Articles

Management Goals for Conserving White Sturgeon in the Sacramento–San Joaquin River Basin

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Abstract

Management objectives for long-lived species are difficult to define because many taxa have delayed maturity and variable recruitment. White Sturgeon *Acipenser transmontanus* is an example of a species with a complex life history that complicates long-term status monitoring and establishment of management objectives. Historically, White Sturgeon in the Sacramento–San Joaquin River basin have been monitored by tracking the abundance of age-15 individuals as outlined by the Central Valley Project Improvement Act. However, infrequent recruitment complicates progress toward Central Valley Project Improvement Act management objectives because abundance of a single cohort fails to represent overall population trends. By using a Leslie population matrix, we demonstrate that the probability of reaching the Central Valley Project Improvement Act objective of 11,000 age-15 White Sturgeon is highly unlikely. We propose an alternative metric of 155,000 adults, which better represents overall population trends of White Sturgeon in the Sacramento–San Joaquin River basin, can be efficiently monitored, and can support both the goal of the Central Valley Project Improvement Act and management objectives.

Keywords: dynamics; goals; management; population; White Sturgeon

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Introduction

The importance of measurable objectives for the recovery of species of conservation concern has been well-established (Salafsky and Margoluis 2003; Ortega-

Argueta et al. 2011). Measurable objectives can be challenged or supported by data, outline assumptions and uncertainties, be subject to peer review, and most importantly, provide accountability (Tear et al. 2005). Population objectives should reflect the life history of the species of concern; generic objectives across taxonomic groups fail to address inherent variability among species and may be inappropriate for reaching defined goals. Identifying population objectives for long-lived species presents a unique challenge because many taxa have delayed maturity and variable recruitment (Musick 1999; Dulvy et al. 2014). In addition, long-lived species are often more vulnerable to overfishing and recovery can take decades after population collapse (Musick 1999).

Sturgeon and paddlefishes (order: Acipenseriformes) are a group of long-lived fishes that are imperiled throughout their distribution, with 17 species categorized as "critically endangered" or "endangered" by the International Union for Conservation of Nature (Pikitch et al. 2005; Haxton and Cano 2016; IUCN 2021). Threats to sturgeon populations include overfishing, barriers to movement, and environmental changes to spawning and nursery habitats (Rochard et al. 1990; Haxton et al. 2016; Hildebrand et al. 2016). Similar to other acipenserids, pervasive threats to White Sturgeon include habitat alteration, hydroelectric development, predation, invasive species, overfishing, water quality degradation, incidental physical trauma, and various effects of climate change. Several populations of White Sturgeon Acipenser transmontanus are of conservation concern including White Sturgeon of the Upper Fraser River and Upper Columbia River that are listed as endangered pursuant to the Canada Species at Risk Act and White Sturgeon of the Kootenay River that are listed as endangered pursuant to the U.S. Endangered Species Act and Canada Species at Risk Act (ESA 1973, as amended; SARA 2002, as amended; Hildebrand et al. 2016).

The life history characteristics of White Sturgeon present a suite of challenges for population and status monitoring. Like other sturgeon, they are particularly sensitive to overfishing because of their longevity and late maturation (Boreman 1997; Blackburn et al. 2019); these traits indicate low intrinsic rebound potential (Simpfendorfer and Kyne 2009; Kindsvater et al. 2016). Evidence suggests North American sturgeon can only sustain exploitation rates of 0.05-0.10 (Rieman and Beamesderfer 1990; Kohlhorst et al. 1991; Secor et al. 2002). Year-class strength of White Sturgeon can be largely regulated by survival at early life stages (Kohlhorst et al. 1991; Irvine et al. 2007; Dumont et al. 2011). Recruitment is often highly variable (McAdam et al. 2005), which can lead to a complex age structure and variable population growth (Parsley et al. 2002; Hatten et al. 2018). Changes in flow, temperature, and habitat suitability have resulted in frequent recruitment failure (Coutant 2004; McAdam et al. 2005; Irvine et al. 2007; Schreier et al. 2013; Jackson et al. 2016). The same population characteristics (i.e., delayed maturity, longevity, variable recruitment) that increase White Sturgeon vulnerability to perturbations also introduce challenges to detecting the effects of those perturbations on population trends. For example, delayed maturity and longevity can mask the effects of overharvest or failed recruitment for decades as previous generations continue to recruit to the adult population (Crouse 1999; Heppell et al. 2005). In addition, if negligible recruitment

