

White Sturgeon in the Lower Columbia River: Is the Stock Overexploited?

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Abstract.—We used computer simulation to examine potential yields and sustainable exploitation rates for white sturgeon *Acipenser transmontanus* in the lower Columbia River. Simulated yields varied with assumptions used for mortality, growth, and stock–recruitment relationship, and with size restrictions imposed on harvest. The stock–recruitment function had the greatest influence on our results. Maximum yields (sustained or at 100 years) ranged from 0.2 to 2.9% of unexploited biomass. Maximum yields were produced with exploitation rates ranging from 0.02 to 0.20, and yields declined or collapsed at higher rates. Size restrictions (sport and commercial harvest of fish only between 92 and 183 cm or 122 and 183 cm, respectively) resulted in higher yields and higher supportable exploitation than no size restrictions. However, size windows did not prevent collapse of the fishery under higher exploitation rates when a stock-dependent recruitment function was used. The fishery on the Columbia River has expanded dramatically in recent time. Most recent yields were about 30% of the peak yield realized when the stock was overfished before 1890, and were at least three times the sustained yields expected from our most optimistic simulations. Cultural development of the river could have reduced the productivity of the stock and made it vulnerable to overexploitation. The present fishery appears to be overexpanded. Current yields probably cannot be sustained, and current harvest risks eventual collapse of the fishery.

Overexploitation of long-lived, relatively slow-growing fishes is a well-known problem (Ricker 1963; Adams 1980; Francis 1986). Expanding fisheries typically produce increasing yields in a “fishing-up” process (Ricker 1975) that cannot be sustained. Yields can decline dramatically, often to levels that represent a small fraction of the peak (Francis 1986). If the fishery expands beyond the effort producing maximum sustained yield (MSY), stocks can be quickly and seriously overfished. Recovery to a level supporting MSY can take many years (Adams 1980; Francis 1986). The fishery for white sturgeon *Acipenser transmontanus* in the Columbia River is susceptible to each of these problems. White sturgeon may live to 100 years or more (Scott and Crossman 1979); Columbia River white sturgeon commonly exceed 30 years in age (Hess 1984). Although white sturgeon can reach tremendous sizes (reports from the Columbia River exceed 450 kg), documented growth is relatively slow (Hess 1984). Increase in weight from age 5 to age 30 averages less than 20% per year.

A commercial fishery for white sturgeon started on the Columbia River in the 1880s. The fishery expanded to a peak yield of nearly 2.5 million kg (80,000 fish) in 1892 and then declined to less than

45,400 kg by 1899 (Figure 1). Yield from the fishery fluctuated between about 45,400 and 227,000 kg from 1899 to the late 1960s.

Following the decline in catch, management agencies enacted new regulations. From 1897 to 1899, the states of Oregon and Washington adopted a 122-cm minimum-length restriction for commercial catches. Managers added a maximum-size restriction of 183 cm for sport and commercial catches and a 92-cm minimum-length limit for the sport fishery in the 1950s. In 1989 the minimum size for sport harvest was increased to 102 cm. Yields have increased since 1970 (Figure 1). Managers attribute some of the increase to the stock rebuilding under protective regulations (Galbreath 1985), but effort has increased in the same period (Figure 2). Both the sport fishery below Bonneville Dam and a native-American treaty fishery above Bonneville Dam increased substantially since the 1970s (Figure 2). The dominant part of the catch in recent years was taken in the 92–183-cm size window by sport fishermen.

Galbreath (1985) suggested that current regulations provide adequate protection from overexploitation. However, stock–recruitment and yield characteristics for Columbia River white sturgeon are unknown, so sustainable exploitation and yield under any management regime have not been estimated.

The Columbia River has also been developed.

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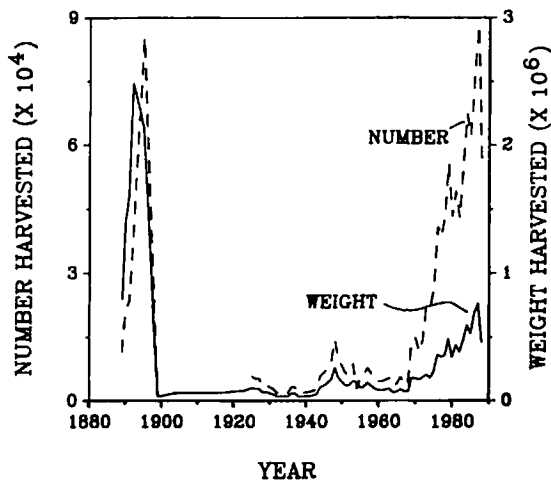


FIGURE 1.—Annual combined sport, commercial, and treaty harvests of white sturgeon from the lower Columbia River, 1889–1988. Data are from Cleaver (1951), FCO and WDF (1971), ODFW and WDF (1988), and Hess and King (1989).

