delta (Sturrock et al. 2015; reviewed in Perry et al. 2016). Otoliths have been collected from SRWRC carcasses and broodstock at the LSNFH intermittently. However, we recommend the collection and analysis of otoliths as part of a core monitoring and tissue archive program focused on juvenile life-history diversity.

Monitoring patterns and consequences of habitat use are fundamental in informing effective restoration efforts. A complementary approach to the otolith reconstructions recommended above to assess the lifetime survival and habitat use of SRWRC too small to acoustically tag (Advancement 3), is to tag representative sizes of juveniles with PIT tags throughout the monitoring program or within specific restoration sites. For example, only 8% of the juvenile salmon collected at Knights Landing RST were >80 mm (the approximate size cutoff for current Juvenile Salmon Acoustic Telemetry System, JSAT, acoustic tags), and 58% met the size threshold for PIT tags (>40 mm for 8-mm tags; Tiffan et al. 2015) in 2011, 2012, and 2014 (CDFW, unreferenced, see "Notes"; Table 3). Many juvenile SRWRC-sized fish can be sampled for genetic tissue (run ID; Advancement 1) and, because PIT tags are not limited

Table 3 Total number and % of catch of different size classes of juvenile salmon from all upstream Sacramento River salmon populations sampled at the Knights Landing Rotary Screw Trap. We estimated that fish greater than 80 mm are individuals that could carry Juvenile Salmon Acoustic Telemetry System (JSATs) tags, while fish >40 mm would be candidates for passive integrated transponder (PIT) tags. Data source: Daniel Martinez, CDFW.

Year	Fish > 80 mm Acoustic tag total (%)	Fish > 40 mm PIT tag total (%)
2011	462 (8%)	2484 (45%)
2012	917 (11%)	4780 (55%)
2014	420 (6%)	5235 (75%)

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by battery life, tags can possibly be recovered later in downstream monitoring surveys, or upon return in adult carcass surveys, or at the LSNFH. Hand-held PIT-tag readers can be used at any monitoring location where fish are handled to identify the unique code of each PIT tag. Passive detections can occur where antennae are deployed on monitoring gear or structures (e.g., salvage facilities and fish ladders such as those at the Anderson Cottonwood Irrigation District's diversion). Linking the meta-data on the size and location of juveniles PIT-tagged in the monitoring network with adult returns provides estimates of survival from the juvenile-to-adult life stage for the different sizes of outmigrants (fry, parr, smolts), although this technology has not been applied broadly to salmon in the Central Valley as it has elsewhere (e.g., ISAB 2016).

A recent feasibility study suggests that along with existing PIT-tag antennas, new designs now make it technically possible to detect tags in Delta channels (Rundio et al. 2017). However, Rundio et al. (2017) notes that further research and development is needed to refine several aspects of the new array designs so the hydrofoil antennas achieve full electrical performance in water, and to identify study designs and analytical approaches that accurately estimate detection probability, survival, and abundance from PIT-tag detection data produced by arrays in open channels.

Age Structure Diversity. Age-2 spawners are uncommon in SRWRC, particularly for females (O'Farrell et al. 2012; Satterthwaite et al. 2017). Yet, in brood year 2016, an anomalously high number of age-2 spawners (40%) were observed, and these included females with lower fecundity than age-3 females (Killam et al. 2016; CDFW 2016). This increased contribution of age-2 spawners could result from a shift in maturation rates caused by extreme environmental conditions because of the drought and aberrant ocean conditions, or could simply be an artifact of the three-fold increase in hatchery production and return of hatchery fish. A shift in maturation rates toward younger spawners could affect overall egg production, but may also increase the diversity of ages represented in the population.

ADVANCEMENT 5: Develop and Collect Metrics of Fish Condition, Including Disease Prevalence

Background

SRWRC rearing occurs in many different locations, and understanding which habitat characteristics inhibit or support survival into future life stages is essential to assess the benefits of addressing limiting factors at any one location. Fish-condition metrics (pathology, energy reserves, and growth rates) are useful to understand habitat effects in specific areas of concern, and cumulatively across life stages and regions, but these metrics are not currently routinely monitored anywhere in the Central Valley network (Figure 1). Understanding abundance and survival within the context of condition provides information needed to assess how stressors experienced in one life stage or habitat influence recruitment to subsequent life stages, and provides insights into the overall health of a population in a given year (MacFarlane 2010; Woodson et al. 2013).