White Sturgeon is considered a species of high concern in California because of evidence of population decline and infrequent recruitment (Moyle et al. 2011; Gingras et al. 2013; Hildebrand et al. 2016). Declining population trajectories of several anadromous species in the Sacramento-San Joaquin River basin (SSJ), including White Sturgeon, led to the Central Valley Project Improvement Act (CVPIA). The CVPIA was passed in 1992 and mandated changes in the management of the Central Valley Project, particularly for the protection, restoration, and enhancement of fish and wildlife resources. The CVPIA states that a program will be implemented to ensure that "natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967–1991." As a result, population goals, termed "doubling goals," were identified for five anadromous species of California including White Sturgeon.

The population objective for White Sturgeon was developed to track the CVPIA doubling goal. The objective focused on doubling the abundance of age-15 fish, with the assumption that age 15 is the approximate mean age at maturity of females in the SSJ. The abundance of age-15 fish during the baseline period was based on mark-recapture data of individuals > 102 cm collected during 1967–1991 and an age– length key developed using data from 1973 to 1976 (Kohlhorst et al. 1980). Abundance was estimated using multiple-census (i.e., Schnabel method) or Petersen techniques if there were sufficient recaptures in subsequent years (Ricker 1975). If tagging did not occur in consecutive years, the age-length key was used to estimate survival from a catch curve (Schaffter and Kohlhorst 1999). Mean annual abundance during the baseline period was estimated as 5,571 age-15 fish. Therefore, the doubling goal of the CVPIA for White Sturgeon was to reach a population level of \geq 11,142 age-15 fish by 2002 (U.S. Fish and Wildlife Service 1995). The current population objective has yet to be reached since it was established in 1995 (Gingras et al. 2013; Blackburn et al. 2019).

Population models have been widely used to estimate the effects of future management actions on population goals for sturgeon species (e.g., Pine and Allen 2001; Paragamian and Hansen 2008; Vélez-Espino and Koops 2009; Jager et al. 2013). Population recovery timeframes can be up to 20–100 y but depend on species-specific vital rates and other conditions. Currently, White Sturgeon in the SSJ remain a species of high concern but are not listed as threatened or endangered under the U.S. Endangered Species Act (ESA 1973, as amended; Hildebrand et al. 2016). The population is subjected to recreational harvest (slot limit = 102-152-cm fork length) and estimated annual exploitation rate has varied from 0.080 to 0.296 in recent years (Blackburn et al. 2019). However, under current harvest conditions and assuming 15% spawning periodicity, the population is predicted to decline annually by 2.8%.

Defining appropriate and effective management and recovery objectives for White Sturgeon and other acipenserids is especially important given their complex population structure and vulnerability to stressors. For White Sturgeon in the SSJ the doubling goal may be feasible with effective management actions, but a sustained level of 11,000 age-15 individuals may be implausible considering inconsistent annual recruitment. Successful management of White Sturgeon in the SSJ could be impeded if the CVPIA goal is unlikely to be achieved because it is poorly defined. The efficacy of management actions, such as reduced harvest or water allocation, cannot be properly assessed if the population metric of age-15 White Sturgeon does not reflect the overall trajectory of the population. Therefore, opportunities to further refine and improve management of the species may be lost, which further illustrates the importance of defining appropriate population objectives. The purpose of this study was to investigate whether a more representative population objective could be defined for the CVPIA doubling goal given the life history of White Sturgeon. The aim of this objective is to support successful management of White Sturgeon in the SSJ and measure progress toward long-term conservation under the CVPIA. However, assessing whether or not the CVPIA doubling goal will lead to species sustainability was outside the scope of this paper.