Hydropower dams, the first constructed in the 1930s, have inundated sections of the once free-flowing river. A white sturgeon population that once moved freely within the river and between the river and the ocean is now restricted to a single free-flowing segment with access to the ocean and several smaller segments (reservoirs) blocked by the dams (Figure 3). White sturgeon do move between reservoirs, but the extent of movements relative to historic patterns is unknown and is thought to be very limited. Habitat throughout the river has been altered by flow regulation, channel modification, diking, and dredging. Habitat alterations have been associated with declines in other sturgeons (Artyukhin et al. 1978; Votinov and Kas'yanov 1978; Deacon et al. 1979). Reproduction and recruitment seem to be particularly vulnerable to the environmental changes caused by dams. Development of the Columbia River might well have resulted in a white sturgeon stock or a collection of stocks that are less productive than the one present in 1885.

To better understand the potential yield of the Columbia River white sturgeon fishery, we used population simulations to examine possible responses of white sturgeon populations to exploitation. We used a range of values for population parameters to represent productive as well as unproductive stocks. We describe potential peak and sustained yields simulated with harvest regulations like those used on the Columbia River. We use our results to examine the range of exploitation

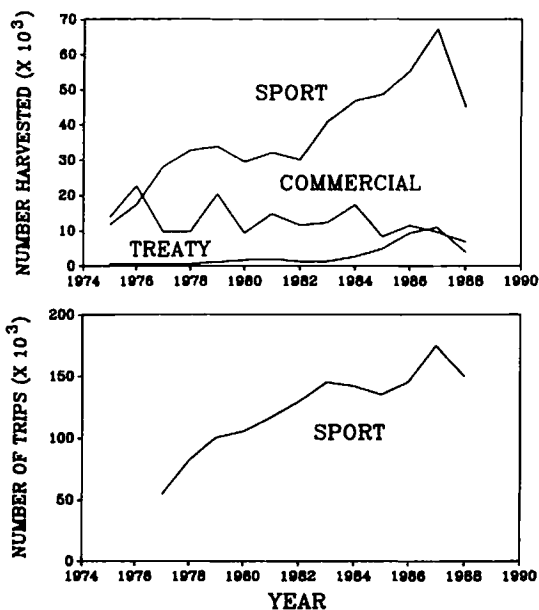


FIGURE 2.—Recent trends in annual harvest of white sturgeon from the lower Columbia River by sport, commercial, and treaty fisheries and in effort by sport anglers. Data are from ODFW and WDF (1988) and Hess and King (1989).

rates that should produce maximum sustained yields based on our assumptions. Our results will be useful for interpretation of future estimates of exploitation rates. We also use our results to compare theoretical sustained yields and peak yields with those observed for the fishery. We reasoned that the ratios of sustainable yields to peak yields from our models are a useful index of fishery potential. We assumed that a ratio of present yield to the historic peak that is substantially higher than our model predictions would be evidence of an overexpanded fishery.

For the sake of simplicity in our analysis, we have considered the fisheries below Bonneville Dam and those in three reservoirs above Bonneville Dam as one. We believe comparison of yields from these pooled fisheries to that taken from the historic free-ranging stock to be a liberal approach (i.e., it is more likely that development of the river has reduced the total productivity of white sturgeon rather than enhanced it). Our prediction of yield ratios should therefore be optimistic.

