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RESEARCH ARTICLE

Decision analysis for greater insights into the development and evaluation of Chinook salmon restoration strategies in California's Central Valley

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Considerable resources have been invested in ecological restoration projects across the globe to restore ecosystem integrity. Restoration strategies are often diverse and have been met with mixed success. In this article, we describe the Chinook salmon (*Oncorhynchus tshawytscha*) decision-support models developed by the Central Valley Project Improvement Act Science Integration Team as part of a larger structured decision-making effort aimed at maximizing natural adult production of Chinook salmon in California's Central Valley, the United States. We then describe the decision-analytic tools the stakeholder group used to solve the models and explore model results, including stochastic dynamic programming, forward simulation, proportional scoring, relative loss, expected value of perfect information, response profile analyses, and indifference curves. Using these tools, the stakeholder group was able to develop and evaluate restoration strategies for multiple Chinook salmon runs simultaneously, a first for the restoration program. We found that actions targeted at one run were detrimental to others, which was unexpected. Furthermore, information uncovered during this process was used to direct efforts towards targeted research/monitoring to reduce critical uncertainties in salmon demographic rates and make better restoration decisions moving forward. The decision sciences have established a wide range of analytical tools and approaches to simplify complex problems into key components, and we believe the concepts described in this article are of great interest and can be applied by many restoration practitioners that undoubtedly face similar difficulties when implementing restoration strategies for complex systems.

Key words: decision-support model, habitat restoration, *Oncorhynchus tshawytscha*, stochastic dynamic programming, structured decision-making, value of perfect information

Implications for Practice

- Restoration ecology practitioners are increasingly using models to help guide restoration priorities and actions. These efforts will have greater insights and success if they utilize quantitative decision analysis tools.
- Decision-analytic tools allow managers to identify factors that largely drive restoration decision-making helping them focus on those aspects of the restoration that are most important and providing the basis for simplification of complex problems.
- Sensitivity analysis measures, such as the value of perfect and imperfect information, provide a common currency for evaluating trade-offs between research, monitoring, and restoration.

Introduction

The loss of global biodiversity and ecosystem integrity over the past century has been largely attributed to the degradation and damage to ecosystems caused by human land development and resource exploitation. To address these declines, the field of restoration ecology was established in the 1980s (Young et al. 2005). Since then, considerable effort has been expended on restoring ecosystems throughout the globe. The Society for Ecological Restoration's project voluntary database documents more than 240 restoration projects worldwide with 45% in North America (SER 2020). These efforts have resulted in billions of dollars in economic impact to local and regional economies (Nielsen-Pincus & Moseley 2013; BenDor et al. 2015).

Despite the widespread implementation of restoration, there is considerable variation in restoration approaches and

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disagreement on the best (Matzek et al. 2017). At its core, ecological restoration includes management objectives, candidate actions intended to achieve those objectives, and models (e.g. conceptual, heuristic, quantitative) to evaluate candidate actions prior to implementation. The decision sciences have developed a variety of analytical tools and formalized an approach to decision-making that has been recently adopted for natural resource management (e.g. structured decision-making [SDM], Conroy & Peterson 2013). Although there are several excellent examples of decision-analytic approaches to inform restoration decision-making (e.g. Kozak & Piazza 2015; Martin et al. 2018), few of these took full advantage of the decision-analytic tools available.

Anadromous fish restoration in California's Central Valley, United States, is a typical example of a long-term, large-scale ecological restoration. Chinook salmon (*Oncorhynchus tshawytscha*) were once abundant throughout the watershed and included four seasonal runs that once supported economically and culturally significant fisheries (Yoshiyama 2007). However, mining, land development, river impoundment and fragmentation, and water use over the past century have led to widespread habitat degradation and fragmentation (Cummins et al. 2008). These changes have, in part, resulted in significant declines in Chinook salmon and other anadromous fishes. In response to the observed declines, the U.S. Congress passed the Central Valley Project Improvement Act (CVPIA) in 1992. The legislation directed the Department of Interior (DOI) to make "all reasonable efforts" to sustain a doubling of the number of naturally produced [adult] anadromous fishes in the Central Valley by 2002. The CVPIA fisheries program is among the largest anadromous fish restoration programs in the world, with funding in excess of \$25 million annually (Cummins et al. 2008). To achieve the doubling goal, the program began restoration efforts focused on screening water diversions, reducing stream temperatures, increasing flows, improving fish passage, and restoring stream and riparian habitats. Unfortunately by 2002, the doubling goal was not achieved and remains unfulfilled today.

In response to a perceived lack of progress towards the doubling goal, the DOI initiated an independent science review of the CVPIA Fish Resource Area Activities. The review identified the need to develop a new comprehensive, science-based approach to restoration that explicitly links activities with program objectives (Cummins et al. 2008). This motivated the initiation of an SDM process in 2013. Since its inception, a group of stakeholders—known as the Science Integration Team (SIT) (Science Integration Team 2002)—have met bimonthly to participate in the SDM process that includes identifying objectives and decision alternatives, developing decision-support models (DSMs), and conceiving restoration strategies. The SIT uses a wide variety of decision-analytic tools to develop and evaluate candidate restoration strategies; identify key uncertainties; estimate the value of future monitoring and research; and develop monitoring priorities. Here, we describe the Chinook salmon DSMs developed by the SIT and highlight the uses of decision-analytic tools to facilitate the development of more efficient and effective restoration strategies. We focus primarily on the quantitative aspects of SDM rather than the process itself. Our objectives are to:

(1) introduce the Chinook salmon DSMs;
(2) identify optimal Chinook salmon restoration policies;
(3) evaluate alternative restoration strategies; and
(4) identify key uncertainties and estimate the value of conducting further research or monitoring.

Methods

Management Area

The Central Valley watershed is located in California, and is comprised of three main drainage systems encompassing 160,000 km^2; the Sacramento, San Joaquin, and Tulare river basins. The majority of the runoff in the Central Valley flows through the Sacramento and San Joaquin rivers and they join to form the Sacramento-San Joaquin River Delta. The spatial extent of the decision problem comprised the Sacramento and San Joaquin rivers, their major tributaries, the delta, and the major tributaries draining into the delta. Within each tributary, the uppermost extent for candidate management actions was defined as the upper limit that could be currently accessed by anadromous fishes. The Sacramento River below Keswick Dam was subdivided into four sections delineated by Red Bluff diversion, the Feather River confluence, the American River confluence, and Freeport, CA (Fig. 1). The San Joaquin River included the segment of river from the Merced River confluence to Vernalis, CA. The delta was bounded to the north at Freeport, Vernalis to the south, and Chipps Island to the west and included the Yolo Bypass and Colusa Basin Drain. The delta was subdivided into 13 subregions to facilitate the modeling of juvenile Chinook salmon that are routed through the delta (Fig. 1). The spatial extent of the model also included Sutter Bypass located east of the Sacramento River below Butte Creek. The spatial grain of the model consisted of individual tributaries, the segments of the Sacramento and San Joaquin rivers, the bypasses, and the delta subregions.

