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Indexing the Relative Abundance of Age-0 White Sturgeons in an Impoundment of the Lower Columbia River from Highly Skewed Trawling Data

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Abstract.—The development of recruitment monitoring programs for age-0 white sturgeons *Acipenser transmontanus* is complicated by the statistical properties of catch-per-unit-effort (CPUE) data. We found that age-0 CPUE distributions from bottom trawl surveys violated assumptions of statistical procedures based on normal probability theory. Further, no single data transformation uniformly satisfied these assumptions because CPUE distribution properties varied with the sample mean (μ_{CPUE}). Given these analytic problems, we propose that an additional index of age-0 white sturgeon relative abundance, the proportion of positive tows (Ep), be used to estimate sample sizes before conducting age-0 recruitment surveys and to evaluate statistical hypothesis tests comparing the relative abundance of age-0 white sturgeons among years. Monte Carlo simulations indicated that Ep was consistently more precise than μ_{CPUE}, and because Ep is binomially rather than normally distributed, surveys can be planned and analyzed without violating the assumptions of procedures based on normal probability theory. However, we show that Ep may underestimate changes in relative abundance at high levels and confound our ability to quantify responses to management actions if relative abundance is consistently high. If data suggest that most samples will contain age-0 white sturgeons, estimators of relative abundance other than Ep should be considered. Because Ep may also obscure correlations to climatic and hydrologic variables if high abundance levels are present in time series data, we recommend μ_{CPUE} be used to describe relations to environmental variables. The use of both Ep and μ_{CPUE} will facilitate the evaluation of hypothesis tests comparing relative abundance levels and correlations to variables affecting age-0 recruitment. Estimated sample sizes for surveys should therefore be based on detecting predetermined differences in Ep, but data necessary to calculate μ_{CPUE} should also be collected.

Recruitment to impounded populations of white sturgeons *Acipenser transmontanus* in the lower Columbia River has been adversely affected by hydropower development and overharvest. The construction and operation of hydroelectric dams have reduced the availability of white sturgeon spawning habitats by altering seasonal discharge patterns (Parsley and Beckman 1994), isolated white sturgeon populations (North et al. 1993), and reduced habitat diversity by creating a series of homogenous reservoirs. Intensive harvest, coupled with the reduced recruitment, has collapsed the existing fisheries for white sturgeons in The Dalles and John Day reservoirs of the Columbia River (Beamesderfer et al. 1995). Parsley and Beckman (1994) and Beamesderfer et al. (1995) have proposed mitigative strategies to recover impounded white sturgeon populations. These strategies include altering individual dam or hydropower system operations to improve spawning conditions, intensive harvest management, and supplementing depleted populations with juveniles collected from more productive areas or with hatchery fish. Flow augmentation measures that are being implemented to enhance the survival of juvenile salmonids in the Columbia River basin (Wood 1993) may also affect the reproductive success of impounded white sturgeon populations.

Evaluating the effects of mitigative strategies on the recruitment of age-0 white sturgeons will require estimates of their relative abundance. To this end, annual bottom trawl surveys are conducted in the Columbia River. Miller and Beckman (1991) proposed using the arithmetic mean of catch per unit effort (CPUE) as an index of age-0 white sturgeon relative abundance. However, the statistical properties commonly associated with CPUE data can confound comparisons of mean CPUE and, thus, may reduce the efficiency and value of age-0 recruitment monitoring programs (Mangel and Smith 1990; McConnaughey and Conquest 1993; Pennington 1996). The observed distribution of

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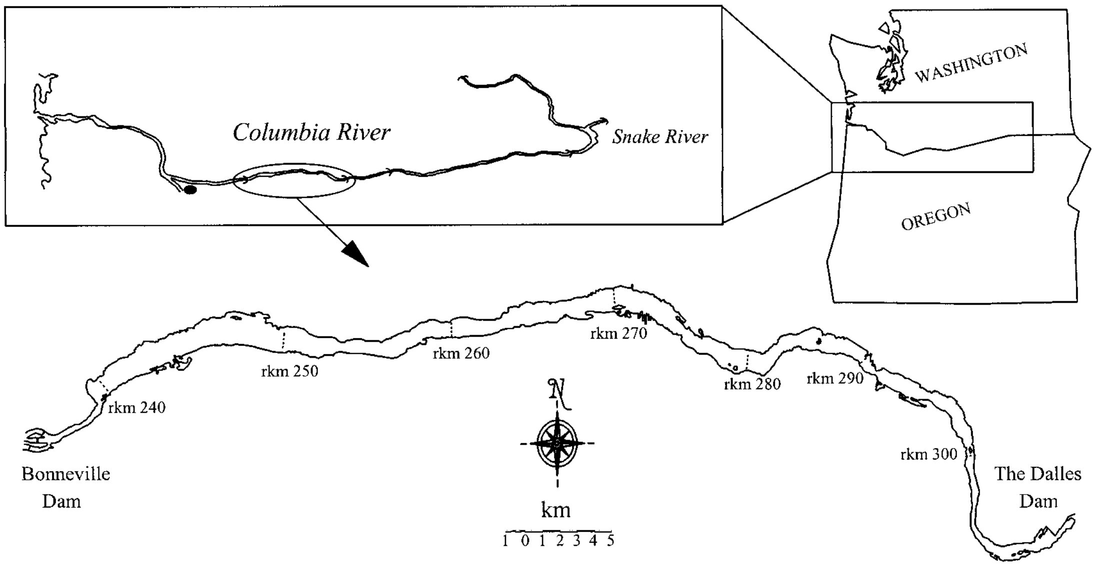