We propose an alternative objective that monitors double the abundance of the spawning population (individuals > 102-cm fork length). During the baseline period of 1967–1991, abundance of White Sturgeon >102 cm was estimated using multiple census or Petersen techniques from eight seasons of tagging. The mean abundance of adults (> 102 cm) across the baseline period was 77,500 individuals. Therefore, a population objective based on the CVPIA doubling goal would be defined as reaching 155,000 adults > 102 cm in length. We used a stochastic population model to assess the feasibility of the current population objective (i.e., 11,000 age-15 fish) by simulating age-specific abundance over time with varying rates of exploitation and recruitment. We assessed historical estimates of age-15 abundance from 1967 to 1991 and evaluated whether the feasibility of the doubling goal will change if it is defined by adult abundance (i.e., 155,000 adults) rather than a single cohort.

Methods

We used vital statistics and a stochastic population model from Blackburn et al. (2019) to evaluate the current population objective for White Sturgeon in the SSJ of 11,000 age-15 fish and the alternative objective of 155,000 adults > 102 cm (Table 1). The goal of the current exercise was to simulate the probability of reaching each objective after a set amount of time. We simulated abundance over a range of hypothetical recruitment and exploitation rates to evaluate potential

management actions on age-specific abundances. The effect of recruitment variability was incorporated by assessing the probability of reaching the objective on the last year of the simulation, as opposed to over the entire period.

Population model

We used a density-independent female-based Leslie matrix model (Blackburn et al. 2019) to simulate agespecific abundance and conducted all analyses in Program R using functions from the "popbio" package (Stubben and Milligan 2007). We began with a starting adult population of 24,000 female fish, the estimated number of age-10 and older White Sturgeon present in the Sacramento and San Joaquin rivers in 2009 (DuBois and Gingras 2011; Hildebrand et al. 2016). We obtained all age-specific abundances and vital rates (Table 1) from Blackburn et al. (2019), where the authors estimated the relative abundance of age-3 and older fish using trammel net surveys from 2014 to 2016 in Suisun and San Pablo bays. Blackburn et al. (2019) estimated age-1 and age-2 White Sturgeon using a linear model to predict the number in each age class (Caswelll 2000). Finally, Blackburn et al. (2019) estimated the number of age-0 juveniles by multiplying the number of mature females spawning in a given year in each age class by their agespecific fecundity (Table 1). Although spawning periodicity can vary among populations, females are thought to spawn every 2-10 y (Semakula and Larkin 1968; Chapman et al. 1996; Paragamian and Wakkinen 2011). Given the best available data, we assumed that 15% of females spawn each year, but the exact interval between spawning events is unknown (Chapman et al. 1996; Blackburn et al. 2019). Based on age-at-length data, we defined White Sturgeon > 102 cm in length as age 10 and older (Figure 1).

Following Blackburn et al. (2019), we used a simulation-based approach to account for uncertainty and variability in the vital rates. Briefly, demographic stochasticity was simulated using parametric bootstrapping in which the fate of individuals in each age class was randomly generated using beta or stretched-beta distributions based on the mean and standard error of their respective vital rates (Morris and Doak 2002; Table 1). For model specifics please refer to Blackburn et al. (2019).

Simulations

We simulated each scenario of varying recruitment and exploitation rates 1,000 times over a 50-y period. We also evaluated the population objectives over varying periods of time (i.e., 30, 40, 50, and 60 y). Results were consistent among time periods, so we used a 50-y period as a compromise between the long generation time of White Sturgeon (20-30 y) and a timescale useful for fisheries managers and policy makers. The CVPIA indicates that harvested individuals of the population should be included in estimates of natural abundance;

Table 1. Mean vital rates and standard errors (SE) used to construct population matrices for the White Sturgeon *Acipenser transmontanus* population in the Sacramento–San Joaquin River basin. Standard errors were not available (NA) for several of the age-specific vital rates.

