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USE OF A MATHEMATICAL MODEL AS A MANAGEMENT TOOL TO EVALUATE SPORT ANGLING REGULATIONS FOR WHITE STURGEON IN THE SACRAMENTO-SAN JOAQUIN ESTUARY, CALIFORNIA

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ABSTRACT

During the mid-1980s, the sport fishery for white sturgeon (*Acipenser transmontanus*) in the Sacramento-San Joaquin Estuary achieved the potential to over-exploit the population. A mathematical model was developed to evaluate the effect of angling regulation changes on abundance, egg production, and catch over a 30-year period. The goal was to adopt regulations that were socially acceptable and that maintained white sturgeon abundance and egg production at the high levels of the mid-1980s. Representatives of the sturgeon angling community suggested some of the regulation alternatives evaluated by the model and selected preferred regulations from biologically acceptable alternatives. These regulations were implemented in March, 1990. Subsequent declines in white sturgeon catch and exploitation rate had a substantial economic impact. Results of additional model evaluations allowed a slight liberalization in the originally-adopted angling restrictions. Monitoring will be continued to evaluate the need for additional regulation changes.

Keywords: abundance, catch, egg production, fishery, management, mathematical model, regulations, sport angling, white sturgeon

INTRODUCTION

The white sturgeon (*Acipenser transmontanus*) population in California is almost entirely confined to the Sacramento and San Joaquin rivers, the largest streams in California's Central Valley, and their common estuary, terminating in San Francisco Bay. A detailed description of the Sacramento-San Joaquin Estuary is provided in Kelley (1966) and Kohlhorst et al. (1991).

White sturgeon is a native fish and the object of an important sport fishery; commercial fishing for sturgeon is prohibited in California. Commercial fisheries greatly reduced white sturgeon populations in rivers and estuaries along the west coast of North America in the late 1800s (Craig and Hacker 1940; Skinner 1962; Semakula and Larkin 1968; Riemen and Beamesderfer 1990). As the result of over-exploitation, all sturgeon fishing was prohibited in the Sacramento-San Joaquin Estuary in 1917; the fishery was reopened in 1954 to sport angling only. The sport fishery was governed by the same regulations from its inception until 1989: a year-round season, 102 cm total length (TL) minimum size limit, and a one fish per day creel limit. An exception was the period from 1956 to 1963, when the minimum size limit was 127 cm TL. Regulations resulting from the activities described in this report have been in effect since 1990.

Tagging studies in the Sacramento-San Joaquin Estuary indicate that abundance of legal-sized white sturgeon has varied dramatically (11,000-128,000) over the last 35 years, while total mortality rates (A) during much of that period were low and relatively stable (0.10-0.18) (Pycha 1956; Chadwick 1959; Miller 1972; Kohlhorst 1979, 1980; Kohlhorst et al. 1991). Thus, fluctuations in legal-sized white sturgeon abundance have been primarily dependent on variable recruitment. However, total mortality rate has increased recently as annual exploitation rate (u) rose from a mean of 0.069 in the 1960s and 1970s to 0.097 in the 1980s. This 41% increase in u resulted from growing popularity of the fishery as abundance reached a peak of 128,000 in the mid-1980s and anglers became more efficient (Kohlhorst et al. 1991).

The California Department of Fish and Game (CDFG) and the sport angling community became concerned in the late 1980s by increased exploitation rate, declining catch, and known susceptibility of sturgeon populations to over-harvest. The need for angling regulation changes to protect the future productivity of white sturgeon led to development of a mathematical population model to be used to evaluate alternative regulations.

This paper describes the model, recounts the cooperative effort between professional fishery managers and the sport angling community to implement biologically and socially acceptable regulation changes, and provides a preliminary evaluation of the effect of these changes on the fishery.

MATERIALS AND METHODS

As the result of meetings with representatives of the sturgeon angling community, CDFG scientists evaluated a range of angling regulation alternatives with the biological objective of maintaining a population of 100,000 white sturgeon $\geq$102 cm TL that annually produces about one billion eggs. These values reflect abundance and egg production in the mid-1980s that were judged desirable by anglers based on fishing success during that period. This led to development of an age-structured population model founded on the best available information about white sturgeon population dynamics in the Sacramento-San Joaquin system.

The model is a series of three nested MINITAB® macros and an associated data file which I used to project the impact of angling regulation changes over the 30-yr period 1990-2019. MINITAB® is a statistical software package capable of repetitive computations and data manipulations using stored instructions called macros.

The structure of the model is given by the following equations:

$$N_t = \left(\sum_{i=9}^{59} (n_{i,t-1})(1 - u_{i,t-1} - v)\right) + r_t$$

$$r_t = (n_{6,t-3})(1 - u_{6,t-3} - v)(1 - u_{7,t-2} - v)(1 - u_{8,t-1} - v)$$

$$n_{6,t} = (E_{t-6})(S_{egg-age\ 6})$$

$$E_t = \sum_{i=11}^{60} ((n_{i,t})(f_i))$$

$$C_t = \sum_{i=6}^{60} ((n_{i,t})(u_{i,t}))$$

with the general notation:

N_t = abundance in year t of white sturgeon $\geq$age 9,

$n_{i,t}$ = abundance of age i fish in year t,

$u_{i,t}$ = rate of exploitation of age i fish in year t,

ν = natural mortality rate,

r_t = recruitment at age 9 in year t,

E_t = population egg production in year t,

f_i = effective fecundity of age i fish,

C_t = catch in year t, and

$S_{egg\text{-}age\ 6}$ = survival from egg to age 6 = 2.2647×10^{-5}.