FIGURE 1.—Location of Bonneville Reservoir and river kilometer (rkm) designations.

CPUE data from bottom trawl surveys is typically skewed to the right, has excessively high variance estimates, and has a large proportion of zeros (Smith 1988; Mangel and Smith 1990; Pennington 1996). Further, the distributions are rarely normally distributed (Hubert 1996), the estimated variance is often proportional to the sample mean (Elliott 1971), and the sample mean may be overly sensitive to large values (Pennington 1996). These properties reduce the value of statistical tests based on normal probability theory and have led to the development of alternate estimators of relative abundance (Mangel and Smith 1990; McConnaughey and Conquest 1993; Pennington 1996).

Estimators based on the presence or absence of organisms in samples have been suggested as alternatives to using the arithmetic mean of CPUE data to index relative abundance (Mangel and Smith 1990). Presence–absence indices have many advantages over the sample mean including being robust to biases and errors in sampling and being insensitive to extreme CPUE values (Mangel and Smith 1990). The relative abundance of other biological populations has been characterized with presence–absence indices (Mangel and Smith 1990; Uphoff 1993; Zimmerman and Parker 1995), and proportion-based indices such as proportional and relative stock density are frequently used to make inferences about the characteristics of fish populations (Gustafson 1988; Miranda 1993).

Documenting the success of white sturgeon recovery efforts will require the development of effective recruitment monitoring programs. In this paper, we develop protocols for planning and analyzing bottom trawl surveys of age-0 white sturgeons. We examine the use of the arithmetic mean CPUE and the proportion of positive tows (Mangel and Smith 1990; Uphoff 1993) to plan bottom trawl surveys of age-0 white sturgeons, to depict trends in the relative abundance of this age-group, to test hypotheses regarding changes in relative abundance, and to characterize the relation of age-0 relative abundance to variables affecting recruitment. We then evaluate the annual variability of age-0 white sturgeon relative abundance in an impoundment of the lower Columbia River.

Methods

Data were obtained from Bonneville Reservoir, the lowermost impoundment of the Columbia River (Figure 1). The construction of Bonneville Dam created the reservoir in 1938, and the upstream extent of the reservoir was further confined by the construction of The Dalles Dam in 1957. The reservoir is 75 km long and has a surface area of approximately 8,400 ha. Bonneville Reservoir has little storage capacity, and river discharges through the two dams are run-of-the-river. The white sturgeon population in Bonneville Reservoir is subject to a sport fishery and tribal commercial and subsistence fisheries.

A 6.2-m high-rise bottom trawl with a 51-mm stretched mesh was used to capture age-0 white sturgeons in Bonneville Reservoir from 1989 to 1991 and from 1993 to 1995. A 15.9-mm delta mesh liner was inserted in the cod end of the trawl. Trawling was conducted in an upstream direction and was typically 10 min in duration. We estimated the distance fished during each tow with a radar range finder. The area fished was then calculated by multiplying the distance by 4.4 m, the estimated width of our bottom trawl. All trawling was conducted during daylight hours.

Our analyses included data from 11 locations sampled with the bottom trawl in all years except 1993 and 1994, when only 6 of the locations were sampled. Sampling locations comprised 11 of 13 sites where age-0 white sturgeons have been captured in Bonneville Reservoir. Two locations were eliminated because the bottom topography made them difficult to sample. Only tows conducted during September and early October were included in the analyses because age-0 white sturgeons captured during these months were easily distinguished from older juveniles by their lengths. Length-frequency histograms also indicated that most age-0 white sturgeons were recruited to our gear by September. Equal numbers of tows were done at each location within years.