Symbol	Definition	Age (i)	Value	SE	Source
n _i _{t=0}	Starting age-specific abundance	0	222,631,649	NA	Blackburn et al. (2019)
		1	1,758	NA	
		2	2,922	NA	
		3	1,826	NA	
		4	2,137	NA	
		5	5,169	NA	
		6	4,912	NA	
		7	6,635	NA	
		8	7,323	NA	
		9	5,497	NA	
		10	2,890	NA	
		11	2,121	NA	
		12	1,354	NA	
		13	3,709	NA	
		14	2,240	NA	
		15	4,244	NA	
		16	283	NA	
		17	3,673	NA	
		18	834	NA	
		19	2,653	NA	
f _i	Fecundity at age <i>i</i>	0–9	0	NA	Devore et al. (1995)
		10	33,298	11,070	
		11	83,641	8,777	
		12	108,812	7,773	
		13	148,367	6,522	
		14	195,114	5,876	
		15	209,498	5,895	
		16	245,457	6,436	
		17	263,437	6,920	
		18	310,183	8,626	
		19	335,355	9,723	
pm;	Probability of female maturity at age i	0–9	0.000	NA	Chapman (1989)
		10	0.025	0.077	
		11	0.086	0.173	
		12	0.143	0.220	
		13	0.291	0.266	
		14	0.543	0.275	
		15	0.622	0.278	
		16	0.788	0.263	
		17	0.849	0.235	
		18	0.942	0.142	
		19	0.966	0.098	
		20+	1.000	0.200	
p _i	Proportion of offspring that are females	10–19	0.500	NA	Chapman et al. (1996)
So	Egg-to-age-0 survival	0	0.002	0.003	Caroffino et al. (2010)
S ₁	Age-1 survival	1	0.250	0.008	Pine et al. (2001)
S ₂	Age-2 survival	2	0.840	0.168	Ireland et al. (2002)
$S_3 - S_{20+\leftarrow}$	Asymptotic survival	3–19	0.946	0.03	Blackburn et al. (2019)

however, adding harvested individuals did not change the overall results of the analysis so we did not include harvest in simulated abundances.

The estimated mean exploitation for White Sturgeon in the SSJ from 2007 to 2015 was 0.136 (95% confidence interval = 0.01–0.262), but for simplicity we assumed exploitation was 0.15 (Blackburn et al. 2019). We varied μ from 0.00 to 0.30 in 0.05 increments, both to address the uncertainty in exploitation estimates and to explore the effect of potential management changes on age-specific abundances. The estimated frequency of recruitment was every 8 y based on empirical evidence from the Bay Study otter trawl surveys (Gingras et al. 2013). We varied the probability of recruitment from every 10 y to every year (p = 0.10-1.0) to simulate potential changes in water management or spawning habitat that could lead to recruitment success.

We assessed the probability of achieving the current population objective (i.e., 11,000 age-15 White Sturgeon) and the alternative population objective (i.e., 155,000 adults) for each scenario of recruitment and exploitation. We simulated the probability of reaching the population



Figure 1. von Bertalanffy growth model, $L_t = 380 \times \{1 - e^{[-0.027(age+2.36)]}\}$, derived from White Sturgeon Acipenser transmontanus sampled during August–October of 2014–2016 in Suisun and San Pablo bays, California. The shading illustrates the probability of female maturity at a given length and age.

objective as the number of iterations out of 1,000 that reached the objective on the last year of the simulation:

$$p_{50} = \underbrace{I_{50}}{1,000}$$

where p_{50} is the probability of reaching the population objective on the last year of the 50-y period and I_{50} is the number of iterations that reached the objective on year 50. We compared the probability of reaching the alternative objective (i.e., 155,000 adults) with the current objective (i.e., 11,000 age-15 White Sturgeon) by taking the difference in probabilities of each objective for every scenario combination of recruitment and exploitation.

Results

With current estimated exploitation rate ($\mu = 0.15$) and recruitment frequency (p = 0.12; once every 8 y), the probability of reaching the population objective for White Sturgeon of 11,000 age-15 individuals at the end of a 50-y period was approximately 7% (Figure 2). The probability of reaching the population objective with varying recruitment and exploitation was low, where the probability rarely exceeded 50%. The probability of reaching the population objective only exceeded 50% on year 50 if recruitment occurred every year. The probability of reaching the objective was inversely related to exploitation and positively related to recruitment.