Input to the model is initial age-structured abundance from age 6 to 60 years, initial recruitment, age-specific *u*, natural mortality rate (ν), and age-specific fecundity. The 6 years from 1984 to 1989 are used as a "warm-up" period. Assumptions include an original (1984) equilibrium population of 100,000 fish $\geq$age 9 (approximately the mean age of recruitment at the minimum legal size of 102 cm TL), A of 16% (ν = 10% and u = 6%) at full recruitment (age 12), and annual production of 971 million eggs. These abundance and mortality rate values are based on tagging results (Kohlhorst et al. 1991). The age structure of the initial population (Table 1) conforms to these parameters, with exploitation rate for partially recruited ages 6-11 adjusted based on age-specific length distributions. Egg production is based on a regression of log(fecundity) on age (Figure 1, strongly influenced by a single age 54 fish), modified by the age-specific fraction of females which are mature, the age-specific fraction of mature females which spawn, and the age-specific sex ratio (Table 2). At each age, the resultant effective fecundity is multiplied by abundance and these products are summed over all ages to estimate annual egg production.

The values used in Table 2 to modify fecundity are not empirical estimates, but are my judgement of reasonable values based on data from this and other sturgeon populations. I assumed a symmetric maturation schedule with earliest spawning at age 11, half the females mature at age 15, and all females mature at age 20. Maturation of a few fish at age 11 is consistent with the size and age of the smallest fish with developed eggs observed in the Sacramento-San Joaquin system (Figure 1). The change in the sex ratio (fraction female) in Table 2 is used in lieu of sex-specific mortality rates to allow the modelled population to match observations that most large sturgeon are females (Magnin 1966; Wisconsin DNR 1967; Folz and Meyers 1985; Brennan and Cailliet 1989), although growth rate of white sturgeon does not differ between sexes (Kohlhorst et al. 1980).

During the "warm-up" period, 1984-1989, I assumed that *u* is 10%, again based on tagging results (Kohlhorst et al. 1991). This results in a 1989 population of 86,428 fish $\geq$age 9 and egg production of 770 million. This is the initial population upon which alternative angling regulation changes begin to act in 1990.

I assumed that angling regulation changes affect the population through age-specific changes in *u*. Natural mortality rate (v) is held constant at 10% and $A = u + v$ (Ricker 1975). Effects of angling regulation changes on *u* were estimated from available information on size and age frequency distributions, growth (Kohlhorst et al. 1980), and temporal and spatial distribution of the catch based on tag returns (Kohlhorst et al. 1991; California Department of Fish and Game, unpublished data).

I assumed that no compensatory changes in v, growth rate, fecundity, or the stock-recruitment relationship occur in response to varying *u*. As rapid over-exploitation of sturgeon stocks has been widespread, the compensatory capacity of sturgeon populations is demonstrably limited, but unquantified.

The model only evaluates the impact of changing mortality on the population and implicitly assumes that environmental factors affecting recruitment and mortality are constant, or vary in the same manner, under all angling regulation scenarios.

RESULTS

Initial Evaluation

Based on the array of potential angling regulation changes that were available (Table 3), 10 alternatives were selected for evaluation (Table 4). Angler representatives, while strongly committed to actions to reduce harvest and maintain the white sturgeon population, were also committed to minimizing the impact of regulation changes on their segment of the fishery. Those anglers fishing on the spawning grounds in the Sacramento River, while supportive of a maximum size limit, were wary of a relatively low maximum, of a closed season in the spring, or of a protected slot limit which greatly restricted their fishery. Conversely, anglers fishing in the downstream feeding areas of San Francisco Bay, where many small white sturgeon enter the catch, generally opposed substantial increases in the minimum size limit. Thus, the selection of alternatives to be evaluated was somewhat eclectic. The alternatives ranged from continuation of the present regulations to a harvest slot of 122-183 cm TL. For this most restrictive alternative, the minimum size limit would be increased from 102 cm TL to 122 cm TL in four annual 5-cm increments based on reasoning by angler representatives that this would be less disruptive to the fishery than a 20-cm increase in one year.

The modelled impact of these alternative regulation changes on white sturgeon abundance, egg production, and catch varied substantially (Table 4). Only four of the alternatives (alternative 4: 102-152 cm TL harvest slot; alternative 8: incremental change to a 122-183 cm TL harvest slot; alternative 9: 114-183 cm harvest slot; alternative 10: 102-183 cm TL harvest slot with no fishing in March) met the dual biological criteria of increasing white sturgeon abundance to 100,000 fish $\geq$102 cm TL and annual production of about one billion eggs. These alternatives resulted in increases in abundance of 16-35% above the base year 1989 after population fluctuations in the first 12-14 years following the regulation change (Figure 2a). The early variability in abundance was due to the combination of initial protection from exploitation and residual effects on recruitment of higher prior exploitation rates.