We evaluated two indices of relative abundance of age-0 white sturgeons. The arithmetic mean of CPUE (μ_{CPUE}) was calculated as the mean of the untransformed CPUE data and presented as the number of age-0 white sturgeons per 2,500 m^2. The proportion of positive tows (Ep; Uphoff 1993) for age-0 white sturgeons was calculated for each year as a ratio of number of tows during which at least one age-0 individual was captured to the total number of tows. The proportions of positive tows were arcsine transformed (arcsine Ep) by the Freeman–Tukey double-arcsine transformation (Westphal and Young 1993), and these values were used in the statistical analyses of Ep. The arcsine transformation is commonly used to normalize percentage or proportion data (Zar 1984).

The proportion of positive tows has been shown to be sensitive to changes in the relative abundance of spatially and temporally aggregated biological populations (Mangel and Smith 1990; Uphoff 1993). To examine whether age-0 white sturgeon CPUE distributions had characteristics of samples taken from spatially aggregated populations, we evaluated the *G*-test (Sokal and Rohlf 1995) and the *U*-statistic (Elliott 1971) to test for goodness of fit to the negative binomial distribution. This distributional model has been used extensively to describe aggregated populations (Anescombe 1948, 1950; Taylor 1953; Sampford 1956; Bliss and Owen 1958; Bissell 1972; Pielou 1977; Taylor et al. 1979; Bannerot and Austin 1983; Dennis and Patil 1984). The dispersion parameter, *k*, of the negative binomial distribution was estimated for each year by using the maximum-likelihood estimate described by Elliott (1971).

We assessed the efficacy of using several data transformations to normalize and stabilize the variance of our CPUE data. We applied the $\log(X + 1)$, square root, fourth root, inverse, and inverse hyperbolic sine transformations to our CPUE data and evaluated Komolgorov's *D*-statistic for goodness of fit to the normal distribution and Levene's test for equality of variance (Anescombe 1948; Downing 1979; Sokal and Rohlf 1995; SAS Institute 1996). Since the spatial aggregation of populations can affect the shape and variance of CPUE distributions, a constant level of aggregation is necessary to apply a common transformation to a series of samples (Elliott 1971). To evaluate whether aggregation varied with μ_{CPUE}, we calculated an index of aggregation (J_A) developed by Ives (1991). This index is an unbiased measure of aggregation (Pielou 1977) and, unlike *k*, measures aggregation independently of the mean. Pearson's product-moment correlation coefficient (*r*) was then calculated to examine the relation of J_A to μ_{CPUE}.

For any two estimators, the most efficient estimator is the one with the smallest variance (Pennington 1996). We performed Monte Carlo simulations to compare the efficiency of Ep and μ_{CPUE} across a range of sample sizes. The dispersion parameter of the negative binomial distribution, *k*, and the arithmetic means from the 1990, 1991, and 1995 age-0 CPUE distributions were used to define three representative negative binomial distributions. From each of these distributions, 1,000 simulated sets of CPUE data for each of six sample sizes (20, 40, 60, 80, 100, and 120) were generated by using the bootstrap option in PROC MULTTEST (SAS Institute 1996). The average variance of Ep and μ_{CPUE} were calculated from the 1,000 simulated data sets and expressed as a percentage of the respective estimator.

McConnaughey and Conquest (1993) suggested that evaluating the consistency in trends between alternate estimators will help identify errors in abundance indices and reduce the potential for false conclusions concerning apparent trends in stock abundance. Thus, we examined the relation of the indices through univariate correlation anal-