Model Overview

The Chinook salmon DSMs were stochastic stage-based models that tracked the number of Chinook salmon in six groups that include four juvenile size classes: small, <42 mm total length; medium, 42–72 mm; large, 72–110 mm; and very large, >110 mm and adult stages natural and hatchery origin (Fig. 2, top). The DSMs operated on a monthly time step and simulated 20 years. Transitions between stages were estimated using submodels that predicted survival, growth, and movement as functions of input parameters (Supplement S1) that represented conditions in the bay, delta, migratory corridors, and natal tributaries. The DSMs were developed by the SIT for fall-, winter- and spring-runs and were refined over a 4-year period. They were parameterized using empirical data, existing models, analyses of existing data, and a minimal amount of expert opinion (Table S1). The DSMs for the three Chinook salmon runs had the same basic structure but differed with respect to timing and DSM inputs (Fig. 2, bottom).

Chinook salmon DSMs began with an initial number of natural and hatchery origin adults returning to freshwater environments.

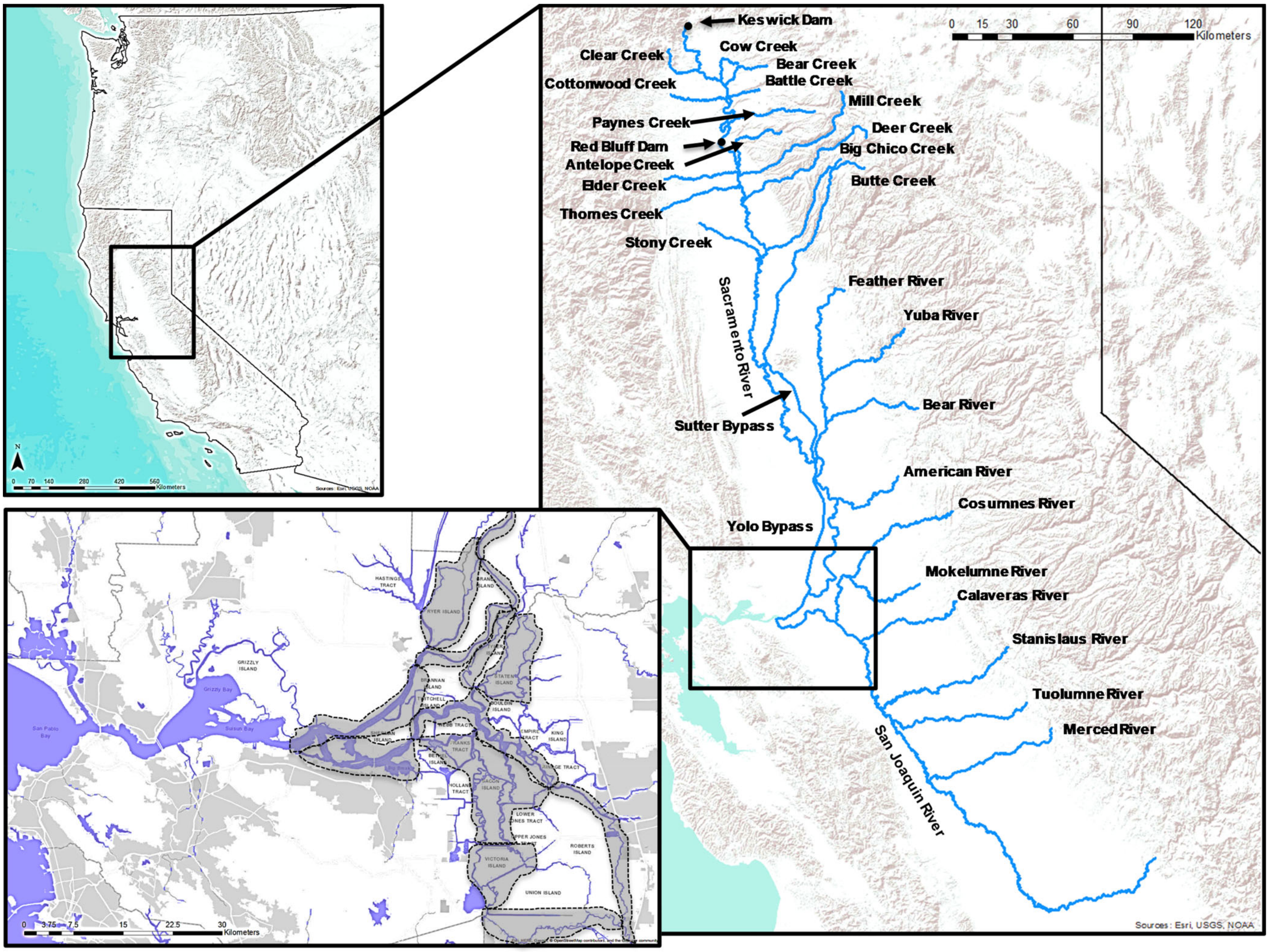

Figure 1 The location of the Central Valley and tributaries and river sections (labeled) and the Sacramento-San Joaquin Delta subregions (shaded) included in the evaluation of Chinook salmon restoration strategies.

These individuals were randomly assigned to each adult return month (Fig. 2, bottom) using a discrete triangle distribution. Returning adults experienced mortality (en route survival submodel) and were allowed to stray among tributaries (stray submodel). Adults that arrived to the spawning grounds also experienced mortality (prespawn survival submodel). The number of spring-run adults surviving on the spawning grounds was truncated by the capacity of holding habitat. Surviving females created a redd in the available spawning habitat and spawned. If the redd capacity was exceeded, females in later arriving groups then destroyed redds of females that previously spawned (i.e. each late arriving female would destroy one redd). The number of small size juvenile Chinook salmon produced by each arrival group was estimated as a function of the number of intact redds, female fecundity, and egg-to-fry survival (Table S1).

Juvenile Chinook salmon reared in natal tributaries, mainstem sections of the Sacramento and San Joaquin rivers, and the delta. Juvenile fish initially reared in their natal tributaries unless rearing habitat capacity was exceeded. Juvenile rearing habitat capacity was a function of juvenile size class-specific territory size. Fish habitat use and movement out of watersheds was based on the following rulesets. At each time step, juvenile fish occupy all available juvenile habitat within a spatial unit with larger fish being assigned to habitat first, followed by smaller fish. If seasonally inundated (floodplain) habitat was available during a time step, juvenile fish were assigned to floodplain habitat first followed by perennially inundated (in-channel) habitat. Juvenile fish assigned to habitat remained in a habitat for the time step. If habitat was unavailable, the juveniles not assigned to a habitat left the watershed and only moved downstream. If a fish grew to the very large size class, it left the watershed during the start of the next time step and migrated to the ocean within that time step. Juvenile Chinook salmon movement was also influenced by environmental factors such as discharge (e.g. pulsed flows) and time of year. Fish leaving watersheds were allowed to rear in available juvenile rearing habitat in downstream reaches, the bypasses, the delta, and the bay. Juvenile fish arriving in the downstream location were allocated to available habitat proportionally with larger fish