Modelled egg production for all biologically acceptable alternatives steadily increased over the 1990-2019 simulation period (Figure 2b). The increase varied from 53% for a 114-183 cm TL harvest slot to 73% for both a 102-152 cm TL harvest slot and an incremental change to a 122-183 cm TL harvest slot (Table 4).

Because of the restrictions imposed by angling regulation changes and the slow recovery of abundance, all biologically acceptable alternatives resulted in reduced simulated catch relative to the base year 1989. The greatest decrease occurred in the first year new angling regulations were in effect; thereafter, the pattern of change varied among the alternatives. Three alternatives, after variable periods of generally declining catches, exhibited steadily increasing catches over the last 12-16 years of the simulation to conclude in 2019 at values 12-29% below the initial 1989 level (Table 4, alternatives 4, 9, and 10; Figure 2c). The 122-183 cm TL harvest slot alternative exhibited a continued sharp decline in catch for 3 years after the initial year of angling regulation change (due to the incremental nature of the increase in the minimum size limit from 102 cm to 122 cm TL), then a period of relatively stable catches followed by a 12-year period of increase; final catch was still 37% below the 1989 catch (Table 4, alternative 8; Figure 2c).

The second meeting between CDFG staff and angler representatives resulted in acceptance of one of the alternatives from among those that met the biological criteria. A maximum size limit of 152 cm TL (alternative 4) was too small to be tolerable to anglers fishing in the spawning area of the Sacramento River and a closure during March (alternative 10), one of the best fishing months, was not acceptable to any angler group. The final decision was to recommend a change in sturgeon fishing regulations to institute a 122-183 cm TL harvest slot arrived at by raising the 102 cm TL minimum size limit to 122 cm TL in four annual 5-cm increments (alternative 8). This was deemed by angler representatives to offer the best chance for restoration of the sturgeon population (true) and to minimize disruption to the fishery because of the phased implementation of the greater minimum size limit (questionable).

This recommendation was adopted by the Fish and Game Commission[1] in 1989 and became effective March 1, 1990. The maximum size limit took effect immediately, while the minimum size increased to 107 cm TL at that time and was increased again, to 112 cm TL, on March 1, 1991. In 1991, the Fish and Game Commission enacted regulations to further increase the minimum size limit for sturgeon to 117 cm TL on March 1, 1992 and 122 cm TL on March 1, 1993.

Second Evaluation

The maximum size limit was readily accepted by sturgeon anglers, as were the initial increases in the minimum size limit from 102 cm TL to 107 and 112 cm TL. Either through lack of communication and publicity by the CDFG or inattentiveness and a "short memory" on the part of many anglers, the

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[1] In California, the Fish and Game Commission, composed of five members appointed by the Governor, has the responsibility for administratively establishing hunting and fishing regulations based on recommendations from the CDFG and the public.

second phase of the angling regulation change, in which the minimum size was raised to 117 and 122 cm TL, precipitated considerable protest from some angler groups.

In the meantime, continuation of the CDFG tagging program in 1990 and 1991 had suggested a substantial decline in white sturgeon abundance in the estuary, from a high of 128,000 in 1984 to 27,000 in 1990, and a decrease in exploitation rate to 3.3% in the year following tagging in fall 1990. These population statistics are applicable to fish $\geq$102 cm TL, so they are comparable to values estimated under previous angling regulations. Thus, the perception by many anglers that white sturgeon fishing had become very poor was substantiated by our most recent estimates of abundance and exploitation rate.

CDFG managers met with angler representatives and charter boat operators in spring 1992 to re-evaluate the need for more restrictive angling regulations. Charter boat operators (charter boats take anglers fishing for a fee) and bait shop owners had suffered economic hardship as the result of the declining white sturgeon fishery and the perception by the angling public that catching a legal-sized sturgeon under the new regulations was improbable. As a result of this meeting, six additional angling regulation alternatives were evaluated using the white sturgeon model (Table 5), four as ways to ameliorate the impact of the changes on those whose livelihood depends on the fishery, and two (catch and release and complete closure of sturgeon fishing) as scenarios providing maximum protection to the resource. In spite of the lower exploitation rate estimated in 1990, I continued to use the conservative value of 10% in the model evaluation. All alternatives had a positive effect on abundance and egg production; those that allowed continued harvest reduced catch from 27 to 42% compared to the base year 1989.

CDFG personnel felt it was inappropriate to reverse course and make major changes in the original recommendations to the Fish and Game Commission. A compromise was reached with angler groups to halt the increase in the minimum size limit at 117 cm TL and retain the maximum size limit of 183 cm TL. This was recommended to the Fish and Game Commission in fall 1992 and was adopted effective March 1, 1993.

DISCUSSION

The age-stratified model of the Sacramento-San Joaquin Estuary white sturgeon population proved to be a useful tool in evaluating the effects of potential angling regulation changes. However, simplifying assumptions affect the realism of the results. Probably the most important of these is the assumption that no compensatory mechanisms exist to respond to changes in mortality rates. As the population expands, it is likely that other mechanisms would come into play to slow or halt the increase. Thus, the magnitude of the positive response to restrictions in harvest predicted by the model is probably overly optimistic.