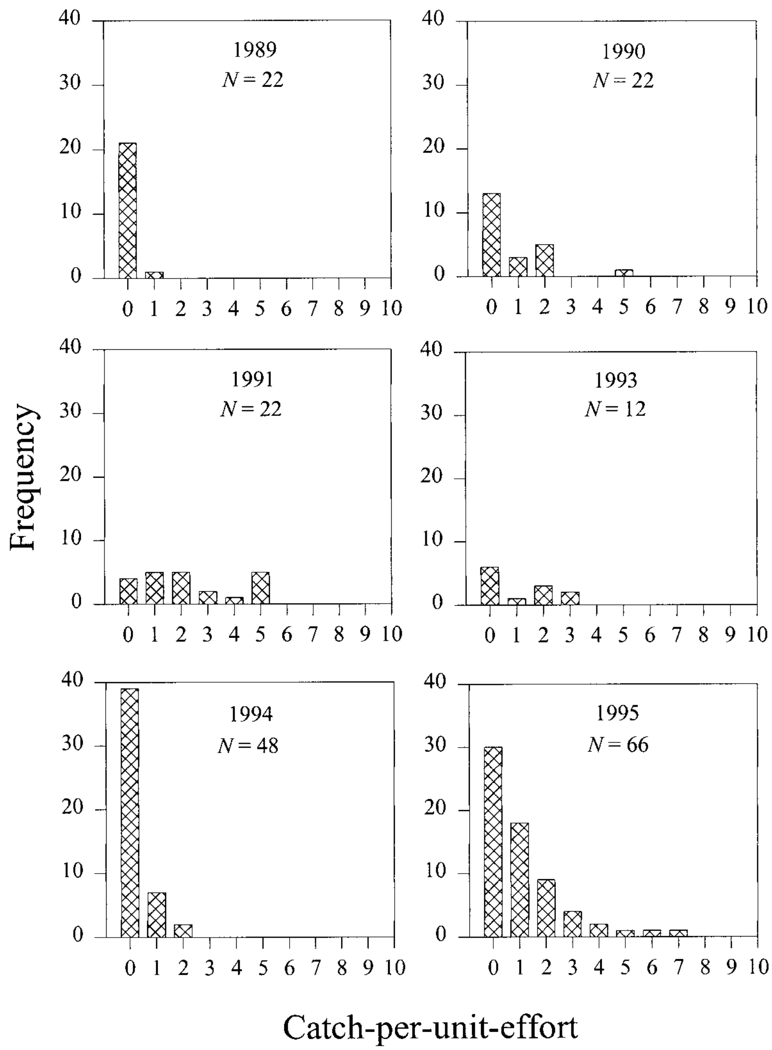

FIGURE 2.—Frequency histograms of the catch per unit effort of age-0 white sturgeons from bottom trawl surveys in Bonneville Reservoir of the Columbia River. Catch per unit effort is the number of age-0 white sturgeons per 2,500 m^2; N = number of tows.

ysis. Pearson's product-moment correlation coefficient (r) was computed to assess the association of the two indices. Residuals from a simple linear regression relating arcsine Ep to μ_{CPUE} were plotted against arcsine Ep to assess the possibility of a nonlinear relation between the two indices (Neter et al. 1989).

To examine whether relative abundance varied among years, we evaluated multiple comparisons of Ep with Freeman–Tukey double-arcsine tests performed in PROC MULTTEST (SAS Institute 1996). Single-step multiplicity adjustments that control the familywise error rates were made by using bootstrap resampling methods and resulted in the calculation of multiplicity-adjusted P-values (Westphal and Young 1993). The Freeman–Tukey double-arcsine tests before multiplicity adjustments (unadjusted P-values) are more powerful and have a lower probability of committing type II errors (Westphal and Young 1993). Westphal and Young (1993) recommended reporting both adjusted and unadjusted P-values.

Results

Bottom trawl surveys of age-0 white sturgeons in Bonneville Reservoir resulted in CPUE distributions (Figure 2) with statistical properties characteristic of samples taken from spatially aggre-

TABLE 1.—Sample size (N = number of tows), proportion of positive tows (Ep), mean catch per unit effort (μ_{CPUE}), variance of μ_{CPUE} (s^2), Ive's index of aggregation (J_A), dispersion parameter of the negative binomial distribution (k), skewness, and mode for catch-per-unit-effort data from bottom trawl surveys of age-0 white sturgeon. Ive's index of aggregation and k were not calculated for the 1989 survey because only one tow contained age-0 white sturgeon.

Year	N	Ep	μ_{CPUE}	s^2	J_A	k	Skew-ness	Mode
1995	66	0.55	1.15	2.38	0.92	1.1203	1.90	0
1994	48	0.19	0.24	0.33	1.50	1.2966	2.24	0
1993	12	0.50	1.08	1.63	0.47	1.7363	0.50	0
1991	22	0.82	2.32	3.30	0.18	4.2660	0.43	[a]
1990	22	0.41	0.79	1.43	1.02	0.6367	1.95	0
1989	22	0.04	0.04	0.03			4.69	0

[a] There was no mode for this survey.

gated populations (Table 1). The distributions were not significantly different ($P > 0.05$) from positively skewed negative binomial distributions with zero as the mode. None of the transformations we employed uniformly resulted in normal distributions (Komolgorov's D, $P < 0.05$) and homogenous variances (Levene's test, $P < 0.05$). Ive's index of aggregation (J_A) varied greatly and was negatively correlated with μ_{CPUE} (r = –0.908; P = 0.033). As the spatial aggregation of age-0 white sturgeons decreased, the distributions became less skewed and the frequency of zero-catch tows dropped markedly.