Methods

Simulations.—We used a life history model of a white sturgeon population to estimate the range over which maximum yield and the exploitation

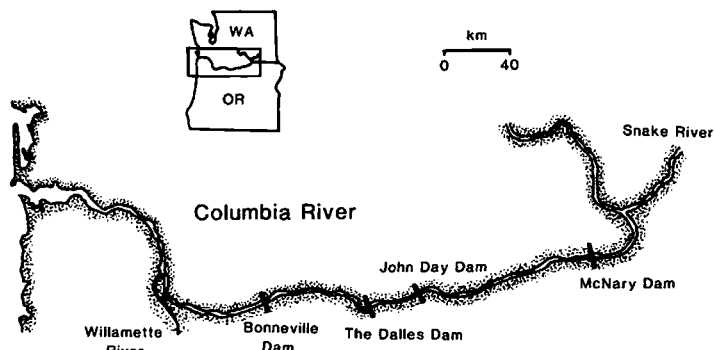


FIGURE 3.—The lower Columbia River between Oregon and Washington.

rate (proportion of the population removed annually) maximizing yield might be expected to vary given the predominant size restriction (92–183-cm window) regulating harvest during recent years. Our model incorporated recruitment, mortality, and growth to predict yield. We used a series of simulations with all combinations of low and high values for recruitment, mortality, and growth. We believe that the values used represent the realistic ranges of these values. Each simulation was run until the population stabilized or for 100 years, whichever occurred first. We ran all simulations with exploitation varied from 0.01 to 0.50. We use the term collapse to represent the condition when yield or the population number approached zero (less than 0.05% of the unexploited biomass or number) within 100 years.

To standardize results, we present yield as a percentage of total biomass in an unexploited population at equilibrium. We identified maximum yield from plots of yield versus exploitation. Because we do not know current numbers in the real populations, our simulations were based on arbitrary population sizes. Yields were compared among alternative exploitation and regulation scenarios on the basis of relative and not absolute differences.

We compared the effects of different size restrictions (none, 92–183 cm, 122–183 cm) on maximum yield with a second series of simulations in which rates of natural mortality and growth were held constant at intermediate values. We simulated the effects of regulation under high and low recruitment scenarios.

We used a third set of simulations to estimate peak yields associated with the fishing-up process, with and without size restrictions. We again used intermediate values for mortality and growth. The recruitment function was unimportant to the estimate of peak yield because yields peaked before

changes in the adult stock could feed back to recruitment. We compared cases in which exploitation increased geometrically (doubled each year) and more slowly (increments of 0.05/year). Simulations were run 1 year at a time until yield began to decline.

We used a final set of simulations to demonstrate the time lags possible in population and yield responses. We used an exploitation scenario that should be similar to recent changes in the Columbia River fishery. We used a model population with intermediate values for the growth and mortality parameters and the low stock–recruitment parameter. We imposed a 92–183-cm size window and exploited the population for 20 years at half the rate producing maximum sustained yield, then increased exploitation by 20% per year (roughly the rate of sport-harvest increase from 1974 to 1986) until the yield declined for 3 years. After the 3-year decline, we used three alternative responses in harvest: (1) exploitation was reduced to the rate producing maximum yield (0.05); (2) exploitation was held constant at the level in the third year of decline, but a 122–183-cm size restriction was imposed; and (3) exploitation was held constant at the level in the third year of decline. We then continued simulations for 50 years with no further changes in exploitation.

Population model.—We used an age-structured population model (Beamesderfer 1988) similar to that described by Taylor (1981) except that recruitment was either a Beverton–Holt-type function of adult egg production or constant. Numbers of sturgeon in each age-class (N_x) after the first year of simulation were calculated as

$$N_{x+1,t+1} = (N_{x,t})(S_x); \quad (1)$$

S_x = age-specific annual survival rate, and t = year. Age-specific annual survival was calculated as

$$S_x = 1 - [m_x + n - (m_x)(n)]; \quad (2)$$

m_x = age-specific harvest mortality (exploitation), and n = conditional natural mortality rate (Ricker 1975).

Density dependence in the model operated only through the stock-dependent recruitment function. The initial population in each simulation was assumed to be at equilibrium with no exploitation. Equilibrium egg production was calculated for the population with a stable age distribution at an arbitrarily selected recruitment to age 1. Mortality from age 0 to age 1 was calculated to produce the selected recruitment at equilibrium.

A density-dependent relationship between egg production and number of age-0 fish was represented by a Beverton-Holt recruitment function of the form

$$R = P / \{1 - A[1 - (P/P_r)]\}; \quad (3)$$

R = number of age-0 fish or recruitment; P = egg production; P_r = egg production at replacement; and A = a parameter with value 0-1 that completely describes the shape of the curve. Egg production was calculated as

$$P = \sum_x (N_x)(p_f)(p_s)(F_x); \quad (4)$$

p_f = proportion of population that is female; p_s = proportion of females that spawn in any year after the age of first maturity (M); and F_x = age-specific fecundity of females.