As with any mathematical model with no stochastic environmental component, environmental variability cannot be taken into account; eg. the known effect of freshwater outflow and spawning stock size on white sturgeon year-class strength is not incorporated into the model (Kohlhorst et al. 1991). This precludes predictive capability of the model and only allows comparison of alternative scenarios, not forecasts of likely future population trends. Thus, results of the evaluation of the angling regulation alternatives do not realistically predict future changes in white sturgeon abundance or egg production.

Notwithstanding the above limitations, the use of the model to compare angling regulation alternatives in an understandable way was crucial to building a consensus among concerned anglers about the best way to maintain the white sturgeon fishery. It allowed CDFG managers to endorse an array of biologically acceptable alternatives for consideration by representatives of a diverse group of angler representatives. When impacts of the regulation changes and the decreasing white sturgeon population created controversy, the model was again instructive in providing a common frame of reference for resolving the conflict between short-term economic considerations and the long-term maintenance of the fishery.

CDFG will continue a tagging program to monitor the response of the white sturgeon population to the present angling regulations and recommend changes if necessary.

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Table 1. Mortality rates and age structure of the initial equilibrium Sacramento-San Joaquin Estuary white sturgeon population (both sexes) assumed to exist in 1984. Based on 100,000 fish age ≥ 9 and an annual mortality rate of 16% after full recruitment at age 12. All recruited and partially-recruited age classes up to age 60 are included.

<table>
<tr><th>Age</th><th>Natural Mortality (v)</th><th>Exploitation Rate (u)</th><th>Annual Mortality Rate (A)</th><th>Abundance</th></tr>
<tr><td>6</td><td>0.100</td><td>0.003</td><td>0.103</td><td>21,990</td></tr>
<tr><td>7</td><td>|</td><td>0.008</td><td>0.108</td><td>19,725</td></tr>
<tr><td>8</td><td>|</td><td>0.022</td><td>0.122</td><td>17,595</td></tr>
<tr><td>9</td><td>|</td><td>0.035</td><td>0.135</td><td>15,448</td></tr>
<tr><td>10</td><td>|</td><td>0.050</td><td>0.150</td><td>13,363</td></tr>
<tr><td>11</td><td>|</td><td>0.057</td><td>0.157</td><td>11,358</td></tr>
<tr><td>12</td><td>|</td><td>0.060</td><td>0.160</td><td>9,575</td></tr>
<tr><td>13</td><td>|</td><td>|</td><td>|</td><td>8,043</td></tr>
<tr><td>14</td><td>|</td><td>|</td><td>|</td><td>6,756</td></tr>
<tr><td>15</td><td>|</td><td>|</td><td>|</td><td>5,675</td></tr>
<tr><td>16</td><td>|</td><td>|</td><td>|</td><td>4,767</td></tr>
<tr><td>17</td><td>|</td><td>|</td><td>|</td><td>4,004</td></tr>
<tr><td>18</td><td>|</td><td>|</td><td>|</td><td>3,364</td></tr>
<tr><td>19</td><td>|</td><td>|</td><td>|</td><td>2,825</td></tr>
<tr><td>20</td><td>|</td><td>|</td><td>|</td><td>2.373</td></tr>
<tr><td>21</td><td>|</td><td>|</td><td>|</td><td>1,994</td></tr>
<tr><td>22</td><td>|</td><td>|</td><td>|</td><td>1,675</td></tr>
<tr><td>23</td><td>|</td><td>|</td><td>|</td><td>1,407</td></tr>
<tr><td>24</td><td>|</td><td>|</td><td>|</td><td>1,182</td></tr>
<tr><td>≥25</td><td>0.100</td><td>0.060</td><td>0.160</td><td>6,191</td></tr>
</table>

Table 2. Variables used to calculate age-specific effective fecundity of white sturgeon in the Sacramento-San Joaquin Estuary.

Age	Estimated Fecundity[1]	Fraction Mature	Fraction of Mature Fish Spawning At This Age[2]	Fraction Female	Effective Fecundity[3]
11	86,398	0.05	1.00	0.50	2,160
12	92,977	0.10	0.50	0.51	2,371
13	100,057	0.20	0.50	0.52	5,203
14	107,677	0.30	0.33	0.53	5,650
15	115,876	0.50	0.40	0.54	12,515
16	124,700	0.70	0.36	0.55	17,283
17	134,195	0.80	0.19	0.56	11,423
18	144,414	0.90	0.22	0.57	16,299
19	155,411	0.95	0.16	0.58	13,701
20	167,245	1.00	0.20[4]	0.59	19,735
|	|	|	|	|	|
60	3,149,495	1.00	0.20	0.99	636,600

[1] Predicted from the regression $\text{Log}_{10}(\text{eggs})=(0.0319 \times \text{Age}) + 4.59$

[2] Assumes 5-year spawning periodicity; thus, the fraction of mature fish spawning = ((fraction mature 5 years earlier that are now spawning again) + (fraction spawning for the first time at this age)) / fraction mature. At age 11, the age of first maturity, all mature fish are spawning. At age 14, no fish were mature 5 years earlier (age 9) and 0.30-0.20=0.10 are spawning for the first time. Dividing 0.10 by the fraction mature (0.30) yields 0.33, the fraction of mature fish spawning at this age. At age 16, the calculation is ((0.05+(0.70-0.50))/0.70=0.36.