Monte Carlo simulations indicated that Ep was more efficient than μ_{CPUE} for all three distributions and all sample sizes simulated (Figure 3). The variances of both μ_{CPUE} and Ep decreased as sample sizes increased, but the average variance-to-estimator ratio was always higher for μ_{CPUE} than for Ep. The Pearson's product-moment (r) correlation coefficient indicated that arcsine Ep and μ_{CPUE} were positively correlated ($r = 0.97$, $P = 0.001$). However, the residuals from a simple linear regression relating arcsine Ep to μ_{CPUE} suggested that the relation between the two indices was not linear. Thus, an exponential model was fit to our data by using nonlinear regression (Figure 4). This model, described by the equation arcsine Ep = $77.2 - 62.6\exp(-0.65\mu_{CPUE})$, suggests that Ep may underestimate changes in relative abundance at higher levels.

Multiple-comparison tests of Ep indicated that there were significant differences in the relative abundance of age-0 white sturgeons among years (Table 2). However, no distinct groups of means were identified. The results of the unadjusted and adjusted tests varied with survey sample size and the magnitude of differences in Ep among years. Of the 15 comparisons of Ep, unadjusted P-values indicated 11 significant differences ($P < 0.05$) compared with 7 by the adjusted P-values, reflecting the conservative nature of multiplicity-adjusted P-values.

Discussion

Catch-per-unit-effort data from bottom trawl surveys of age-0 white sturgeons had properties similar to those commonly reported for CPUE data collected from spatially aggregated marine biota (McConnaughey and Conquest 1993; Pennington 1996); suggesting that sampling the biota of large rivers can pose similar analytic and logistic problems as those encountered by scientists sampling marine environments. As such, we found that age-0 white sturgeon CPUE data violated assumptions associated with statistical procedures based on normal probability theory. Further, because the properties of the CPUE distributions varied with μ_{CPUE}, we were unable to employ transformations that uniformly satisfied these assumptions (Hubert 1996). These statistical properties complicate the planning of bottom trawl surveys of age-0 white sturgeons. Sample size estimations based on normal probability theory require an a priori estimate of population variance that is assumed to be homogenous among samples (Sokal and Rohlf 1995). However, we show that variance estimates of CPUE distributions from age-0 white sturgeon bottom trawl surveys were positively correlated with μ_{CPUE}. Thus, estimated sample sizes may be either too small or too large if the pooled variance of the samples is smaller or larger than the original estimate. The value of age-0 surveys will be reduced if sample sizes are insufficient to detect biologically significant results. Conversely, if more samples are taken than needed, the cost of age-0 white sturgeon surveys will be unnecessarily high.

We recommend the use of Ep, as an alternative to μ_{CPUE}, to estimate sample sizes before conducting age-0 recruitment surveys and to evaluate