Habitat restoration is likely to be one of the major regional changes to the Central Valley landscape for juvenile salmon in the coming decades. A desired response from restoring juvenile rearing habitats is increased fish growth and energy reserves, which correspond to increased survival in the ocean (Duffy and Beauchamp 2011; Woodson et al. 2013). Evidence from within the Central Valley demonstrates that salmon reared on floodplains experience accelerated growth relative to individuals reared in more channelized habitats (Sommer et al. 2001). Throughout the Delta, restoring shallow water habitats is expected to be important for fry migrants, depending on the response of the warm water predator community. In the Columbia River estuary, for example, 32% to 45% of juvenile salmon sampled in shallow water habitats had entered the estuary soon after emergence (Bottom et al. 2012). Metrics of juvenile conditions and abundance are needed across a range of environmental conditions measured pre- and post-habitat restoration at restored and unrestored locations, as well as at mainstream river segments. Delta entry and exit could be used in conjunction with life-cycle models to assess the success of restoration efforts at the population level.

Condition can be generally categorized by nutritional indices (stomach fullness, liver glycogen, concentrations of triglycerides in the muscle), growth proxies (RNA–DNA ratio and 10-day otolith increment), morphometric characteristics (Fulton's condition factor and hepatosomatic index), and physiochemical and contaminant stress (elevated liver and gill histopathology indices; Sidebar 6). In Delta Smelt, Hammock et al. (2015) used suites of indices across levels of biological organization (cellular, organ, individual) to assess fish condition at temporal scales ranging from hours to weeks to understand short-term habitat-specific condition and longer-term cumulative condition across life stages and habitat regions. For example, stomach fullness, RNA–DNA ratios, and plasma insulin-like growth factor-I reflect recent foraging success and short-term nutritional status (Buckley 1979; Beckman et al. 1998; MacFarlane and Norton 2002). Lipid dynamics, and especially the level of triglycerides, are a useful metric to assess the amount of energy reserves present in juvenile fishes, which may be an important determinant of ocean survival, especially in years where ocean conditions are poor (Lindley et al. 2009; MacFarlane 2010). Also, otoliths can be used to reconstruct fish growth rates throughout their lives and provide information on size-at-age (Neilson et al. 1985; Limm and Marchetti 2009; Miller et al. 2013; Woodson et al. 2013).

Recommendations

1. Additional research is needed to identify which condition metrics for monitoring SRWRC are the most informative, logistically feasible, and cost-effective. This additional research is needed to select the best metrics to incorporate into system-wide monitoring program by life stage.
2. The pathogen load should be monitored in individual SRWRC and water samples during the summer and fall in the Upper Sacramento River. Disease mortality (Windell et al. 2017, CMs 1 and 2) is one of multiple factors that may be involved in the high inter-annual variation in egg-to-fry survival for SRWRC likely linked to water temperatures (Figure 5); it is important to identify zones and periods of high virulence, as is routinely done in the Klamath Basin (qPCR; Sidebar 7).

Discussion

Two endemic myxozoan parasites, *Ceratonova shasta* and *Parvicapsula minibicornis*, have been associated with a high incidence of disease in juvenile salmon from the Feather and Klamath rivers. The parasites were also detected in all runs of adult salmon and juvenile fall-run Chinook Salmon sampled in March and April in the Sacramento River (USFWS 2016). Pilot study efforts initiated in 2015 indicated that 15% of SRWRC juveniles sampled at RBDD showed signs of early infection by *C. Shasta*. Similarly, 86% and 94% of sentinel late-fall Chinook Salmon caged at RBDD and Balls Ferry (locations relevant to SRWRC rearing) showed severe infection by both parasites, suggesting that disease was a possible cause of high early life-stage mortality (USFWS 2016). Notably, pathogens caused a high level of pre-spawn mortality (27%) for the SRWRC broodstock at the LSNFH in 2015 (Voss and True 2016). In the Klamath River, where water project operations influence disease outbreaks linked to salmon mortality, extensive monitoring of *C. shasta* and *P. minibicornis* is routine (Hallett et al. 2012; Ray et al. 2012, 2014). *C. shasta* is a progressive disease, and fish along the monitoring network need to be evaluated over time because early-stage infections could progress to a diseased state over time (Bartholomew et al. 2007; True et al. 2013).