[3] Effective fecundity = estimated fecundity x fraction mature x fraction of mature fish spawning x fraction female.

[4] At ages $\geq$20, the fraction of mature females that spawn at each age varies from 0.15 to 0.25 because of the maturity schedule from ages 11 to 19. The mean value of 0.20 is used for all ages $\geq$20.

Table 3. Alternatives for changes in sturgeon angling regulations in the Sacramento-San Joaquin system and the approximate reduction in catch expected from each. Impacts were estimated from the spatial and temporal distribution of tag returns and from the size distribution of tagged fish.

Regulation Change	Approximate Percent Reduction in Catch
Season closure	
January	13%
February	13%
March	18%
April	11%
May	7%
June	6%
July	3%
August	2%
September	3%
October	5%
November	7%
December	12%
Area closure	
Suisun Bay	27%
San Pablo Bay	28%
South San Francisco Bay	11%
Upper Sacramento River	4%
Season and area closure	
March-May, Upper Sacramento River	3%
March-May, San Pablo and Suisun bays	19%
December-February, San Pablo and Suisun bays	24%
Prohibit night fishing for sturgeon	16%
Upper Sacramento River only	3%

Punchcard restricting annual individual catch	Unknown
Increase minimum size limit from 102 cm TL to:	
107 cm TL	7%
112 cm TL	18%
114 cm TL	24%
117 cm TL	34%
122 cm TL	49%
127 cm TL	62%
Establish a maximum size limit of:	
152 cm TL	8%
178 cm TL	1%
183 cm TL	<1%
Retain present minimum size limit of 102 cm TL, establish a slot limit protecting fish from:	
127 to 152 cm TL	31%
127 to 183 cm TL	38%
122 to 183 cm TL	51%

Table 4. Estimated effect of alternative sport fishing regulations on the white sturgeon population in the Sacramento-San Joaquin Estuary after the regulations have been in effect for 30 years (1990-2019). Assumptions include an original (before 1984) equilibrium population of 100,000 fish $\geq$age 9, with annual recruitment to age 9 of 15,448, total mortality (A) after full recruitment of 16% (10% natural [v] and 6% exploitation [u]), and egg production of 971 million. From 1984 to 1989, it is assumed that exploitation rate was 10%, resulting in a 1989 population of 86,428 fish $\geq$age 9, egg production of 770 million, and catch of 8,782 fish. This is the initial population upon which alternative angling regulations begin to act in 1990. Continuation of 1989 regulations is represented by the 102-cm minimum size limit alternative.

	Abundance		Egg Production		Catch	
Regulation	Number	Percent Change	Number (Millions)	Percent Change	Number	Percent Change
Minimum size limit						
1) 102 cm TL	38,737	-55%	319	-59%	3,911	-55%
2) 114 cm TL	51,440	-40%	414	-46%	3,951	-55%
3) 127 cm TL	73,636	-15%	606	-21%	3,960	-55%
Harvest slot limit						
4) 102-152 cm TL	101,438	+17%	1330	+73%	7,765	-12%
5) 102-183 cm TL	80,487	-7%	1000	+30%	7,067	-20%
6) 102-127, $\geq$152 cm TL	63,068	-27%	567	-26%	4,668	-47%
7) 102-127, $\geq$183 cm TL	82,644	-4%	797	+4%	5,107	-42%
8) 122-183 cm TL[1]	116,716	+35%	1330	+73%	5,518	-37%
9) 114-183 cm TL	100,614	+16%	1180	+53%	6,238	-29%
10) 102-183 cm TL No fishing in March	99,843	+16%	1240	+61%	7,033	-20%

[1] Minimum size limit increases from 102 cm TL by 5 cm per year for 4 years.

Table 5. Results of the 1992 evaluation of additional sturgeon angling regulation alternatives for the Sacramento-San Joaquin Estuary. Methods, assumptions, and initial conditions are the same as described in Table 4.