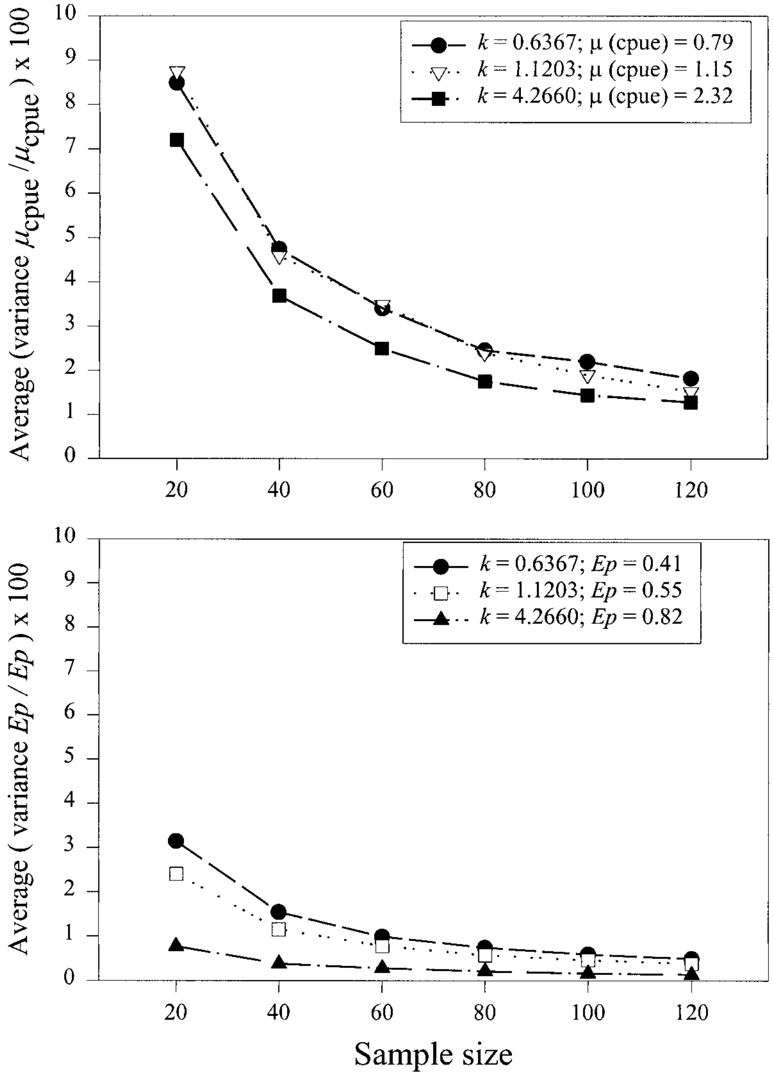

FIGURE 3.—The relation of the average relative variance of the sample mean (μ_{CPUE}) and proportion of positive tows (Ep) to sample size for each of 1,000 simulated catch-per-unit-effort data sets generated from bootstrap resampling of three negative binomial distributions. The dispersion parameter of the negative binomial distribution, *k,* and the arithmetic means from the 1990, 1991, and 1995 age-0 CPUE distributions were used to define the three negative binomial distributions. Relative variance is the variance of the estimators expressed as a percentage of the respective estimator.

statistical hypothesis tests comparing the relative abundance of age-0 white sturgeons among years. There are several advantages in using Ep to index the relative abundance of age-0 white sturgeons when CPUE data exhibit properties similar to those we observed. Our Monte Carlo simulations indicated that Ep was consistently more precise and therefore more efficient than μ_{CPUE}. This suggests that for a given level of effort, the precision of relative abundance estimates for age-0 white sturgeons can be increased by using Ep. Further, because Ep is binomially rather than normally distributed, age-0 white sturgeon surveys can be planned and analyzed without the negative aspects of violating the assumptions of normality and equal error variances of procedures based on normal probability theory (Zar 1984; Gustafson 1988; Miranda 1993; Sokal and Rohlf 1995; SAS Institute 1996). Methods are readily available to evaluate differences in binomial proportions and to

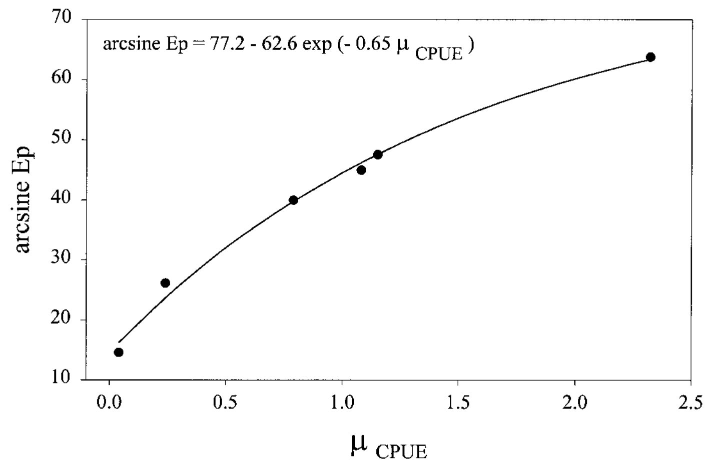

FIGURE 4.—Fitted nonlinear regression model for the relation between the arcsine-transformed proportion of positive tows (arcsine Ep) and sample mean of catch per unit effort (μ_{CPUE}).

calculate the sample size necessary to detect predetermined differences in Ep with specified probabilities of making type I and type II errors (Gustafson 1988; Peterman 1990; Miranda 1993; Sokal and Rohlf 1995). However, we show that Ep may underestimate changes in relative year-class strength at high levels. The nonlinear relation between Ep and μ_{CPUE} suggests that as age-0 white sturgeons become less aggregated, Ep may reach a maximum value, reflecting our ability to detect the presence of age-0 individuals. Only marginal increases in Ep may be realized as this value is approached, whereas μ_{CPUE} will increase disproportionately, reflecting an increase in the number of individuals captured per tow (i.e., number of individuals per group detected). Underestimating relative year-class strength at high levels will confound our ability to quantify the benefits of management actions if relative abundance is consistently high. When developing sampling plans for age-0 white sturgeon surveys, estimators of relative abundance other than Ep should be considered if data suggest that most samples will contain age-0 white sturgeons (Mangel and Smith 1990).