Age-specific fecundity was estimated as

$$F_x = a L_x^b; \quad (5)$$

L_x = age-specific length (cm), and a and b = parameters in the length-fecundity equation. Age-specific lengths were calculated with a von Bertalanffy model:

$$L_x = L_\infty(1 - e^{-k(x-t_0)}) \quad (6)$$

L_∞ = length (cm) at infinity, k = the growth coefficient, and t_0 = theoretical age at length 0.

Yield (Y ; weight of white sturgeon harvested) was calculated as

$$Y = \sum_x (N_x)(m_x)(W_x); \quad (7)$$

W_x = age-specific weight (kg). Age-specific weight was calculated as

$$W_x = cL_x^d; \quad (8)$$

c and d = length-weight equation parameters.

Parameter estimation.—We estimated fecundity, age at first maturity, and proportion of females spawning each year (Table 1) from data on

TABLE 1.—Parameter estimates used in simulations of a white sturgeon population.

Parameter ^a	Estimate		
	Intermediate	Minimum	Maximum
A (3)		0.5	1.0
a (5)	0.00013		
b (5)	4.13		
c (8)	0.00000065		
d (8)	3.43		
k (6)	0.045		
L_∞ (6)	285	229	340
M	15		
n (2)	0.075	0.05	0.10
p_f (4)	0.5		
p_s (4)	0.143		
t_0 (6)	0		

^a Numbers in parentheses indicate text equations for which parameters are defined.

white sturgeon in the Columbia River below Bonneville dam (S. King, Oregon Department of Fish and Wildlife, personal communication). We fit a length-fecundity relationship with a least-squares regression (Figure 4). Although estimates of these recruitment parameters are useful for realism of results under stock-dependent recruitment, they had relatively minor influence in our simulations. The stock-recruitment function was by far the dominant feature in simulated population responses. We therefore did not vary estimates of these parameters in our simulations.

We did vary parameter estimates for recruitment, mortality, and growth. We selected 0.5 for the parameter A in the stock-recruitment function to describe a reasonable lower bound in the shape of the curve and used constant recruitment to represent the upper bound (Figure 5). In the latter case, our model was equivalent to the Ricker equi-

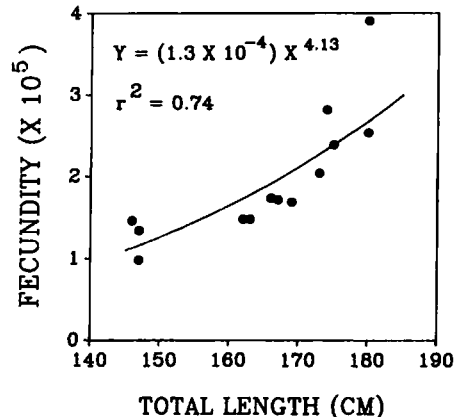


FIGURE 4.—Fecundity versus total length of white sturgeon from the lower Columbia River.

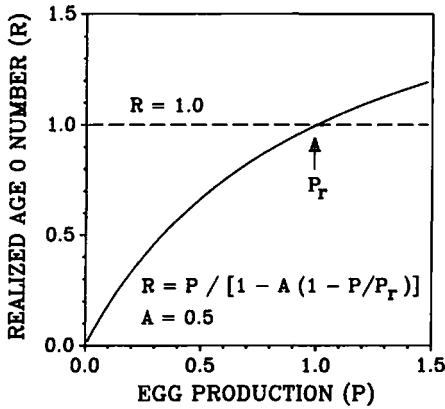


FIGURE 5.—Recruitment models used to simulate white sturgeon populations and fisheries in the lower Columbia River. The stock-dependent model is a Beverton-Holt function (Ricker 1975). R = number of age-0 fish or recruitment; P = egg production; P_r = egg production at replacement; A is a parameter from 0 to 1 that describes the shape of the curve.

librium yield model (Ricker 1975). The upper bound represents an exceptionally productive population, whereas the lower bound represents a population in which productivity is reduced but not unreasonably low (Kimura et al. 1984; Francis 1986).