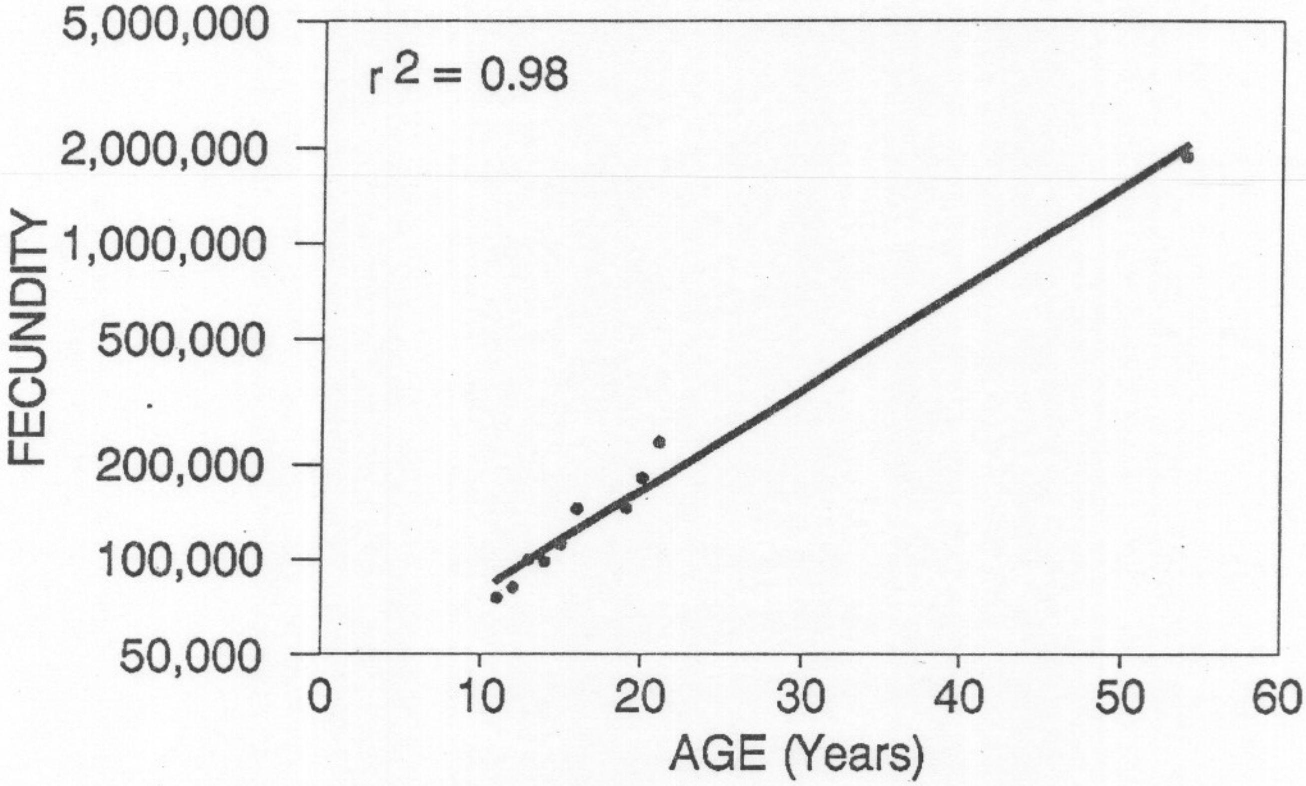
Regulation	Abundance Number	Abundance Percent Change	Egg Production Number (Millions)	Egg Production Percent Change	Catch Number	Catch Percent Change
Harvest slot limit						
112-183 cm TL	96,827	+12%	1140	+48%	6,382	-27%
117-178 cm TL	109,787	+27%	1280	+67%	6,075	-31%
117-183 cm TL[1]	105,591	+22%	1220	+59%	5,975	-32%
102 cm TL minimum size limit, closed season for 3 consecutive months between December and March	87,099	+1%	856	+11%	5,112	-42%
Catch and release only (1% handling mortality)	220,996	+156%	2670	+246%	0	-100%
Closed season (complete prohibition of sturgeon fishing)	268,224	+210%	3380	+339%	0	-100%

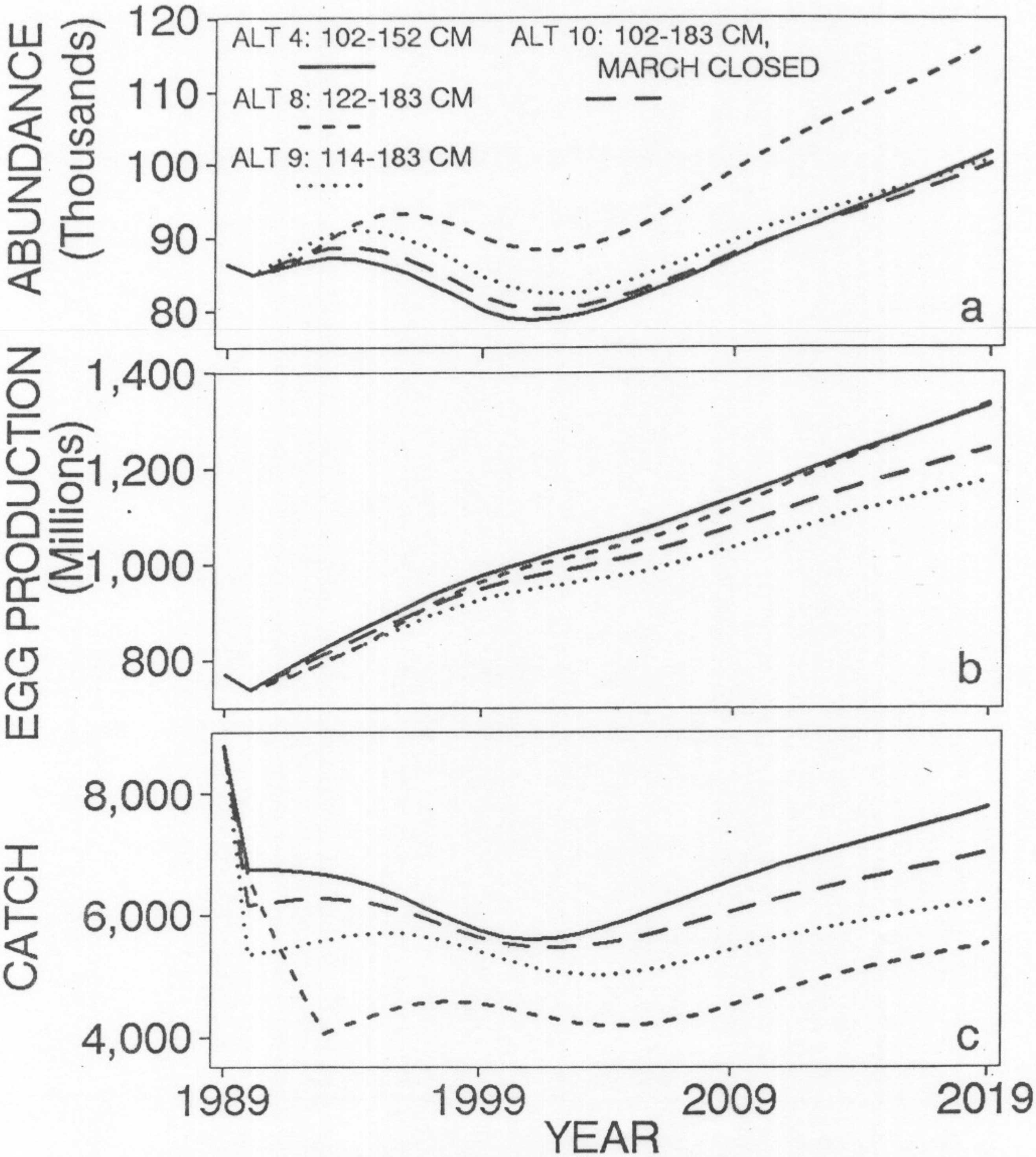
[1] Minimum size limit increases from 102 cm TL by 5 cm per year for 3 years