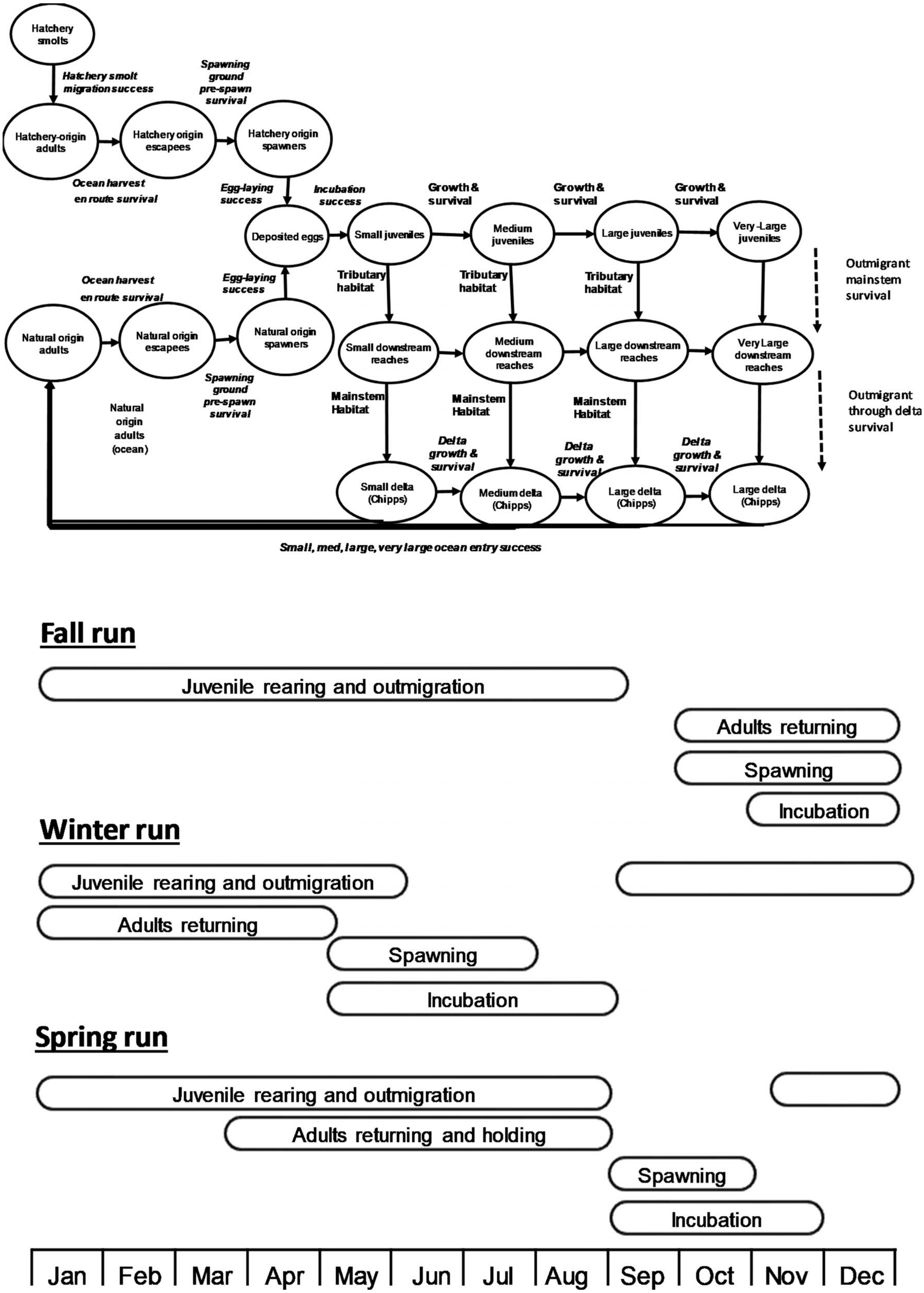

Figure 2 Conceptual Chinook salmon population dynamics used to evaluate Chinook salmon restoration strategies (top) and timing of life history activities for the three Chinook salmon runs with labeled bubbles representing the times that the activities occurred (bottom). Labeled arcs (top) indicate submodels that were used to model state transitions.

being assigned first. For example, if 100 and 200 fish from two tributaries arrived at a downstream location, 33% and 67% of the fish from each tributary, respectively, would be allocated to the available habitat. The transitions among the juvenile size classes occurred at the end of a time step and were modeled as a function of fish growth and rearing survival, which differed with habitat type: seasonally inundated (floodplain, including the Yolo and Sutter bypasses) and perennially inundated (in-channel). Juvenile fish migrating to downstream locations survived as a function of outmigrant survival. Once in the delta, fish survived and grew assuming delta-specific growth rates (Table S1) and survival (delta rearing survival submodel). When a fish arrived in the delta due to lack of upstream habitat, it remained in the delta until it increased to the very large size class or if the delta habitat capacity was reached. Very large size juveniles that arrived to the delta left to the bay during the same time step. Fish actively migrating through the delta were routed and survived as a function of water pumping operations, flows, and water temperatures (delta routing submodels). All juveniles that left the delta migrated to the bay and then the ocean and survived as a function of ocean entry survival. In the last month of the juvenile rearing/outmigrating period, all surviving juvenile fish were routed to the ocean with one exception. For spring-run only, small- and medium-size class fish that were reared in their natal tributary in the last month exhibited a yearling life history strategy. Yearling fish continued to experience habitat-specific mortality over the summer, but growth did not resume until September. In November, yearling fish immediately migrated to the ocean.

Spawning and rearing habitats are known to change through time due to fluvial processes (Gregory & Bisson 1997). In systems with sediment trapping dams, these changes usually result in degradation or a decrease in habitat through time unless habitats are maintained through management. To approximate the habitat degradation process in the tributaries with sediment trapping dams, the DSMs included habitat degradation rates for spawning habitat that varied with tributary and were based on expert opinion (Table S1). Habitat degradation occurred on an annual time step and was applied before the start of the adult spawning. We assumed that perennial juvenile rearing habitat degradation rate was half the spawning habitat rate and that streams without dams were in dynamic equilibrium (i.e. the maximum potential habitat amounts remained constant across time).

All modeling was conducted using R statistical software (R Core Team 2018). The DSMs were calibrated by minimizing the sum of squared differences between the predicted (simulated) and observed (Azat 2019) natural origin adult escapement using a genetic algorithm (R package *rgenoud*; Sekhon & Mebane Jr. 1998; see Supplement S2 for a detailed description of the model calibration process).

Model Inputs

The Chinook salmon DSMs required multiple inputs that represented environmental conditions (i.e. flows, temperatures), existing amounts of habitat, fish inland harvest rates, and water diversions (Table S2). Hydrologic and operations inputs were created using outputs from existing runs of CalSimII (a modification of Draper et al. 2004). Notably, this flow model required that inputs aligned with historical water years because it was designed to evaluate potential water operation rulesets across previous water years. Thus, DSM flow inputs aligned with 1980–2000, but incorporated current water operation rulesets. The source for water temperature inputs varied based on data availability and matched the same years as the flow inputs. Water temperatures were created using HEC-5Q models, measured water temperatures, statistical models relating air temperature to water temperature, and by matching tributaries that were similar in hydrology and geomorphology. Habitat inputs also varied by data availability. When possible, these inputs were created using previously published flow-habitat relationships that were scaled to the length of the tributary. In the absence of these estimated relationships, suitable instream areas were scaled from a nearby, geomorphically similar watershed. Miscellaneous inputs, except predator prevalence, were derived from a variety of published sources. All DSM input databases are documented and are currently available in an R package (https://flowwest.github.io/cvpiaData/).