TABLE 2.—Results of Freeman–Tukey double-arcsine tests comparing the proportion of positive tows (Ep) among years. Unadjusted *P*-values represent probabilities before multiplicity adjustments and adjusted *P*-values represent probabilities after multiplicity adjustments (Westphal and Young 1993; SAS Institute 1996).

Comparison	Unadjusted *P*	Adjusted *P*
1989 versus 1990	0.001	0.018
1989 versus 1991	0.000	0.000
1989 versus 1993	0.001	0.017
1989 versus 1994	0.057	0.397
1989 versus 1995	0.000	0.000
1990 versus 1991	0.003	0.030
1990 versus 1993	0.310	0.953
1990 versus 1994	0.029	0.221
1990 versus 1995	0.139	0.717
1991 versus 1993	0.032	0.245
1991 versus 1994	0.000	0.000
1991 versus 1995	0.010	0.100
1993 versus 1994	0.019	0.170
1993 versus 1995	0.386	0.985
1994 versus 1995	0.001	0.001

When the assumptions of parametric statistical tests are violated, nonparametric tests are often suggested as alternatives (Stewart-Oaten 1995). However, when using nonparametric tests to determine differences in means, the shape and variance of the distributions being evaluated must be the same (Johnson 1995). Nonparametric tests evaluate whether distributions are identical but do not specifically indicate how they differ (e.g., mean, variance, shape, etc.; Johnson 1995). Thus, using nonparametric tests to evaluate changes in μ_{CPUE} may result in the detection of statistical significance in biologically insignificant results. For instance, Petranka (1990) provided an example in which a Mann–Whitney test, a commonly used nonparametric procedure (Sokal and Rohlf 1995), detected a significant difference between two distributions with identical means and medians but different variances. Since the shape and variance of age-0 white sturgeon CPUE distributions varied with μ_{CPUE}, we do not recommend the use of nonparametric tests to evaluate changes in age-0 white sturgeon μ_{CPUE}.

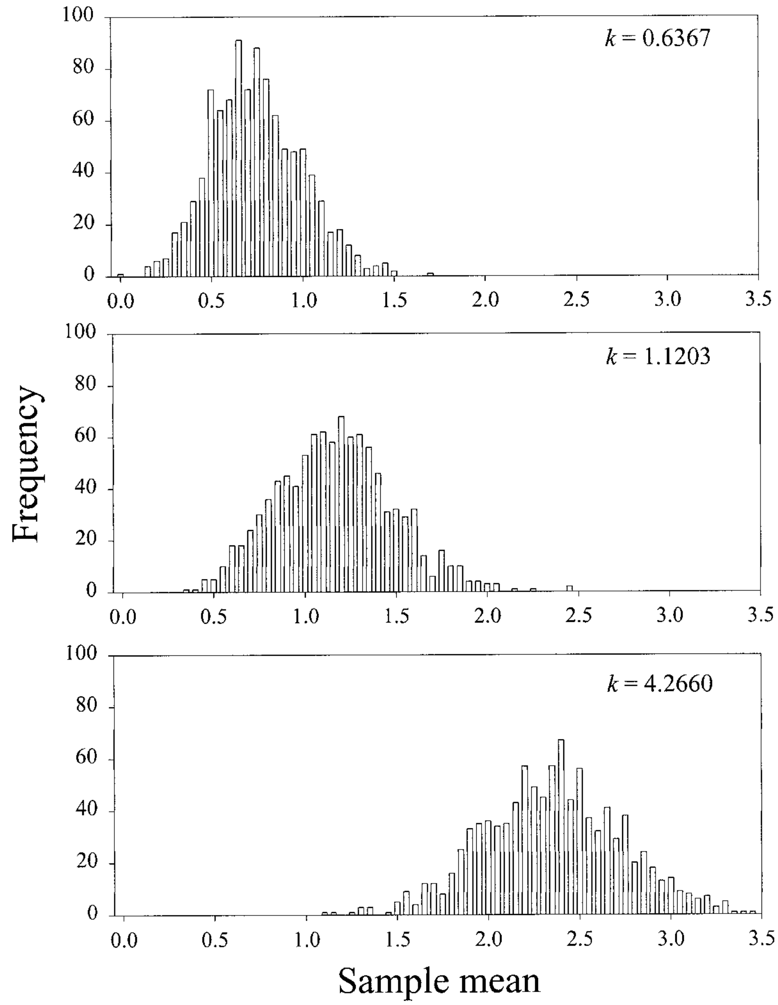

FIGURE 5.—Frequency distributions of the sample means calculated from each of 1,000 simulated catch-per-unit-effort data sets generated from bootstrap resampling of three negative binomial distributions. The dispersion parameter of the negative binomial distribution, k, and the arithmetic means from the 1990, 1991, and 1995 age-0 CPUE distributions were used to define the three negative binomial distributions; $N = 20$.