We estimated the range of natural mortality (n ; Table 1) based on data presented by other authors (Table 2). We assumed that white sturgeon reached a maximum age of 75 years (though older fish are reported) because fish older than 75 years contributed little to total stock biomass, even under the lowest mortality rates.

We described growth with the von Bertalanffy model (Ricker 1975). We described upper and lower limits by using maximum and minimum values for L_∞ and k that gave curves tracing observed limits of age-length data for white sturgeon reported by other authors (Figure 6). We arbitrarily set t_0 equal to 0. Parameters for the length-weight equation were from Lukens (1985).

Results

The simulated response of yield to exploitation (under a 92–183-cm size restriction) varied sub-

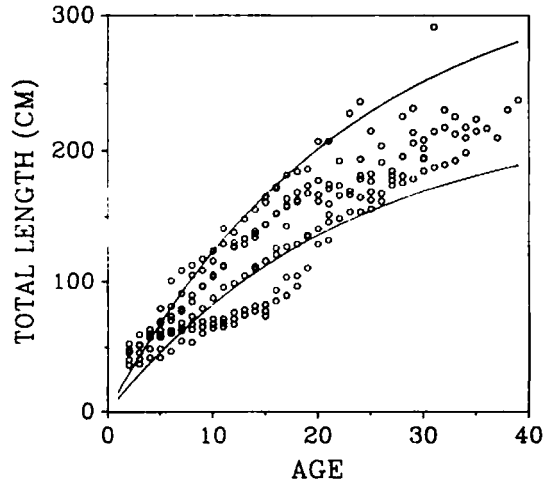


FIGURE 6.—Growth models (lines) used to simulate white sturgeon populations and fisheries in the lower Columbia River. Data are from the Columbia (Malm 1979; Hess 1984), Snake (Cochnauer 1983; Lukens 1985; Coon et al. 1977), Sacramento (Pycha 1956; Kohlhorst et al. 1980), and Fraser (Semakula and Larkin 1968) rivers.

stantially depending upon our assumed values for growth, mortality, and the recruitment function (Figure 7). Maximum yields ranged from about 0.2 to 2.9% of unexploited biomass. Exploitation rate producing maximum yield ranged from about 0.02 to 0.20 (Figure 7). Selection of the recruitment response had the most important influence on our results. Simulations with stock-dependent recruitment produced the lowest yields and supported the lowest exploitation rate. Populations with stock-dependent recruitment collapsed under the same exploitation levels producing maximum yields with constant recruitment (Figure 7).

Simulations with estimates of growth and mortality intermediate between extremes showed that the size limits may provide a benefit in yield at higher exploitation rates (Figure 8). When we used stock-dependent recruitment, a population simulated with no size restriction collapsed with exploitation of 0.10. A 92–183-cm window and 122–183-cm window resulted in collapse at exploitation rates of about 0.20 and 0.30, respectively. The

TABLE 2.—Estimates of annual rate of natural mortality (n) reported for white sturgeon populations.

Location	n	Ages	Reference
Fraser River	0.05	>10	Semakula and Larkin (1968)
Sacramento River	0.05–0.10	10–20	Kohlhorst (1980)
Snake River, Upper	0.06	16–30	Cochnauer (1983)
Snake River, Hell's Canyon	0.12	6–25	Lukens (1985)

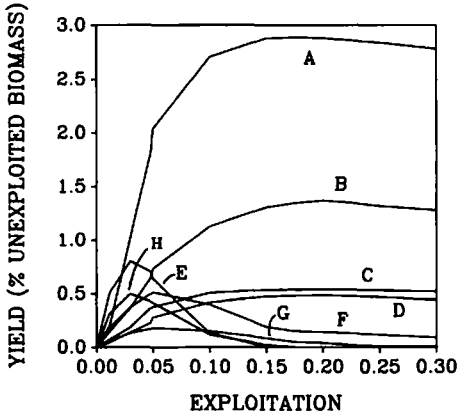


FIGURE 7.—Simulated yields in relation to exploitation rates under a 92–183-cm size window for white sturgeon populations. Curves represent simulations with different combinations of stable (*S*) and stock-dependent (*D*) recruitment, and high (*H*) and low (*L*) values for natural mortality and growth parameters, respectively, as follows: A = *S, H, L*; B = *S, H, H*; C = *S, L, L*; D = *S, L, H*; E = *D, H, L*; F = *D, H, H*; G = *D, L, H*; H = *D, L, L*.

size windows also produced substantially better yields than no limit when exploitation ranged from 0.05 to 0.20, but did not produce a higher maximum yield. When we used stable recruitment, a 92–183-cm size window produced lower yields than no size restriction with exploitation under about 0.15 (Figure 8) and similar yields at higher levels of exploitation. The 122–183-cm size window produced the highest yields of all simulations with exploitation higher than about 0.11.