Candidate Actions

Chinook salmon restoration activities in the Central Valley typically involve habitat restoration, barrier removal or fish passage improvement to allow access to upstream habitats, actions to minimize fish entrainment, such as screening water diversions, and actions to increase flows during critical periods to increase habitat and connectivity. At the coarse resolution of our model, actions that facilitate access to additional habitats, such as barrier removal, were identical to habitat restoration actions because they resulted in an increase in the available habitat inputs to the DSM. Thus, we reduced the set of candidate management actions to four: restore spawning habitat, restore perennially inundated juvenile rearing habitat, restore seasonally inundated juvenile rearing habitat, and decrease or screen water diversions. To facilitate comparisons within and among actions across watersheds, we compiled information on project costs and the amount of change that resulted from implementation of restoration projects to derive roughly equal units of effort (Supplement S2). The water diversion action unit corresponded to an average increase in small juvenile survival of 0.5%. Importantly, we used that value rather than changing the diversion inputs during simulations because data on small diversions within the Central Valley were unavailable. Based on the design specifications of recent habitat restoration projects in the Central Valley, we assumed an annual probability of seasonal habitat inundation of 0.67, a 2-month inundation duration, and an equal probability of inundation initiation in January–March. Candidate actions for the downstream mainstem sections of the Sacramento and San Joaquin rivers included only juvenile habitat restoration.

Optimal Chinook Salmon Restoration Policy Development

Habitat restoration can be thought of as a Markovian decision process (MDP) that consists of a sequence of actions through time with each action influencing the state of the system within the given time step. However, the trajectory of states over time (i.e. system dynamics) is dependent on the entire sequence of restoration actions, and decision-making is focused on optimizing (or at least prioritizing) these actions relative to maximizing the sum of naturally produced adult Chinook salmon. Thus, we used stochastic dynamic programming (SDP) to determine the optimal restoration actions in each natal tributary across combinations of habitat availability, juvenile survival, and number of female spawners (Supplement S3). These state-dependent restoration policies were used during simulations to identify the optimal restoration action to be implemented for each annual time step. Stochastic dynamic programing uses backward induction to solve an MDP and identify the optimal state-dependent management actions (Bellman 1957). The objective of SDP is to maximize the sum of all future returns, here, the number of naturally produced adult Chinook salmon. It has been used to solve a variety of natural resource problems ranging from endangered species management (Brignon et al. 2017; Duarte et al. 2017) to animal harvest management (Walters & Hilborn 1976; Lubow 1996; Gerber 2015). Stochastic dynamic programing incorporates stochasticity and uncertainty through the use of state-transition matrices (Marescot et al. 2013). We used four system state metrics: the amount of spawning habitat per female spawner, the amount of perennial juvenile rearing habitat per female spawner, the amount of seasonal juvenile rearing habitat per female spawner, and small size class juvenile survival. To incorporate seasonal fluctuations in habitat availability and differences in juvenile outmigrant survival based on the distance from a tributary to the ocean, we subdivided the tributaries into six groups and created optimal policies for each group (Table S3; see Supplement S3 information for a detailed description of restoration policy development).

When using SDP the number of dimensions can become intractable if there are too many systems and information states. Given the complexity of the upstream conditions for the non-natal mainstem sections of the Sacramento and San Joaquin rivers, we approached optimal policy development differently for these areas. In particular, we evaluated the benefit of restoring perennially or seasonally inundated rearing habitat each year in each mainstem section by estimating the number of adult fish returns in subsequent years from that year's juvenile cohort. The action that resulted in the most adult fish returns was considered optimal for that mainstem section in that specific year. Thus, our approach to identify the optimal policy in the mainstem sections of the Sacramento and San Joaquin rivers only considered future returns based on that year's cohort. It did not consider the sum of all future returns in the same way SDP did for the natal tributaries.

Restoration Strategy Development and Evaluation by Forward Simulation

We used forward simulation to evaluate the relative gains when implementing the optimal restoration policies and to evaluate other stakeholder strategies that did not include the implementation of the optimal restoration policies. Using the results of preliminary modeling efforts and knowledge of the system, the stakeholder group proposed 14 candidate restoration strategies to evaluate (Table 1). Strategy zero was a null model because no actions were implemented. The remaining strategies were strategies that selected the optimal state-dependent restoration actions for sites each year during each stochastic iteration based on the system state (e.g. spawning habitat per female spawner) using a 5-year running average on the number of female spawners. Thus, the selected optimal restoration actions varied by iteration based on the state of the stochastic system. We restricted the DSMs such that only five restoration actions were implemented each year, except strategy 11, which required six per year. This annual level of effort was based on the number of new restoration projects implemented by the CVPIA fisheries program each year and to ensure that restoration efforts were roughly equal across candidate strategies.

To evaluate each candidate strategy, we simulated Chinook salmon dynamics from 1980 to 2000 with each run-specific DSM. We seeded the DSMs with adult fish for the initial 5 years of the simulations using the average escapement estimates from 2013 to 2017 (Azat 2019). These fish spawned, and their young moved through the system following the DSM rulesets. This allowed the simulations to begin with a reasonable starting age distribution of adults returning from the ocean. Once these cohorts made it to the ocean, the DSM inputs were reset to begin at 1980. This allowed the simulations to incorporate 20 years of restoration actions. Each candidate strategy was simulated for 1,000 iterations and output the estimated number of naturally produced adults per year for the entire Central Valley.

We identified the best performing restoration strategies by ranking each scenario from best to worst based on the total number of naturally produced adults across the 20-year simulation period (i.e. the sum). To facilitate comparisons across the three runs with very different run sizes, the total number of naturally produced adults across years was calculated (i.e. one number per strategy) and used to calculate utilities (U) for each objective using proportional scoring (Conroy & Peterson 2013) as:

$$U(x_i) = \frac{[x_i - \text{worst}(x_i)]}{\text{best}(x_i) - \text{worst}(x_i)},$$

where x_i is the total number of naturally produced adults and worst(x_i) and best(x_i) are the smallest and greatest total number of naturally produced adults across scenarios for salmon run i. The scores for each run were combined into an objective function using two methods. The first method equally weighted and summed the scores for each Chinook salmon run as:

$$U(x) = \sum_{3}^{i} \frac{U(x_i)}{w_i},$$

where w is the weight of run i (i.e. one-third for each run). The second method we used was to multiply the three run-specific scores together. Both methods resulted in scores for candidate decisions that ranged from zero (worst strategy) to one (best strategy). However, the second method guaranteed that the worst strategy (score = 0) for any run would result in a combined score of zero. For each run, we also calculated the expected loss of implementing a candidate strategy relative to the best strategy as:

Table 1 The candidate strategies evaluated by the science integration team when developing the near term restoration strategy. Locations of tributaries are in Fig. 1.