Returning adult salmon have a fixed amount of somatic energy to accomplish an energetically demanding salt-to-freshwater transition, spawning migration, pre-spawning holding, and spawning. Thus, their lifetime fitness depends on physiological condition and health during the spawning migration. The extent to which an adult's condition can buffer and defend against susceptibility to deleterious diseases can vary considerably (reviewed in Cooke et al. 2012). Recent work that couples telemetry with biomarkers in sockeye salmon (*Oncorhynchus nerka*) revealed that early measures of adult physiology and disease in the ocean, at mouths of rivers, and on the spawning grounds can predict the rate of migration failure. This early physiology monitoring could be a useful approach in predicting how adult stranding in the flood bypasses affects migration success (Cooke et al. 2006; Crossin et al. 2009).

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In summary, although including condition metrics within regular SRWRC monitoring at all life stages is needed, these condition metrics must be explored further to identify those most important to specific regions or life stages. For example, in the Upper Sacramento River egg-to-fry phase, pathogens and disease may be important to monitor, while in the Middle River and tidal estuary, juvenile growth and energy reserves may be most appropriate. Combining short- and long-term stress indicators may also be needed to differentiate acute effects from cumulative, sub-lethal effects.

ADVANCEMENT 6: Provide timely public access to monitoring data in open data formats

Background

Core monitoring data are incredibly valuable, but only if they are of high quality, available in a format easily accessible for scientific analyses, and provided in a timely manner relevant to their use in management decisions and scientific analyses. Much of SRWRC monitoring data in the Upper and Middle Sacramento River remain publicly unavailable (Table 2). Indeed, the primary method for acquiring data is through contacting an agency lead who stores data on a local computer. Information is sometimes disseminated via an email list-serve of interested parties or summarized in annual reports, with reporting sometimes delayed by years. This approach often requires data to be manually extracted from multiple reports into a database before it is analyzed (Pipal 2005), which impedes efficient and timely use of scientific information to inform management, and allows for transcription errors.

Recommendation

All entities that provide core monitoring data for SRWRC should make their data available in a timely manner and provide them in a format that can be integrated into data-aggregating websites. This would require establishing a time-series of monitoring data for key locations, and updating the websites or data portals as new data are collected.

SIDEBAR 6

Tools for Enhanced Monitoring: Condition Indices

- Nutritional indices (stomach fullness, liver glycogen, concentrations of triglycerides)
- Growth proxies (RNA–DNA ratio, otolith increment widths)
- Morphometric characteristics (Fulton's condition factor, hepatosomatic index)
- Disease and physiochemical contaminant stress (elevated liver and gill histopathology indices, biomarkers)

Key Benefits

- Suites of indices assess condition during short temporal scales (hours to weeks) and longer-term cumulative condition (Hammock et al. 2015)
- Identifies foraging success and nutritional reserves (Beckman et al. 1998; MacFarlane 2010)

Example Applications

- Otolith-derived growth rates during freshwater rearing explain variability in salmon ocean survival (Woodson et al. 2010)
- Condition indices across levels of organization (cellular, organ, individual) for Delta Smelt varied among Delta regions (Hammock et al. 2015)

Discussion

Previous efforts have attempted to standardize salmon data collected by multiple agencies in the Central Valley (Honey et al. 2004; Pipal 2005; USFWS 2010). However, significant lags and institutional barriers exist when making monitoring data available to the scientific community, resource managers, and the public in a consistent and timely fashion. Challenges exist because of the multiple entities responsible for sampling in different geographic regions; variation in individual agency policies on data ownership, access, and availability; a lack of consensus on how to make data publicly available; a general disconnect among data collectors and data users; and failure to keep pace with rapidly advancing computer technologies.