In comparison, the probability of reaching the alternative population objective of 155,000 adult White Sturgeon on year 50 was more than five times higher (i.e., 37%) than reaching 11,000 age-15 fish at current

exploitation and recruitment rates (Figure 2). Scenarios with a recruitment frequency less than every 4 y illustrated a lower probability (< 75%) of reaching the objective on the last year of the simulation. Though, the probability of achieving the alternative objective was generally much higher than the current objective, especially at exploitation rates < 0.15 (Figure 3).

Discussion

The current CVPIA population goal tracks the status of White Sturgeon in the SSJ as the abundance of age-15 individuals. Unfortunately, the population goal may not be feasible when defined as 11,000 age-15 fish. Yearclass strength of White Sturgeon in the SSJ is highly variable. Recruitment failure is common and a strong year class occurs approximately once every 8 y (Gingras et al. 2013). Carried forward, monitoring annual abundance of a single age class would not be a representative metric for population growth and the objective could only be achieved in years that coincide with very high recruitment events (McAdam et al. 2005). In addition to the low feasibility of the current population objective, age-15 White Sturgeon represent a small proportion of the mature adult population. Age-15 females have a probability of maturity of approximately 50% and are vulnerable to harvest. Although this cohort may provide a metric of the number of individuals recruiting to maturity, it fails to represent most of the spawning population, including fish that have escaped legal harvest.

The probability of achieving the doubling goal was higher if defined as double the spawning population size rather than double the abundance of age-15 White Sturgeon. The probability of reaching 155,000 adults





Figure 2. The probability of reaching population objectives for White Sturgeon *Acipenser transmontanus* in the Sacramento–San Joaquin River basin with varying exploitation rates (proportion of adult population harvested annually) and recruitment probabilities (probability of a successful recruitment year) using a stochastic population model with a starting adult abundance of 48,000 (i.e., estimated abundance of age 10+ White Sturgeon in 2009). The locally weighted scatterplot smoother (LOESS) depicts the number of 1,000 simulations that reached 11,000 age-15 White Sturgeon and 155,000 adult White Sturgeon (ages 10+) on the last year of simulated abundance (t = 50). Shaded area indicates the 95% confidence interval of the LOESS smoother.



Figure 3. Difference in the simulated probability of reaching a population objective of 155,000 adult White Sturgeon *Acipenser transmontanus* (ages 10+) in the Sacramento–San Joaquin River basin compared with the current objective of 11,000 age-15 White Sturgeon on the last year of simulated abundance (t = 50) using a stochastic population model with a starting adult abundance of 48,000 (i.e., estimated abundance of age 10+ White Sturgeon in 2009). Differences were evaluated across varying rates of exploitation and recruitment probabilities. A positive difference indicates that the simulated probability of reaching the alternative objective is higher than the current objective.

over 102 cm in length was higher in nearly all scenarios than reaching an objective of 11,000 age-15 fish. Recruitment is variable, so tracking a single cohort does not reflect overall population trends and undermines perceived progress toward the CVPIA population goal. By tracking spawning population size, abundance estimates are less sensitive to recruitment variability and reflect overall trends toward population goals.

Results from our population modeling demonstrate a higher probability of reaching the alternative population objective than the current population objective at the end of the period. However, a few assumptions of our modeling approach should be considered. First, we based reproductive vital rates in the population model on the best information available, but the information on spawning periodicity and fecundity may be outdated and additional research would be useful (Chapman 1989; Devore et al. 1995; Chapman et al. 1996; see also Blackburn et al. 2019). Though, the probabilities of reaching population objectives were similar when a range of spawning periodicities was used in the population model. Second, changes in estimated mortality could influence the population growth rate. However, evaluation of population dynamics of White Sturgeon in the SSJ reveal that adult survival had the greatest influence on population growth compared with juvenile and subadult survival (Blackburn et al. 2019). Therefore, outcomes in our modeling approach are likely more sensitive to varying exploitation and recruitment frequency than survival at early life stages. Third, frequency of recruitment is based on a coarse index of relative juvenile abundance estimated from otter trawl data, which has led to the assumption that recruitment occurs approximately every 8 y (Gingras et al. 2013). Targeted sampling of juvenile White Sturgeon would be beneficial for modeling efforts to understand the effects of recruitment variability at a finer scale. Despite these uncertainties, the probability of achieving the current population objective remains low as demonstrated by our modeling exercise and the failure to achieve the CVPIA goal over the past 25 y under the current framework.