Strategy	*Description*
0	Implement no restoration
1	Juvenile perennial habitat restoration focused in upper and lower-mid Sacramento River; Butte, Deer, and Battle creeks; and the Stanislaus and Feather rivers
2	Juvenile perennial habitat restoration focused in upper and lower-mid Sacramento River; Butte, Deer, and Clear creeks; and the Stanislaus and Feather rivers
3	Juvenile perennial habitat restoration focused in upper and lower-mid Sacramento River; Butte and Clear creeks; and the Stanislaus, Mokelumne, and Feather rivers
4	Juvenile perennial habitat restoration focused in the mainstem Sacramento and San Joaquin rivers
5	Juvenile perennial habitat restoration focused in the upper, upper-mid, and lower-mid Sacramento River and Cow and Clear creeks
6	Juvenile perennial habitat restoration focused in the upper and lower-mid Sacramento River; American River; and Clear Creek with maintaining existing habitat in Clear and Butte creeks and the Upper Sacramento River
7	Juvenile seasonally inundated habitat restoration focused in the mainstem Sacramento and San Joaquin rivers
8	Optimal habitat restoration actions for winter-run in the mainstem Sacramento with an emphasis on the Sacramento River below Red Bluff diversion dam
9	Optimal habitat restoration actions for spring-run in the upper-mid and lower Sacramento River; Battle, Butte, Clear, Deer, Mill, and Antelope creeks; and the Feather River with an emphasis on the Sacramento River and Battle, Butte, and Clear creeks
10	Optimal habitat restoration actions for spring-run in the upper-mid Sacramento River and Battle, Butte, Clear, Deer, Mill, and Antelope creeks; and the Feather River with effort equally allocated across tributaries
11	Optimal habitat restoration actions for fall-run with one action per year in each diversity group listed in Table S2 and one action per year in the mainstem Sacramento and San Joaquin rivers
12	Optimal habitat restoration actions for fall-run in the upper and lower Sacramento River and the American, Stanislaus, and Calaveras rivers with effort equally allocated across tributaries
13	Optimal habitat restoration actions for fall-run in the upper and lower Sacramento River and the American, Stanislaus, and Mokelumne rivers with effort equally allocated across tributaries

$$RL_i = \frac{\text{Max}(X) - X_i}{\text{Max}(X)}$$

where RL is relative loss of objective X (i.e. natural adult production) for strategy i.

Identify Key Uncertainties Using Sensitivity Analyses

We used sensitivity analysis to evaluate the behavior of the DSMs, ensure they were performing as expected, identify components that largely drive the identity of the best strategy, and identify components that could be improved in future modeling efforts through monitoring or research. We used one-way, response profile sensitivity analysis to evaluate the sensitivity of best scenarios to the DSM components (Conroy & Peterson 2013). During the sensitivity analysis, we used current conditions for all DSM parameters (e.g. survival) or inputs (e.g. habitat availability). We then varied the value of each component one at a time from 0.5 to 1.5 times their current value in increments of 0.1 and then estimated the total number of naturally produced adults each year for each candidate restoration strategy over the 20-year period. We then plotted these values to examine how the rankings of the top three strategies (i.e. the three with the greatest number of naturally produced adults) changed over the range of values for the DSM parameters and inputs. We also estimated the relative value of improving parameter estimates or inputs by calculating the expected value of perfect information (EVPI; Conroy & Peterson 2013). The EVPI is the expected increase in a decision maker's objective, here number of naturally produced adult Chinook salmon, if the uncertainty regarding a parameter value or DSM input were completely eliminated.

When combining scores across objectives (here, runs), stakeholders may be concerned that the objective weights may affect the combined utility scores. Therefore, we also evaluated the sensitivity of the strategy rankings to the weighting for each run with indifference curves (Conroy & Peterson 2013). For this analysis, we evaluated alternative weighting for winter- and spring-run (one at a time) by varying the run-specific weight across a wide range of values and allowing the two other runs to divide the remainder equally. The combined utility scores were plotted across the range of varied weights to identify the value of weights where the rankings of the candidate strategies changed.

Results

Optimal Restoration Policies

Optimal restoration actions differed by optimization group but tended to reveal the same patterns. When juvenile survival was low, the optimal actions included seasonal inundated habitat restoration when spawning habitat was high, whereas perennially inundated habitat actions were best with increasing survival (Fig. 3, top). Increase spawning habitat was generally the optimal action when spawning habitat per female spawner was low and the perennially inundated rearing habitat was relatively high. One notable exception to these patterns was for the San Joaquin River tributaries. At very low juvenile survival, optimal restoration actions were to increase seasonal rearing habitat when spawning habitat was high (Fig. 3, bottom). In addition, restoring perennial rearing occurred over the greatest range of system state combinations.

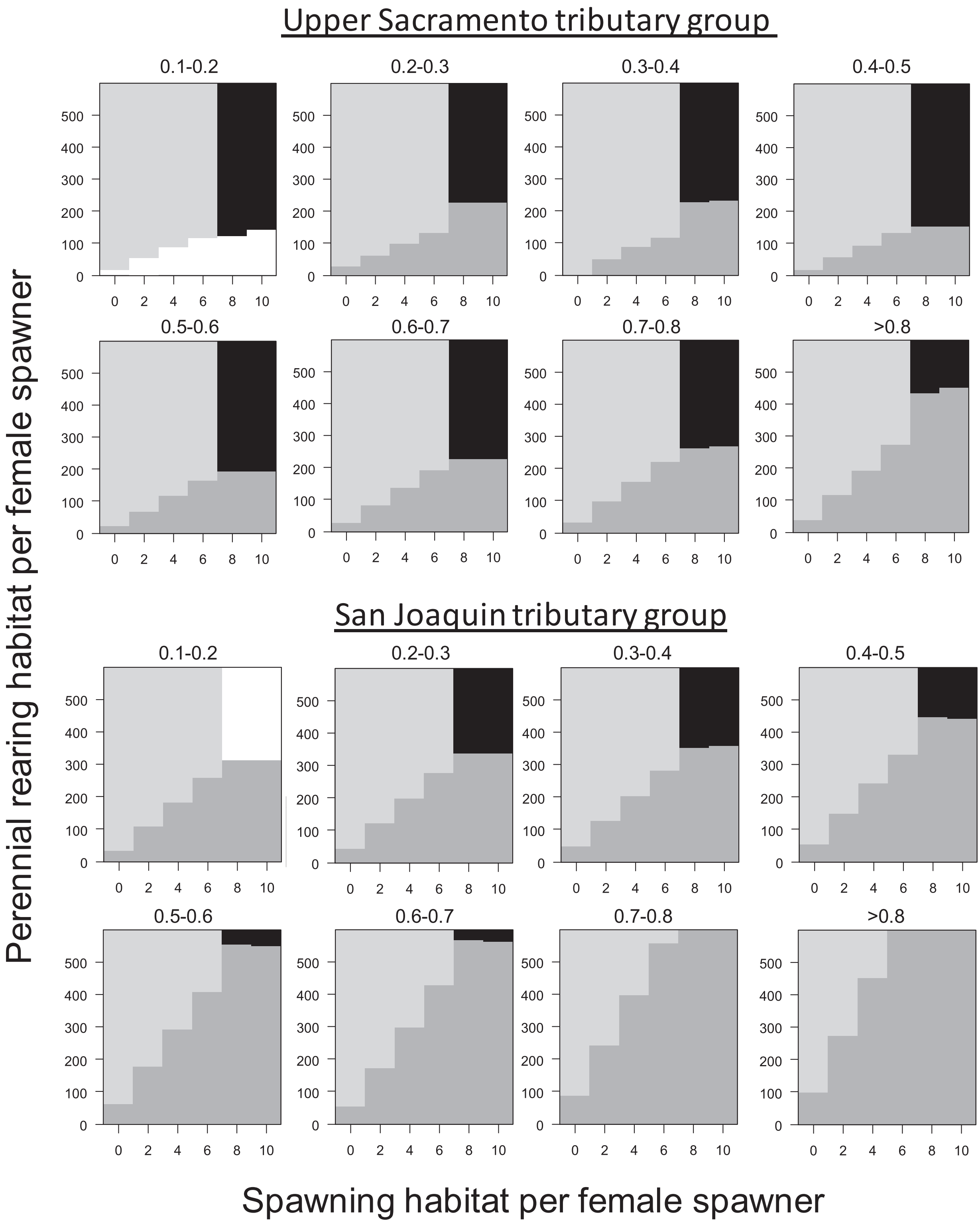

Figure 3 Example policy plots displaying optimal restoration actions, increase spawning habitat (light gray), increase perennially (dark gray), and seasonally (white) inundated rearing habitat, and increase survival 0.5% (black) for various combinations of spawning habitat (m^2) per female spawner, perennially inundated rearing habitat (m^2) per female spawner, and small size class juvenile monthly survival (ranges above each plot) for two tributary groups. In all cases, seasonally inundated habitat was initially zero.