Recently, making data available to the public has been increasingly emphasized, and explicit policies to do so have been developed (Federal M-13-13

SIDEBAR 7

Tools for Enhanced Monitoring: Quantitative PCR (qPCR) for *C. shasta*

- Used to identify *Ceratonova shasta* (True et al. 2013), a microscopic parasite that causes intestinal necrosis in salmonids

Key Benefits

- Identifies exposure hotspots (Bartholomew et al. 2007; Stocking and Bartholomew 2007) and infection mortality thresholds
- Informs models to predict daily survival rates based on prevalence of infection (Ray et al. 2014)

Example Applications

- Used since 2006 in Klamath River basin
- *C. shasta's* intermediate host linked to water quality and habitat features on the main-stem Klamath below the Iron Gate Dam, termed the "infectious zone," providing managers with a target region and population for management
- Infection causes significant mortality (Stocking et al. 2006)

Open Data Policy; California AB-1755 Open and Transparent Water Data Act). One successful model for data access and availability for salmon monitoring data comes from the Columbia River Basin, where entities that collect data make it available on their agency's website, and the data are brought in daily (from federal, state, and tribal databases) through aggregating software to provide a comprehensive and readily accessible database (Columbia Basin Research, Data Access in Real Time [DART]). This website hosts current and historical environmental and biological data, which are publicly available, and used to inform daily and seasonal hydro-electric power operations, provide alerts when salmon populations may be exposed to unfavorable conditions (observed or forecasted), and conduct scientific analyses.

To accelerate the use of monitoring data to inform management decisions and scientific analyses, Bay–Delta Live (*http://www.baydeltalive.com*) and SacPAS (*http://www.cbr.washington.edu/sacramento/*) are emerging as data-aggregating websites for the Central Valley, but they require that data first be made available. Data collectors and data users should meet and discuss the feasibility and utility of the temporal scale of reporting (e.g., daily, weekly, monthly, seasonally, and annually) for each key data set and monitoring location. For example, some data may be most valuable (and reliable) when summarized annually, and other data may be useful for daily decision-making.

VALUE OF MONITORING IMPROVEMENTS FOR MANAGEMENT

Numerous management actions throughout the Central Valley, Delta, estuary, and ocean can influence fish demographic responses, including the timing and magnitude of water releases from reservoirs, harvest regulations, habitat restoration, hatchery practices, and water exports from the Delta. The actions influence demographic responses through their effects on abundance, timing of outmigration, fish condition, and life-history diversity at different life stages and geographic regions (Windell et al. 2017). Assessing these and other management actions will require fish responses to experimental manipulations to be measured, site-specific monitoring, and/or integrating the information into predictive tools such as life-cycle models. Expanding the current monitoring enterprise to enhance quantitative assessments of changes in SRWRC responses over time is feasible and foundational to advancing sound science-based management decisions in the Central Valley and to supporting effective water management and resilient salmon populations.

KEY MANAGEMENT ISSUES

We present the following six outstanding issues to describe the value to management of improving the monitoring network for SRWRC. These issues could be addressed if a robust time-series of true genetic SRWRC abundance was available, along with measures of fish condition. These issues are examples of how information from an expanded and better-integrated monitoring network could help manage water resources, restore habitat, and recover Central Valley salmon and steelhead. In

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summary, implementing the advancements and recommendations presented above would:

- Provide an annual status of number of successful spawners, juvenile SRWRC productivity, habitat use, and overall health of the cohort entering the ocean
- Generate robust estimates of juvenile SRWRC abundance at key locations system-wide, and allow survival among years and environmental covariates to be evaluated to identify key factors that influence juvenile production
- Identify locations and life stages where cohort strength is being reduced each year, and identify potential management actions to address the reduction
- Provide an annual depiction of the spatial variability in juvenile and adult SRWRC health and condition
- Generate empirical abundance estimates of juvenile SRWRC entering the Delta, which would refine current methods used to permit "take" at the Central Valley Project and State Water Project water export facilities
- Provide early indicators of annual cohort strength that could be used to adjust ocean harvest regulations to reduce effects on weak year classes of SRWRC
- Support real-time water project operations
- Monitor the effectiveness of habitat restoration actions over time
- Provide empirical data to set parameters for and/or test predictions from life-cycle models

ISSUE 1: *What are the effects of floods and droughts on the number and condition of SRWRC that enter the ocean?*

Natural-origin SRWRC experienced anomalous in-river temperatures and ocean conditions during the 2013 to 2016 drought, followed by the wettest year on record (WY 2017). With the current monitoring, how many (Advancement 2) natural-origin genetic SRWRC (Advancement 1) are produced from the freshwater landscape downstream of RBDD, where they are rearing (Advancement 4), and their condition (Advancement 5) remain unclear. Significantly, the number of juvenile SRWRC that entered the ocean each year remains unknown, which prevents the influence of freshwater versus marine conditions on adult returns each year from being assessed. Similarly, there is no information on whether the abundance and condition of SRWRC leaving freshwater in 2014 to 2016 (drought conditions) was higher or lower than other years (e.g., WY 2017; flood conditions) or under previous drought conditions.

