EFFECTS OF FOUR DENSITY LEVELS ON TULE FALL CHINOOK SALMON DURING HATCHERY REARING AND AFTER RELEASE

J. L. Banks and E. M. LaMotte

Made in the United States of America
Reprinted from North American Journal of Aquaculture
Vol. 64, No. 1, January 2002

North American Journal of Aquaculture 64:24–33, 2002
American Fisheries Society 2002

Effects of Four Density Levels on Tule Fall Chinook Salmon during Hatchery Rearing and after Release

J. L. BANKS*[1]

Abernathy Fish Technology Center, U.S. Fish and Wildlife Service, 1440 Abernathy Road, Longview, Washington 98632, USA

E. M. LAMOTTE

Spring Creek National Fish Hatchery, U.S. Fish and Wildlife Service, Mile Post 61552, State Road 14, Underwood, Washington 98651, USA

Abstract.—Tule fall chinook salmon *Oncorhynchus tshawytscha* were reared in a hatchery with a semiclosed water recycle and reconditioning system at a customary density of 364,000 fish per pond and at reduced densities of 273,000, 182,000, and 91,000 fish per pond. Fingerlings from four brood years were used to evaluate rearing density effects on growth and mortality during rearing and on smolt survival and adult contribution after release. During the rearing of each brood, about one-third of the original population in each pond was released by random removal in March and a second third was released in April. All remaining fish were released in May. An inverse relationship was apparent between rearing density and fingerling growth ($R = -0.868$). Rearing losses were low (<1.4%) in all test groups and were not affected by density. Decreased levels of rearing density produced only limited and inconsistent increases in smolt survival rate (from 0.18% to 0.27%) after release. This weakness in treatment effects was reflected in a nearly linear relationship ($R = 0.985$) between decreased rearing density and decreased adult contribution and return to the hatchery.

Although fish culturists at North American hatcheries with Pacific salmon rear-and-release programs deal with many important issues each year, few of the decisions they make are more important than the ones involving the efficient management of basic resources such as rearing space, water flow, and fingerling stocking levels. Optimum allocation of these resources to enhance smolt quality and maximize adult contribution to the fishery may seem like a simple task. However, many interacting factors can complicate it. For example, water quality, species' tolerance of crowding, disease considerations, and type of rearing unit are unique to individual hatcheries and often interact with rearing density to affect survival after release. In their literature review of rearing density studies with salmon, Ewing and Ewing (1995) concluded that "the best way to determine the correct relationship is to conduct density experiments at each facility, with the awareness that unknown conditions may affect the results." In view of the large number of salmonid hatcheries in the Pacific Northwest, limited research budgets, and the time required to conduct survival-oriented rearing density studies, it seems advisable to focus research efforts on individual hatcheries or stocks of fish that are of primary importance to the fisheries of the region.

The objective of this study was to investigate the effects of four rearing densities (364,000, 273,000, 182,000, and 91,000 fish per pond) on four broods of Tule fall chinook salmon *Oncorhynchus tshawytscha* during rearing and after release at Spring Creek National Fish Hatchery (U.S. Fish and Wildlife Service) in Washington State. Fingerlings from the 1989, 1990, 1991, and 1992 brood years were used to evaluate rearing density effects on growth and mortality during rearing and on smolt survival and adult contribution after release.

"Tule" fall chinook salmon have historically been regarded as a mainstay of the chinook salmon fishery in the Pacific Northwest, with about 70% of the catch occurring within Washington State and British Columbia waters (Vreeland 1989). Spring Creek National Fish Hatchery has been a leading contributor to the catch of Tule fall chinook salmon among the 18—and sometimes more—hatcheries in the Columbia Basin that rear this stock (Vreeland 1989).

Spring Creek National Fish Hatchery is located on the Washington shore of the Columbia River about 32 km upstream of Bonneville Dam. The

* Corresponding author: jbanks@tdn.com
[1] Present address: 2363 40th Avenue, Number 8, Longview, Washington 98632, USA.