Strategy by Forward Simulation

Strategy 6 was the best for fall- and winter-run and 9 for spring-run based on total natural adult production (Fig. 4). Strategies 1–3, 5, and 6 were also among the best for both fall- and winter-run based on natural production. All of these strategies involved juvenile habitat restoration focused on the mainstem Sacramento River and Clear Creek. Interestingly, winter- and spring-run natural adult production under strategy 7 and

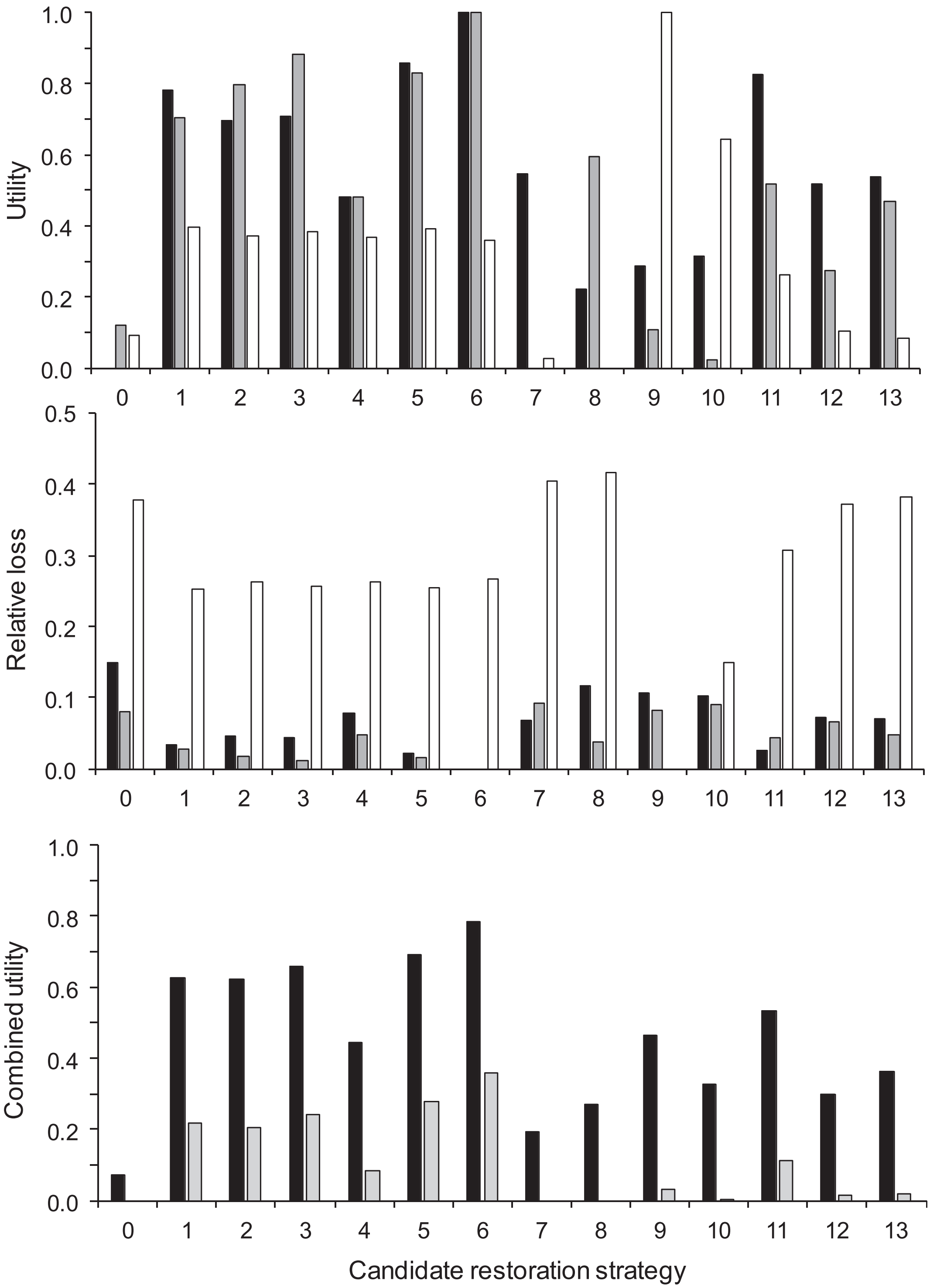

Figure 4 Strategy-specific utilities for fall- (black), winter- (gray), and spring-run (white) Chinook salmon (top), relative loss in natural adult production for fall- (black), winter- (gray), and spring-run (white) Chinook salmon (middle), combined utilities (bottom) with additive with equal weighting (black) and multiplicative (gray).

Table 2 The number of times the top 3 strategies changed during response profile sensitivity analysis of decision-support model inputs and the mean and range "parenthesis" for expected value of perfect information, by Chinook salmon run. Model inputs are grouped by type and may include several individual inputs as indicated by the range.

	Changes in Top Decisions			*Expected Value of Perfect Information*		
	Fall	*Winter*	*Spring*	*Fall*	*Winter*	*Spring*
Habitat						
Bypass habitat area	0	0	0	0	0	0
Adult holding habitat (spring-run only)			0			0
Spawning habitat	0	3	1	2,679	0	0
Perennially inundated juvenile habitat	3	5	3	1,386 (63–2,709)	0	0
Seasonally inundated juvenile habitat	3	5	1	0	0	13
Delta juvenile rearing habitat	0	0	0	10,413	0	0
Discharge and temperature						
Delta inflow	0	4	0	0	0	0
Median discharge	9	19	8	705 (9–2,709)	8 (0–21)	0
Proportion natal discharge	0	0	0	0	0	1 (0–1)
Proportion flow at Yolo and Sutter bypasses	0	0	0	0	0	0
Proportion pulse flow	0	0	0	0	0	0
Mean temperature	6	14	5	486 (0–1842)	0	1 (0–1)
Operations						
Cross channel gate is open						
Exports from CVP and SWP	0	0	0	0	0	0
Total diversion	0	5	0	69	44	1 (0–1)
Miscellaneous						
Initial number of adults	0	5	1	0	0	0
Predator contact points	0	4	0	70	10	101
Hatchery smolts						
Angler (instream) and ocean harvest rates	0	0	0	0	0	0
Predator prevalence	0	0	0	0	0	0
Hatchery returning adults' stray rate	0	0	0	0	0	0

Table 3 The number of times the top 3 strategies changed during response profile sensitivity analysis of model parameters and the mean and range "parenthesis" for expected value of perfect information, by Chinook salmon run. Model parameters are grouped by submodel and may include several individual model parameters as indicated by the range.