Otolith reconstructions can inform the extent to which adults that survived the drought as juveniles exhibited certain rearing behaviors (Advancement 4) or used specific habitats (e.g., non-natal tributary or Delta rearing) that may be critical to growth (Advancement 5) during droughts. Similarly, otoliths can also inform how habitats that are available for juvenile rearing in wetter years (e.g., off-channel habitats such as floodplains) influence rearing behavior, growth, and relative survival to adulthood in comparison to drier years. Annual measures of through-Delta survival, coupled with environmental conditions (Advancement 3), would provide comparable annual metrics of SRWRC survival among years, as well as information on specific geographic domains associated with elevated mortality and environmental covariates. Understanding how SRWRC juveniles use the freshwater landscape among different hydrologic regimes will become increasingly important with climate change projects that anticipate an increase in extreme conditions (Cloern et al. 2011).

ISSUE 2: *Should the ocean mixed-stock salmon fishery be further constrained to protect SRWRC?*

Currently, the harvest control rule specifies maximum allowable ocean fishery impact rates based on the geometric mean of the previous 3 years of SRWRC escapement. When the geometric mean falls below 500 SRWRC spawning adults, the allowable impact rate is zero, which would result in the closure of mixed-stock ocean salmon fisheries south of Point Arena, California. However, the relationship between production of SRWRC at RBDD and adult returns is highly variable, likely because of variability in downstream and early ocean survival (Windell et al. 2017, CM 2 through CM 6). Developing genetic-based SRWRC abundance estimates at Chipps Island (Advancements 1 and 2) will allow for a more accurate measure of SRWRC juvenile year-class strength. Combining the more accurate measure of SRWRC juvenile year-class strength, the general condition of juvenile SRWRC entering the ocean (Advancement 5), and coastal ocean ecosystem metrics will allow relationships among juvenile production, ocean survival, and adult SRWRC abundance in the ocean to be developed over time. These relationships can then be used to evaluate harvest control rules that manage the mixed-stock fishery to better protect SRWRC during periods of poor environmental conditions. Thus, improved monitoring in freshwater can substantially inform mixed-stock fishery and harvest management.

ISSUE 3: *Is the Delta an important contributor to SRWRC adult abundance and stability in returns?*

Current monitoring suggests that many winter-run-sized fish pass Knights Landing at small sizes and reside in the Delta for 41 to 117 days before they exit the Delta at Chipps Island (del Rosario et al. 2013). Yet, evidence suggests that longer Delta residence times lead to higher mortality rates in salmon smolts (Perry et al. 2010; Michel et al. 2015). It is conceivable that Delta rearing for SRWRC is an important and successful strategy because they historically used these habitats, and they enter the habitat under cooler winter temperatures when predator metabolism is lower (Yoshiyama et al. 1998). It is equally conceivable that although many enter the Delta at small sizes, the individuals captured leaving the Delta in the spring represent fish that reared predominantly in the Upper or Middle Sacramento River and rapidly transited the Delta, while those that entered the Delta at smaller sizes perished. The use of otolith reconstructions to estimate the proportion of adults that successfully reared in the Delta can serve as a monitoring metric on inter-annual variation in the success of this life-history strategy (Advancement 4). This metric coupled with abundance estimates of SRWRC that enter and exit the Delta annually (Advancement 1 and 2) will provide currently unavailable information on the variability in mortality of wild SRWRC in the Delta. Identifying regions and timing of successful Delta rearing could trigger additional condition monitoring to understand habitat quality and growth thresholds for long-term survival. This is needed to set habitat-restoration goals, identify habitat-restoration actions, and focus habitat-restoration funds on critical geographic areas where carrying capacities may be limiting productivity.