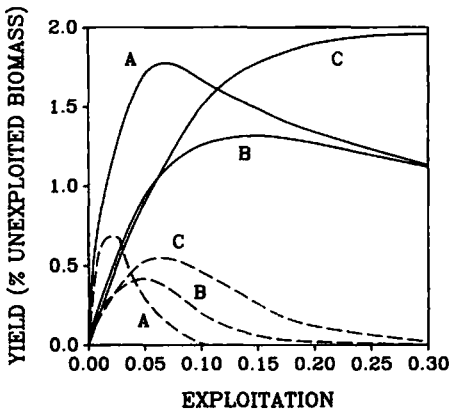


FIGURE 8.—Simulated yields of white sturgeon in relation to exploitation under three sets of size windows (A = none; B = 92–183 cm; C = 122–183 cm) with stable (solid lines) and with stock-dependent (dashed lines) recruitment. Models used intermediate values for natural mortality and growth parameters.

TABLE 3.—Peak and sustained or 100-year yields (percent of unexploited biomass) from simulated “fishing up” (Ricker 1975) and sustained exploitation of white sturgeon.

Simulation	Regulation	
	No size window	92–183-cm window
Peak yield		
Fishing up, exploitation increased 0.05/year	14	9
Fishing up, exploitation doubled each year	29	40
Sustained yield		
Stock-dependent recruitment	0.5	0.4
Stable recruitment	1.7	1.3

Peak yield varied from 9 to 40% of unexploited biomass with the rate of fishing up and with the imposition of a size window (Table 3). Sustained yields with no size restriction were 2–12% of peak yield under the same regulation. Sustained yields with a size window were 1–14% of peak yields. We could expect sustained yields when most of the catch was taken in a 92–183-cm window to be 1–9% of the 1885 peak yield (i.e., under no size restriction).

In the final simulations with initial exploitation at half the rate producing the maximum 100-year yield, yield declined slowly for 20 years (Figure 9). We fished that population up to a peak yield of about 2.7% of unexploited biomass before yields began to decline again. Exploitation was 0.32 at

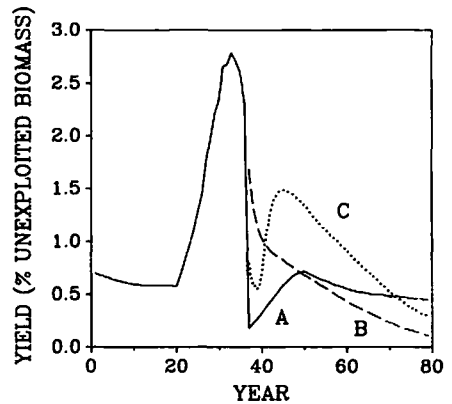


FIGURE 9.—Simulated yields from a white sturgeon population under three scenarios for exploitation following a peak and decline from fishing up. Exploitation rate under a 92–183-cm size window was constant at 0.025 for 20 years and then increased at 120% per year. After 3 years of declining yield, exploitation was (A) reduced to 0.05; (B) held at a maximum rate; or (C) held at the maximum rate with a 122–183-cm size restriction.

the peak and 0.46 by the third year of decline. In all of the alternative simulations following the peak, yields declined dramatically. When exploitation was reduced, yields recovered to the sustainable level in about 7 years. Exploitation sustained at the postpeak high resulted in decline toward collapse over a prolonged period. The most restrictive size limit produced a secondary peak in yield and delayed the long-term decline in yield.

Discussion

Results of our simulations were strongly dependent upon the recruitment functions we used. If recruitment for Columbia River white sturgeon is stock-dependent and not highly productive, maximum yields should occur with relatively low exploitation (<0.15). Exploitation rates higher than 0.15 could eventually collapse the fishery. If recruitment is stronger, sustained yield and supportable exploitation should be higher, but exploitation rates producing maximum yields should still be less than 0.25.