Received February 20, 2001; accepted July 17, 2001

hatchery is unique in that it relies entirely on a semiclosed water recycle and reconditioning system (Burrows and Combs 1968) for its entire production of 16 million chinook salmon smolts annually. The customary rearing density at Spring Creek hatchery consists of 364,000 swim-up or "first-feeding" fish per pond stocked directly from the incubators into 91.2-m^3 rectangular circulating ponds (Burrows and Chenoweth 1970). This rearing density is light in comparison with production levels at more conventional salmon hatcheries (Ewing and Ewing 1995). In the past, hatcheries using rectangular circulating ponds and water recycle and reconditioning systems have experienced losses, sometimes catastrophic ones, due to bacterial gill disease (*Flexibacter* sp.) when high rearing densities were used (personal observations). In view of the potential for disease problems, our goal was to determine whether reduced rearing densities could be used as a management tool to improve smolt quality and increase survival rates after release. Hatchery efficiency would be significantly improved if current levels of adult contribution could be maintained while rearing smolts at reduced densities.

Methods

All test rearing was conducted using the existing fish cultural facilities and the customary practices of the hatchery. Experimental densities were established at 364,000, 273,000, 182,000, and 91,000 fish per pond (100, 75, 50, and 25% of the normal density, respectively) using first-feeding fish stocked directly from the incubators. A portion of each test population was randomly released on three occasions (Table 1). In mid-March, about one-third of each test population was randomly removed by release on-site into the Columbia River. A similar number of fish were released from each pond in mid-April, and all remaining fish were released into the Columbia River in mid-May. The period between stocking and first release averaged 87 d. Rearing periods between first and second release and second and final release averaged 33 and 32 d, respectively. Because of the nature of the recycle rearing system, water temperatures were nearly stable within any 24-h period and did not vary greatly between rearing periods or between brood years.

Fish were reared at each density in paired ponds that were 22.9 m long × 5.2 m wide × 0.8 m deep with the turning vanes removed and water inflow jet headers turned to face at a 45° angle toward the center wall. Water for rearing was supplied by a spring located on the hatchery site. During rearing of the 1991 and 1992 broods, a deep well was used to supply water to the recycle system in addition to the spring source. Pond water flows were established at 1,325 L/min in all ponds from stocking through early January. Flows were then increased to about 1,900 L/min until early February, when flows were set at 2,725 L/min for the remainder of rearing.

All fish were stocked into test ponds in December using incubator stack and tray assignments produced by a computerized random number generator. Fish were started feeding on Biostarter diet (Bio-Oregon, Warrenton, Oregon) until they reached a mean size of about 1.8 g. The fish were then fed Abernathy Dry Diet (specifications available from U.S. Fish and Wildlife Service, Region 1 Office, Portland, Oregon) through final release. Growth rates were monitored and feeding levels

TABLE 1.—Stocking and release dates, duration of rearing, and mean water temperature during rearing of four broods of Tule fall chinook salmon smolts in 91.2-m^3 ponds.[a] The numbers in parentheses are the total days between stocking and final release and the mean temperature, respectively, for each brood year.

Event	Date	Days between events	Temperature (°C)
1989 brood year			
Stocking	19 Dec 1989		
First thinning release	16 Mar 1990	86	9.4
Second thinning release	18 Apr 1990	33	9.9
Final release	17 May 1990	30	10.2
		(149)	(9.8)
1990 brood year			
Stocking	22 Dec 1990		
First thinning release	21 Mar 1991	88	8.6
Second thinning release	18 Apr 1991	28	9.5
Final release	16 May 1991	28	9.0
		(144)	(9.0)
1991 brood year			
Stocking	10 Dec 1991		
First thinning release	5 Mar 1992	85	9.4
Second thinning release	16 Apr 1992	42	10.1
Final release	21 May 1992	35	10.7
		(162)	(10.1)
1992 brood year			
Stocking	18 Dec 1992		
First thinning release	18 Mar 1993	89	8.9
Second thinning release	15 Apr 1993	28	9.6
Final release	20 May 1993	35	10.2
		(152)	(9.6)

[a] Populations were established at test densities of 91,000, 182,000, 273,000, and 364,000 fish per pond in paired ponds in December. About one-third of the original population in each pond was released at each of the thinning releases in March and April. All remaining fish were released in May.

calculated semiweekly by crowding, randomly netting, weighing, and counting fish samples ($N > 200$) from each rearing pond.