ISSUE 4: *How can monitoring abundance of juvenile SRWRC near the city of Sacramento improve "take" estimates at the Central Valley and State Water Projects?*

The juvenile production estimate (JPE) of the number of SRWRC that enter the Delta is used to determine the allowable annual "take" (loss) of natural-origin SRWRC at the water export facilities. The NMFS Biological Opinion (NMFS 2009) allows the export facilities to "take" 1% of the natural production of SRWRC that enter the Delta. Currently, a key component of the JPE calculation is the estimated (assumed) survival of juveniles from RBDD to the Delta, which has been difficult to quantify for most SRWRC that leave at smaller sizes because they are too small to be acoustically tagged. The JPE calculation relies on measurements of: 1) abundance of natural- and hatchery-origin adults that spawn in-river using the Cormack–Jolly Seber model (Bergman et al. 2012; Killam et al. 2014); 2) annual sex ratios obtained from the trap in Keswick Dam; 3) pre-spawn mortality of females estimated from carcass surveys; 4) total number of viable eggs (based on the average fecundity of females spawned at LSNFH multiplied by number of females (excluding pre-spawn mortality); and 5) abundance of juveniles passing RBDD. By dividing the number of fry estimated at RBDD by the number of viable eggs laid, an estimate of egg-to-fry survival and juvenile passage (using an estimate of fry equivalency for smolts) can be generated (Poytress 2016; Figure 5). The estimate of juveniles at RBDD is then multiplied by the estimated survival to the Delta to estimate the production of wild winter-run that enter the Delta (JPE).

The estimate of survival to the Delta is uncertain, and because survival is multiplicative, the assumed

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value plays a large role in the estimate (CDFW 2016). An abundance estimate of genetic SRWRC (Advancements 1 and 2) would provide a more direct estimate of the JPE. An empirical estimate of natural-origin SRWRC abundance at the city of Sacramento could improve the management of the water export facilities because the "take" would be placed in the context of the actual abundance of SRWRC that enter the Delta, rather than JPE estimates derived using data from unverified assumptions. In addition, the measured abundance of SRWRC at the Sacramento trawl could be used to calculate survival estimates from RBDD to the Delta, the primary data gap in the current JPE estimate.

ISSUE 5: *How can the core monitoring improvements be used to support life-cycle and decision-support models?*

To date, many life-cycle models and predictive tools have resorted to laboratory and empirical data from outside the Central Valley. Specific monitoring data on wild and hatchery SRWRC will lead to tools that more accurately reflect the unique growth patterns, habitat use, and population dynamics of SRWRC. These data can be used to calibrate life-cycle models in the near term to improve their ability to predict long-term habitat restoration, water management, population recovery, and harvest planning efforts with greater certainty. Acoustic telemetry data have been central to the parameterization of the NMFS SRWRC life-cycle model by providing reach-specific survival estimates, routing behaviors, and smolt migration rates as a function of freshwater flows. Information on flow–survival and movement relationships for multiple runs of salmon in conjunction with other water-quality measurements and environmental co-variates (Advancement 3) are necessary to support salmon life-cycle modeling. Empirical data on abundance and condition across the monitoring network can be used to parameterize the life-cycle model and evaluate how increases in higher-quality habitat (e.g., restoration at particular locations for a specific life stage) influence SRWRC population dynamics. The improved strategies to estimate survival and real-time data availability (Advancements 3 and 6) can be used in the near term to support predictive modeling and realtime decision-making. Fundamentally, to inform decisions on how to prioritize management actions, life-cycle models are required to integrate how changes in management actions across the multiple salmon life stages produce population-level changes. Testing the predictions of quantitative demographic metrics is foundational to life-cycle model development and application.

ISSUE 6: *What are the population-level benefits of restoration efforts at different life stages and geographic locations?*

One of the greatest challenges in recovering salmon is understanding where to focus restoration efforts to have the greatest population-level benefit, because of limited information on where and under what conditions in the life-cycle habitat quantity or quality limits productivity. Further, it is unclear how increasing habitat at one life stage may interact with and influence survival at consecutive life stages and regions. Many projects aimed to restore healthy salmon populations have been identified across different salmon life stages in riverine and tidal habitats (e.g., NMFS 2014; USFWS 2015; EcoRestore [*http://resources.ca.gov/ecorestore/*]). Implementing the monitoring recommendations discussed above provides the data required to evaluate the likely population-level benefits of different life-stage and geography-focused restoration scenarios using a life-cycle model to prioritize actions.