In unaltered environments, white sturgeon recruitment might conceivably be independent of adult stock, at least at higher population numbers. The population could more than fully seed the available habitat for prerecruited life stages. Expansion of the Columbia River sturgeon fishery in the late 19th century was not followed by extinction, but by a fishery and yields that were sustained at 2–5% of the peak. A similar response was observed following expansion of the white sturgeon fishery in the Fraser River, British Columbia (Semakula and Larkin 1968). The available data suggest that historic white sturgeon in the Columbia and Fraser rivers were resilient to exploitation. Production of young fish was sustained even though much of the adult stock was removed in a short period.

Other sturgeon species have declined dramatically following habitat alteration and destruction. Sturgeon populations in Idaho rivers altered by dams appear incapable of supporting any exploitation (Cochner and Lukens 1984; Cochner et al. 1985). With development, habitat is lost, perhaps reducing rearing capacity and the number of recruits, but not necessarily creating a stock-dependent relationship. Declines in fecundity, growth, spawning frequency, spawning success, and egg quality, however, might also be associated with environmental change (Artyukhin et al. 1978; Votinov and Kas'yanov 1978). These changes may reduce reproductive potential and push a stock below the full seeding level. In effect, such changes

could make a stock less productive: a stock with a stock–recruitment function moved toward or below the lower bound in our simulations.

Construction of dams on the lower Columbia River has restricted migration, altered flows, and eliminated some habitats. Similar development reduced spawning success and reproductive potential of sturgeons (*Acipenser baeri*, *A. gueldenstaedti*) in the Soviet Union (Artyukhin et al. 1978; Votinov and Kas'yanov 1978). We believe it reasonable to assume that Columbia River white sturgeon are less productive than in 1885. Changes in the river may well have influenced spawning success and the nature of the stock–recruitment relationship. Even if recruitment was once very strong, it is probably less so now.

Kimura et al. (1984) suggested that most fish stocks have recruitment functions lying between the two extremes we used in our simulations. We believe that our models provide useful bounds for consideration of white sturgeon management, but not necessarily the limits of possibility. We suggest that alteration of the Columbia River system may have pushed the actual relationship toward or even beyond our lower bound. The stock-dependent simulations may not represent the most conservative interpretation of the effects of exploitation on Columbia River white sturgeon.

Our results suggested that white sturgeon cannot support heavy exploitation even with size restrictions on the harvest. If recruitment is stock dependent, exploitation higher than 0.05 could result in a substantial loss of yield. Exploitation greater than 0.10 may risk collapse of the fishery. We have no precise estimates of recruitment or exploitation for the Columbia River white sturgeon fisheries. We cannot conclude that the stock is seriously overexploited. We do believe, however, that the current yields are well above what can be sustained, and overexploitation is a good possibility. From 1930 to 1969, commercial harvest averaged about 91,000 kg, or about 4% of the 1885 peak (Figure 1). Our simulations suggested that sustained yield (with a 92–183-cm size restriction) could be near that level (1–9% of the historic peak). After 1970, sport and commercial fisheries expanded. Total yield in 1987 was about 800,000 kg, or about 35% of the 1885 peak. The 1987 yield was more than three times the relative sustained yield in even our most optimistic simulations (those with stable recruitment). Unless the post-1885 decline was the result of a dramatic decline in effort and not in the exploitable stock, or unless the current stock is more productive than in the past,

recent exploitation must have increased beyond that producing maximum sustainable yield.

Based on our results, we believe that current yields of white sturgeon from the Columbia River will decline dramatically. Although length restrictions on the fisheries probably provide a significant benefit, they will not necessarily prevent overexploitation. More seriously, overexploitation might risk stock collapse. Hydropower and other development of the Columbia River may well have resulted in a less-productive stock and a population more vulnerable to overharvest. Our last set of simulations suggested that decline and collapse of the fishery could take many years, even with very high exploitation. Our simulations were dependent on the recruitment function we used and thus represent only one possibility. The recruitment responses for white sturgeon in the Columbia River could be even less productive than that in our simulations, particularly for fish isolated in river segments between dams. Current research suggests that reproductive success in isolated reservoirs may be sporadic, and recruitment failures may not be uncommon (L. Beckman, U.S. Fish and Wildlife Service, personal communication). Until we have better information, more conservative management is warranted. Effort should be reduced; further expansion of the fishery is dangerous.

Acknowledgments

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