	Changes in Top Decisions			*Expected Value of Perfect Information*		
Submodel/Parameter	*Fall*	*Winter*	*Spring*	*Fall*	*Winter*	*Spring*
Adult en route survival	0	8	1	0	15 (0–62)	0
Adult prespawn survival	0	9	5	0	0	0
Adult straying	0	0	2	372 (0–2,052)	0	38 (0–152)
Egg-to-fry survival	6	16	3	52 (0–115)	2 (0–5)	0
Juvenile river rearing survival	6	35	6	1,008 (0–7,760)	127 (0–608)	242 (0–2,278)
Juvenile delta rearing survival	9	25	0	21,954 (0–169,362)	42 (0–217)	0 (0–1)
Juvenile bypass rearing survival	3	5	5	1,414 (0–7,760)	60 (0–358)	411 (0–2,278)
Juvenile movement with flows	3	2	0	4 (0–160)	30 (0–118)	0
Juvenile Sacramento River outmigrant survival	0	0	0	0	0	0
Juvenile San Joaquin River outmigrant survival	0	0	0	83 (50–117)	0	0
Juvenile ocean entry survival	6	14	5	1874 (3–5,318)	260 (2–508)	949 (2–2,621)
Juvenile territory size	3	5	3	8,936	43	358 (358–358)
Juvenile growth rate	6	7	5	75,166 (26299–124,032)	4,756 (0–9,513)	1766 (1430–2,101)
North delta routing and survival	2	28	6	843 (0–9,595)	132 (0–1721)	146 (0–2004)
South delta routing and survival	0	0	0	19 (0–202)	0	0
Fecundity	3	4	5	6,657	0	0
Redd size	3	0	4	12,075	0	199
Sex ratio	0	4	4	0	0	0
Habitat degradation	6	5	1	719 (296–1,142)	11 (0–22)	5 (0–10)

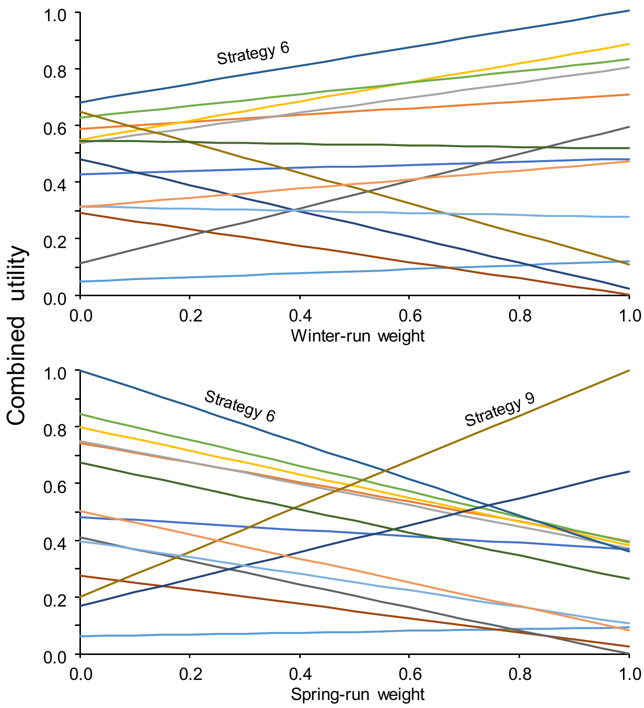

Figure 5 Indifference curves for the weight of winter-run (top) and spring-run (bottom) Chinook salmon. Each line represents a candidate restoration strategy and the top line in each plot is the best restoration strategy.

spring-run natural adult production under strategy 8 were smaller than the no-action strategy. The combined utilities suggested a similar pattern with strategies 5 and 6 with the greatest utilities and 0, 7, and 8 with the lowest, regardless of whether the utilities were weighted or multiplied (Fig. 4).

The relative loss metric suggested that decreases in natural production relative to the best strategy was minor for both fall- and winter-run (Fig. 4, middle). Relative loss for spring-run Chinook salmon was much greater under most strategies except the two best spring-run strategies. However, relative loss for spring-run was constant across the best fall- and winter-run strategies one to 3, 5, and 6 with loss averaging about 25% of the best spring-run strategy (Fig. 4, middle).

Sensitivity Analysis

The sensitivity analysis indicated that the most influential DSM inputs included the current estimates of existing habitat, median discharge, and temperature across all runs and initial abundance and total amount of water diverted for winter-run (Table 2). Sensitivity analysis of the DSM parameters indicated that the DSMs were most sensitive to multiple juvenile survival parameters at all points in their life history (i.e. rearing, migrating) and at all locations included in the DSMs (i.e. tributaries, mainstem, delta, and ocean; Table 3). The second most influential parameters included juvenile growth and body size parameters, followed by reproduction parameters and habitat degradation rate. For winter- and spring-run, adult survival along the migratory corridor and on the spawning grounds were also influential (Table 3).

The value of perfect information estimates for the DSM inputs mirrored the sensitivity analysis with the greatest expected gain for fall-run of more than 10,000 naturally produced adults per year, on average, if the amount of juvenile rearing habitat in the delta was known with certainty (Table 2). The estimated value of perfect information was similarly high for spawning habitat and perennially inundated juvenile rearing habitat. In contrast, the value of perfect information for winter- and spring-run were much lower (Table 3) presumably because the run sizes were also smaller than fall-run. The value of perfect information for the DSM parameters was substantially greater than for the DSM inputs (Table 3). The greatest gain across runs was for juvenile growth rate in each habitat type, which averaged more than 75,000 naturally produced adults per year, on average. Large gains in annual production were also observed if the factors affecting juvenile survival at all locations were known with certainty particularly for juvenile fall-run rearing in the delta, which averaged more than 21,000 adults per year (Table 3).

Indifference curves indicated that the strategy with the greatest utility was unaffected by the weight of winter-run in the combined utility (Fig. 5). However, the best restoration strategy changed from 6 to 9 as the weighting of spring-run Chinook increased. The two strategy lines cross at a weight of 0.55 (Fig. 5) indicating that decision makers would have to value spring-run 2.4 times (0.55/[0.45/2]) more than fall- and winter-run before adopting strategy 9.

Discussion

Quantitative models are increasingly developed to evaluate restoration actions for a variety of ecological systems. Unfortunately, in practice, many of these models are developed without input from the stakeholders that are expected to use them. In our experience, this often leads to confusion concerning what the model is capable of evaluating; the underlying processes or rulesets that govern model results; and the data used to parameterize the model. Ultimately, this approach can lead to mistrust in the model and, in turn, doubt in results that are produced by the model, which understandably limits its use for real-world decision-making. The SDM process involves the stakeholder group throughout model development, evaluation, and refinement to facilitate understanding of, and trust in, the model and each of its components. Although stakeholder input at every stage of model development can slow the decision-making process (particularly with large stakeholder groups), we believe it is an essential, but often overlooked, component to the overall success of a restoration program. In our example, the SIT participated in a series of workshops to iteratively work through the SDM process. During this time, members of the SIT shared their knowledge of tributaries within the Central Valley and their, sometimes competing, hypotheses on how fish respond to environmental heterogeneity within the watershed. This information was translated into the initial conceptual models that were the foundation for the first version of the SIT's Chinook salmon DSMs. Over time, the SIT has refined the DSMs to better approximate their hypotheses concerning system dynamics, and the DSMs have increasingly relied on inputs that were either collected by members of the SIT or are data in which they have greater confidence. Through this iterative process, the SIT has developed a sense of ownership of, and trust in, the DSMs, which was essential to the understanding and acceptance of the simulation results.