Captions for Figures

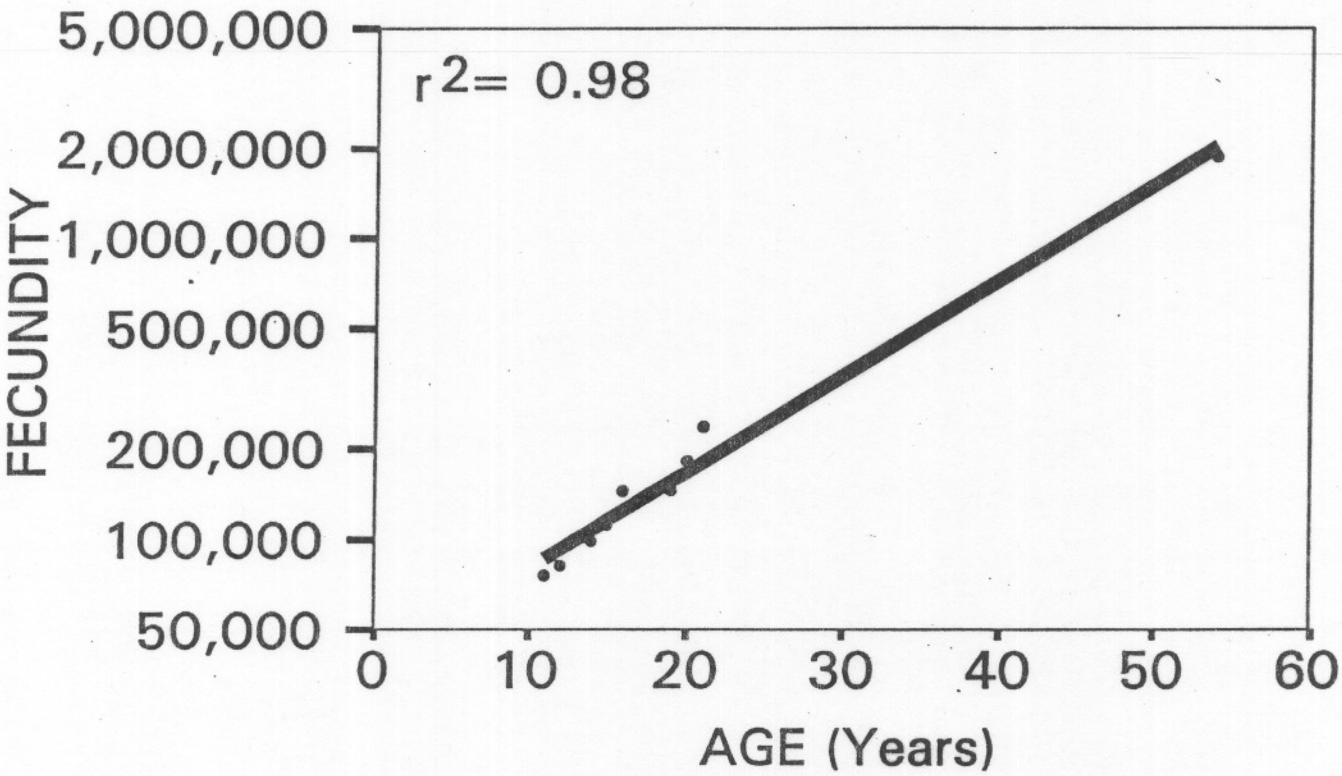
Figure 1. Relationship between fecundity and age for white sturgeon in the Sacramento-San Joaquin Estuary. The line represents the regression $\log_{10}(\text{eggs}) = 0.0319(\text{age}) + 4.59$.