The CVPIA population objective is contingent on baseline estimates of mean abundance of age-15 White Sturgeon in the SSJ and flaws in the methodology of this estimate should also be considered. The abundance of age-15 individuals during the baseline period was calculated by applying an age-length key that was developed using a subsample of age-length information from 1973 to 1976 (Kohlhorst et al. 1980) to the estimated abundance in each year (8 seasons from 1967 to 1991). An age-length key can be used to estimate an unbiased age-frequency distribution if the following assumptions are met: no overlap in size between successive ages in a population, the relative numbers of age classes do not change from year to year, or the sample was taken from the same population at the same time (Westrheim and Ricker 1978; Paukert and Spurgeon 2017). Considering these assumptions, it is apparent that an age-length key should only be applied if the sample was taken from the same population at the

same time, because sizes of successive ages frequently overlap and the relative numbers of age-classes change annually as a result of variable recruitment (Kohlhorst et al. 1980; Gingras et al. 2013). Growth rates measured from archived fin rays show that mean growth has varied during 1980–2016 (Blackburn 2018), providing further evidence that the use of an outdated age–length key could introduce substantial bias to contemporary estimates of age-15 White Sturgeon.

Many conservation goals require decades to achieve; therefore, a single long-term goal may be inadequate without additional short-term objectives that measure progress (Tear et al. 2005). For long-lived species, delayed maturity can present a challenge for monitoring populations. Failed recruitment or the effects of harvest can be masked for decades as fish recruit to the fishery (Crouse 1999). Therefore, it is necessary to not only monitor spawning population size but also recruitment of fish during early life stages. For example, a supporting objective of increasing detectable recruitment to every 4 y would allow managers to monitor short-term progress toward the CVPIA doubling goal and measure the effectiveness of management actions. Recruitment of White Sturgeon in the SSJ was positively associated with years classified as wet and therefore streamflow augmentation is a possible conservation action that could alter recruitment frequency (Gingras et al. 2013; Jackson et al. 2016).

White Sturgeon in the SSJ are sensitive to the harvest of adults and reducing harvest could have positive effects on population growth (Blackburn et al. 2019). An additional supporting objective of reducing the exploitation to < 0.05 would improve the probability of achieving the primary objective (155,000 adults) to at least > 50% according to our model. Management actions to reduce exploitation could include the introduction of total allowable catch and reducing illegal take. The inclusion of supporting objectives would be advantageous in that both can be measured, they reflect management decisions on a shorter timeframe, and both work toward the overall population objective of increasing adult abundance.

The CVPIA population objective for White Sturgeon in the SSJ of 11,000 age-15 individuals was established nearly 3 decades ago and has yet to be achieved. We have demonstrated the low probability of achieving the objective in the next 50 y. The poor feasibility of the objective is likely a consequence of the complex life history of a long-lived species, undermining perceived progress toward objectives for White Sturgeon. Monitoring adult abundance eliminates the need for an agelength key and annual recruitment variability will likely be buffered by monitoring a large cross-section of the population. Thus, a population objective based on abundance of adults may more reliably reflect progress toward the goal of the CVPIA. An alternative objective would also support effective management of White Sturgeon by reducing uncertainty in population trends; however, long-term sustainability of the population relies on adequate conservation goals. Periodic review and validation of the CVPIA doubling goal may be warranted to increase the understanding of White Sturgeon conservation in this system (Williams and Brown 2018).

Supplemental Material

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Reference S1. U.S. Fish and Wildlife Service. 1995. Working paper on restoration needs: habitat restoration actions to double natural production of anadromous fish in the Central Valley of California. Volume 3. Stockton, California: U.S. Fish and Wildlife Service.

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