CONCLUSIONS

Recovering endangered SRWRC requires understanding how changes in management actions at relevant life stages and locations influence population status over time. A life-stage monitoring network that provides quantitative demographic information that is comparable among years is critically needed, given the current status of the species, and the highly variable freshwater and ocean hydroclimatic regimes in California that are projected to increase in frequency in the future. The proposed advancements outlined above focus on the need to develop quantitative fish demographic metrics across multiple life stages and geographic domains; the specific methods to achieve these recommendations are anticipated to evolve as the proposed technologies continue to advance.

Monitoring alone will not recover salmon. Although a life-stage monitoring program is critical for tracking SRWRC status and trends, additional investments in modeling to develop and test predictions and adaptive management experiments will be required to address many outstanding management questions for SRWRC in the Central Valley. Implementing the additional monitoring identified in the six advancements described above will: (1) improve the overall value of the existing core monitoring data for management decisions; (2) generate annual quantitative, population-relevant metrics at key life stages and geographic domains; (3) enable these quantitative, population-relevant metrics to be used to improve SRWRC management through the timing and magnitude of reservoir releases, harvest management, habitat restoration, and hatchery practices, based on an improved understanding of SRWRC responses to environmental conditions at key life stages and locations; and 4) advance science-based management decisions, synthesis efforts, and life-cycle model and decision-support tool development.

When the recommended quantitative metrics become available, the CMs developed for each life-stage domain can be used as a guiding framework to test hypotheses on mechanisms that influence fish responses (Windell et al. 2017). Using this framework will ensure adequate environmental monitoring is in place to assess the efficacy of management actions that occur in specific geographic domains on the abundance, survival, outmigration timing, and life-history diversity of SRWRC. For example, quantitative data exist on the abundance of adults and juveniles past RBDD in the Upper Sacramento River. Therefore, the Upper Sacramento River CM can now be used to develop focused studies and more fine-scale monitoring (e.g., establish monitoring immediately downstream of the SRWRC spawning area) to understand mechanisms and hypotheses that may contribute to variation in annual egg-to-fry survival (Windell et al. 2017, CM 1; Martin et al. 2017). This framework is particularly relevant given that most SRWRC mortality (74%, average from 1996 to 2016) occurs within 50 miles upstream of the RBDD monitoring location (Poytress 2016).

Our proposed six, system-wide advancements are feasible and applicable across multiple salmon runs. Many of the recommendations can be implemented within the existing monitoring enterprise to significantly increase the science and management value with relatively small increases in investment, and others may require increased budgets. For example, collecting additional information/tissues from fish encountered in the existing sampling program — such as genetic tissues (Advancement 1), otoliths (Advancements 3 and 5), condition (Advancement 5), or tagging (Advancement 4) — is relatively cost-effective. Other recommendations may be achieved by applying innovative approaches (e.g., multi-state gear efficiency model) to bolster the results of existing studies or management efforts (Advancement 2). Other advancements, such as monitoring fish survival with acoustic telemetry technology, have been partially implemented during the past decade by various funding entities and researchers. The cost to expand the program to a real-time acoustic telemetry monitoring tool — to include multiple species, increased sample sizes, deployment and maintenance of real-time receivers year-round with water quality stations, modeling support to convert detections into survival probabilities, and in-season reporting—will be higher than today (Advancement 6). However, the benefits from expanding the program are large and certain, because such expansion anticipates the need for science to support current and future management decisions. For example, the temporal and spatial resolution of this monitoring metric (reach-specific survival) can be used to develop a through-Delta survival standard for multiple salmon runs, and to track changes in survival as a function of the operations at a north-of-Delta diversion, modifications to the Fremont Weir, and tidal habitat restoration.

Implementation of these advancements will build on the existing monitoring network and make the information currently obtained more valuable and useful for informing water management and conservation actions. Implementing the advancements would generate data within the first year of implementation, and document cohort strength through time and across space. Data collected over multiple years would begin a quantitative time-series of key metrics that will increase in value the longer they are collected (Hughes et al. 2017). They would

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would also provide among-year comparisons of scientific and management relevance, not the least of which is the ability to disentangle freshwater from marine sources of salmon mortality. With expanded environmental and biological monitoring in place, key management issues, such as the six described above, can be addressed.

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