Identifying environmental conditions that drive year-class strength will allow managers to assess the effects of hydropower development on age-0 white sturgeon recruitment and to make recommendations on how to manage the water resources in the Columbia and Snake rivers to benefit white sturgeons. Whereas Parsley and Beckman (1994) have described the effects of hydroelectric dam operations on white sturgeon spawning habitat, the effects of dam construction and operation on white sturgeon egg and larval survival and, subsequently, recruitment to age 0, remain poorly understood. To examine the relation between relative abundance of age-0 white sturgeons and environmental variables, we recommend the use of μ_{CPUE}, because Ep may obscure correlations if high values are present in time series data. Because the distributions of means, even those of nonnormal distributions, rapidly approach normality as sample size increases (Johnson 1995), the assumptions of descriptive and predictive statistical methods (e.g., linear regression) can be satisfied, and thus, these methods can validly be used to assess the relation of environmental variates to μ_{CPUE}. Using the three hypothetical CPUE distributions previously presented, we show that the frequency distributions of sample means calculated from each of the 1,000 simulated data sets do not exhibit severe departures from normality, despite the nonnormality and relatively small sample size ($N = 20$) of the original data sets (Figure 5).

We demonstrated that the relative abundance of age-0 white sturgeons in Bonneville Reservoir varied among years by statistically evaluating differences in Ep. Variations in age-0 relative abundance are typically attributed to population characteristics such as stock–recruitment relations and environmental variables that influence the survival of eggs and larvae. White sturgeons are long-lived and iteroparous, mature at an advanced age, and have protracted spawning cycles (Rochard et al. 1990). Spawning stock size of fishes with these life history characteristics probably do not fluctuate dramatically from year to year unless the broodstock are overharvested. Harvest regulations designed to protect white sturgeon broodstock have been in place in Bonneville Reservoir since 1950, reducing the potential impacts of harvest on broodstock. Thus, the variability in the relative abundance of age-0 white sturgeons in Bonneville Reservoir may be driven more by climatic and hydrologic conditions that affect the survival of eggs and larvae than by variations in the numbers of white sturgeons available to spawn in a given year.

The methodologies we describe here should be applicable to the design and analysis of age-0 white sturgeon surveys in other areas of the Columbia and Snake rivers. Catch-per-unit-effort data from age-0 white sturgeon surveys in other areas of the Columbia River will probably be highly variable and contain a large proportion of zeros. Collections of age-0 white sturgeons from impoundments on the Columbia River upstream from The Dalles Dam occur less frequently than from Bonneville Reservoir (Parsley and Beckman 1994), and no age-0 white sturgeons have been collected from the Kootenai River (P. J. Anders, University of Idaho, personal communication), where white sturgeons have been listed as endangered under the Endangered Species Act. Until these populations recover, the probability of detecting the presence of age-0 individuals will remain low. Other sampling gears may be more efficient at detecting the presence of age-0 white sturgeons than bottom trawls and may obviate the need to use Ep. However, the logistics of sampling a large river and the habitats where age-0 white sturgeons are typically found limits the choice of gears that can be used to conduct these surveys. Gill nets have been used to capture age-0 white sturgeons in the Columbia and Snake rivers, but preliminary analyses indicate that this gear also results in highly skewed CPUE distributions with a substantial proportion of zeros (U.S. Geological Survey, unpublished data), suggesting that the spatial aggregation of age-0 individuals detected in our analyses is not solely an artifact of sampling with bottom trawls.

As management actions to recover white sturgeons are implemented, the use of both Ep and μ_{CPUE} as indices of the relative abundance of age-0 white sturgeons will allow biologists to efficiently plan and analyze annual age-0 white sturgeon surveys and, thus, to document the efficacy of management policies designed to increase the recruitment of age-0 white sturgeons. Ideally, age-0 white sturgeon surveys should be planned so that hypothesis tests comparing relative abundance can be evaluated and time series data can be used to describe the relation of relative abundance to variables potentially affecting recruitment. Estimated sample sizes for surveys should therefore be based on detecting predetermined differences in Ep, but data necessary to calculate μ_{CPUE} should also be collected.

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