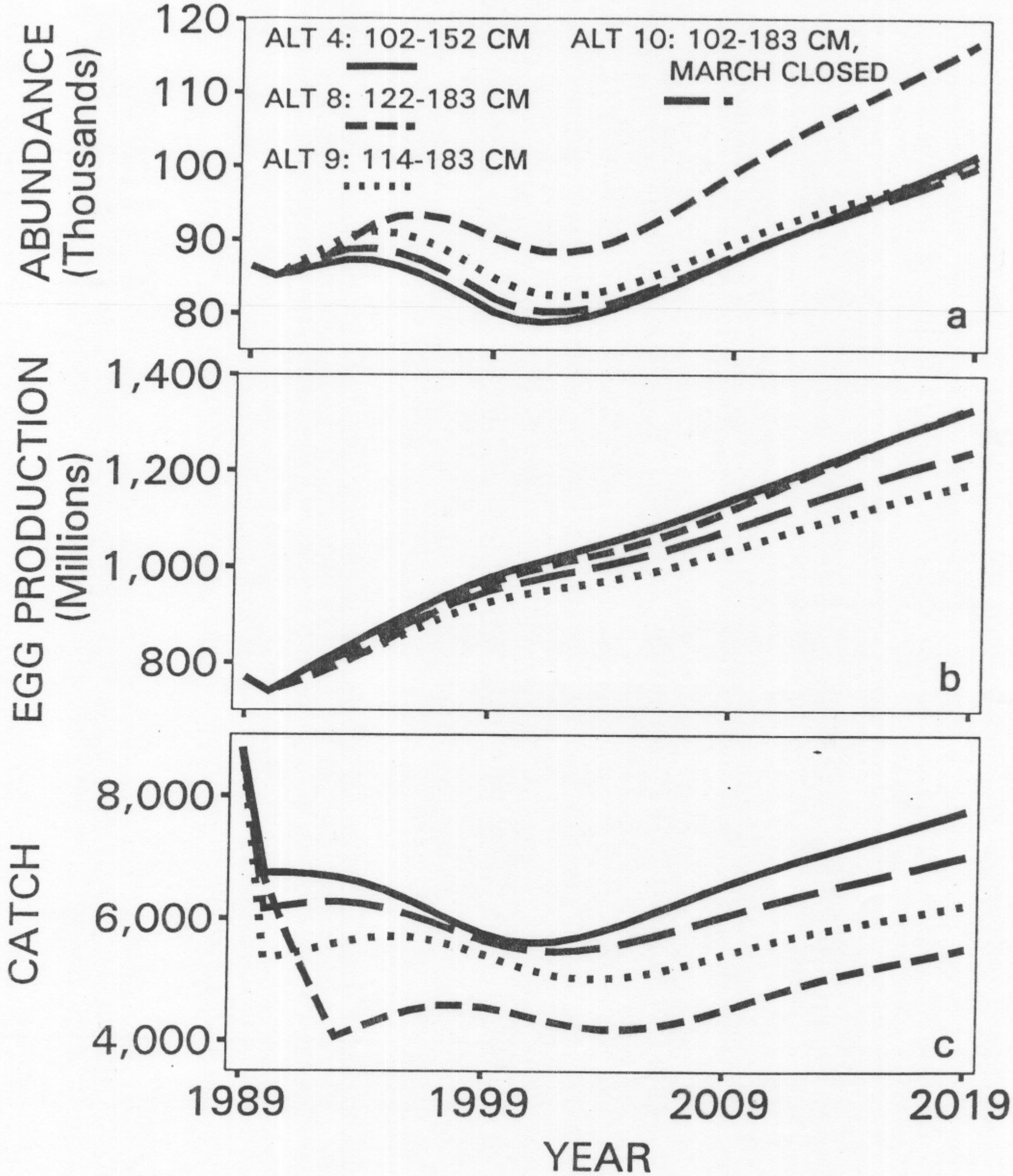
Figure 2. Simulated effect, over 30 years, of biologically acceptable alternative angling regulations on a) abundance, b) egg production, and c) sport catch of white sturgeon in the Sacramento-San Joaquin Estuary. Alternative regulations are more fully described in the text and in Table 4.


r 2 = 0.98
5,000,000
2,000,000
1,000,000
500,000
200,000
100,000
50,000
FECUNDITY
0
10
20
30
40
50
60
AGE (Years)



ALT 4: 102-152 CM
ALT 10: 102-183 CM, MARCH CLOSED
ALT 8: 122-183 CM
ALT 9: 114-183 CM
ABUNDANCE (Thousands)
120
110
100
90
80
a
EGG PRODUCTION (Millions)
1,400
1,200
1,000
800
b
CATCH
8,000
6,000
4,000
c
1989
1999
2009
2019
YEAR


5,000,000
2,000,000
1,000,000
500,000
200,000
100,000
50,000
FECUNDITY
r2= 0.98
0
10
20
30
40
50
60
AGE (Years)


ALT 4: 102-152 CM
ALT 8: 122-183 CM
ALT 9: 114-183 CM
ALT 10: 102-183 CM, MARCH CLOSED
ABUNDANCE (Thousands)
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EGG PRODUCTION (Millions)
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b
CATCH
8,000
6,000
4,000
c
1989
1999
2009
2019
YEAR