Results of the decision-support model simulations and sensitivity analyses were used to develop a Chinook salmon restoration strategy for California's Central Valley. The strategy centered on two processes: reducing habitat fragmentation in the Sacramento and San Joaquin river basins and increasing the spatial diversity of Chinook salmon populations. Habitat fragmentation in riverine landscapes is one of the major factors responsible for the loss of aquatic biodiversity and productivity (Ward et al. 2002; Jansson et al. 2007; Seliger & Zeiringer 2018). Spatial diversity is also an important factor that can promote stability and persistence in salmon populations (Lindley et al. 2007; Carlson & Satterthwaite 2011). The simulation results indicated that restoration strategies that focused on non-natal reaches of the mainstem Sacramento and San Joaquin rivers were among the most beneficial for all three runs. A restoration strategy focused in mainstem reaches would also increase connectivity from natal tributaries to the delta. The simulations also indicated that strategies that took spatial diversity into account were among the best for fall-run with minimal loss to winter- and spring-run. Based on these DSM predictions, the final restoration strategy created from the 13 strategies consisted of a set of restoration actions that focused on juvenile habitat in the mainstem Sacramento and San Joaquin rivers and in tributaries within each salmonid diversity group that was predicted to have the greatest gain in natural production. Further analyses of the DSM predictions and behavior provided additional insights that aided in restoration planning.

Prior to the initiation of the SDM process, there was a common belief among CVPIA restoration practitioners that actions targeted at a specific salmon run would likely benefit all sympatric salmonids (*Oncorhynchus* spp.) or at a minimum that restoration actions would not harm non-target salmonids. The simulated total adult natural production for winter- and spring-run under two juvenile habitat restoration strategies were lower than the *do nothing* strategy, suggesting that restoration actions intended to benefit one run could be worse than no investment in restoration. At a fundamental level, juvenile rearing habitat in the Chinook salmon DSMs hold and grow juveniles. Holding juveniles too long or at times when environmental conditions in the natal tributary, migratory corridor, and ocean become harmful (e.g. high water temperatures, after the ocean turns, so on) can result in decreased juvenile survival and subsequent reduction in natural adult production. Thus, some actions intended to benefit one run may be detrimental to another because the runs differ with respect to the timing of life-history events. Such results are often not intuitive, particularly given the complexity of the system, but can be revealed when using DSMs to develop restoration strategies across multiple runs. This highlights the value of using quantitative DSMs for evaluating how hypotheses concerning system dynamics might affect restoration outcomes.

Ecological models have become increasingly more complex over the past two decades as ecologists attempt to create more realistic approximations of system dynamics (Guo et al. 2015). Not all ecological models, however, are useful for decision-making (Schuwirth et al. 2019). Useful DSMs contain only those elements that are necessary to solve the problem (i.e. requisite decision modeling; Phillips 1984). The Chinook salmon DSMs developed by the SIT contained 165 parameters. Of these, only 19 fall-run, 50 winter-run, and 28 spring-run parameters changed the rankings on the three best restoration strategies during sensitivity analyses. To decision makers in the Central Valley, this means that a relatively small number of parameters are important with respect to their decision, which is consistent with most decision analysis problems (Conroy & Peterson 2013). This does not mean that other parameters did not affect natural adult production estimates, only that these other parameters did not influence the identity of the best decisions (strategies). In requisite decision modeling, DSMs are simplified by iteratively removing the uninfluential parameters or by making them constants and re-evaluating model behavior and sensitivity (Clemen & Reilly 2001). Using this process, we simplified the Chinook salmon tributary dynamics submodel to include 12 parameters and 5 system states. This allowed us to use SDP and the rulesets developed by the SIT to identify the state-dependent optimal policies for each tributary and greatly facilitated the development of the restoration strategies. These simplifications and refinements of DSMs are often required to take full advantage of decision-analytic tools, particularly those used to obtain globally optimal solutions to stochastic problems, such as SDP.

When working in a team environment, stakeholders can, and often do, have conflicting ideas about system dynamics and the structure and composition of the DSM needed to approximate these conflicting ideas. Although differences of opinion can lead to productive discussions, they can also end in gridlock within the decision-making process. Sensitivity analyses can be useful for resolving or postponing conflicts among stakeholders and allows the process to continue to move forward. For example, members of the SIT had profound differences of opinion on the relative effect of predation on juvenile salmon survival and how predation should be included in the DSMs. To resolve the disagreements, we included a predation effect in the DSMs and found that it was highly influential on restoration priorities during sensitivity analyses. This prompted the initiation of research focused on understanding the relative role of predation and identifying potential restoration actions to reduce predation.

Similarly, in situations with multiple restoration objectives, disagreements about the relative importance of each objective can frequently be resolved using indifference curves. Indifference curves often reveal that the best decision does not change regardless of how an objective is weighted, as illustrated by winter-run Chinook salmon. When the best decisions change one or more times with the objective weight, it provides a common frame of reference for initiating a discussion. For instance, the discussion of the relative importance of spring-run Chinook salmon began with the question: are spring-run twice as important as fall- and winter-run? The decision sciences have developed these and other tools that help teams identify things that matter from those that do not with respect to the decision at hand.

Ecological restoration programs often struggle with decisions on how to prioritize resources for restoration, monitoring, and research. The EVPI provides a means for comparison among research, monitoring, and restoration actions using a common measure. We found that perfect information on juvenile survival would increase fall-run natural adult production, on average, 5,047 per year. This value is more than twice the expected maximum annual increase in natural adult production following the implementation of one unit of fall-run habitat restoration, 1,845 per year on average. Such a large difference motivated the SIT to focus future research and monitoring on improving juvenile survival estimates for better decision-making and ultimately greater natural adult production. Measures such as EVPI and the expected value of imperfect information (Conroy & Peterson 2013) provide managers and decision makers with the means to evaluate trade-offs and identify optimal levels of monitoring and research effort.

Considerable resources have been invested in ecological restoration projects across the globe to restore ecosystem integrity. Given the inherent complexity in ecological systems, it is not surprising that restoration strategies are diverse and these efforts have been met with mixed success. The decision sciences have developed a wide range of tools and approaches to simplify complex problems into key components. In this article, we demonstrated how the SIT was able to use many of these analytical tools to inform the development and evaluation of restoration strategies for multiple Chinook salmon runs in California's Central Valley. In doing so, we highlighted tools and approaches that we believe are of great interest to many restoration practitioners that undoubtedly face similar difficulties.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Parameter estimates and sources for fall-run (f), spring-run (s), and winter-run (w) Chinook salmon decision-support model submodels.
Supplement S2. Chinook Salmon Decision Support Model Calibration.
Supplement S3. Optimal Chinook salmon restoration policy development.
Figure S1. Calibration results for fall-run (A), spring-run (B) and winter-run (C) Chinook salmon.
Table S1. Mean and standard deviation (SD) of Chinook salmon model parameters used to create state-transition matrices and simulate Chinook salmon population responses to candidate restoration actions.
Table S2. A description of the Chinook salmon decision-support model inputs.
Table S3. Tributaries and sections of the Sacramento and San Joaquin Rivers included in the Chinook salmon decision-support model, their associated optimization and diversity groups, and salmon runs: fall (F), winter (W), and spring (S).
Table S4. Small juvenile Chinook salmon (< 45 mm) outmigrant survival from natal tributary mouths, by optimization group through the delta used to create state-transition matrices for stochastic dynamic programming.

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