Pond densities and loadings at release were expressed as kilograms of fish per cubic meter of rearing space and per liter of water inflow per minute and as a density index $[W/(L.V)]$ and flow index $[W/(L.F)]$ as defined by Piper et al. (1982). For consistency, formula components were converted to metric units, that is, W = the weight of fish in kiloggrams, L = the length of fish in centimeters, V = rearing volume in cubic meters, and F = water flow in liters per minute (the density and flow indices can be transformed to English units using the multiplication factors 0.158 and 21.786, respectively).

Influent and effluent dissolved oxygen levels were measured with an Oxyguard portable oxygen meter (OxyGuard International A/A, Birkerod, Denmark). All dissolved oxygen measurements were made in the afternoon just prior to the day the fish were released. Water temperatures were recorded using a Taylor recording thermometer (Taylor Instruments, Oak Brook, Illinois). Measurements of pond inflows were made using a custom calibrated manometer designed to fit over the pond inflow jet headers. Fish in all test groups were given periodic health examinations throughout rearing.

To evaluate treatment effects on survival and contribution after release, about 25,000 randomly sampled fish in each test group received pond-discrete coded wire tags (Northwest Marine Technology, Inc., Shaw Island, Washington) and adipose fin clips. All tagging was done in February prior to the first release in March.

Care was taken to ensure the random release of fish from each test pond. The populations were crowded and random dip-net samples ($N > 200$) were counted, weighed, and used to determine target weight loads to remove from each pond. Weight loads in each crowded population were then reduced by weighing and releasing random dip-net subsamples from each pond.

After release, coded-wire-tagged fish were recovered through the coastwide sampling program conducted by various government agencies on the Pacific Coast. The ratio between observed recoveries in the various fisheries and catch sampling effort was used to estimate the fishery catch of each coded-wire-tagged group. Tagged adults returning to the hatchery were also recovered at the adult holding facility at the hatchery. Estimated fishery recoveries and hatchery returns of each tagged group were combined to obtain total recovery estimates of each replicate. Total adult contribution from each experimental group was then estimated using tagged to untagged release ratios for each tagged group.

Prior to statistical analysis for treatment effects, all data were screened for equality of variance using Levene's test and examined for departure from normality using the Shapiro–Wilk test (W-statistic). Arcsine-square-root transformations were performed prior to analysis of all percent rearing mortality and percent adult recovery data. Logarithmic transformations (base 10) were used to transform all mean smolt weight at release and adult contribution data before analysis. All data were transformed back to their original form for presentation in Results. Three-way factorial analysis of variance (ANOVA) (rearing density × rearing period × brood year) and two-way factorial ANOVA (rearing density × brood year) were used to test for treatment effects on fingerling mortality and growth during rearing and on smolt survival after release. Whenever significant main-factor interactions were observed, the analysis was reduced to either a two-way analysis (rearing density × rearing period) or a one-way analysis (rearing density) within individual broods. Orthogonal contrasts were used to determine the significance of differences of means among treatments in all factorial analyses. In all one-way ANOVA analyses, the Student–Newman–Keuls test was used to determine statistical differences among means. Differences in all analyses were considered significant at the 95% confidence level ($P \leq 0.05$). Data were analyzed using BMDP statistical software (Dixon 1990) and methods of statistical testing outlined in Snedecor and Cochran (1967).

Results

Treatment Effects during Rearing

Over the 5-month period of test rearing, fish in each brood increased in size from about 0.4 g to 11.4 g (Table 2). The fish averaged 3.6 g at the first release in mid-March and 6.8 g at the second release in mid-April. Within the three-way ANOVA(rearing density × release date × brood year), however, there were significant interactions between rearing density and release date and between brood year and release date. Rearing density effects, therefore, were reduced to a two-way ANOVA within each brood year. At release of the 1989 and 1992 broods, fish reared at the lowest rearing density were significantly larger than those

TABLE 2.—Mean weights (g/fish) at three releases of four broods of Tule fall chinook salmon smolts reared in 91.2-m^3 ponds at four densities.[a] Cell values are the means of paired ponds; standard errors are given in parentheses. Within the three-way ANOVA model (rearing density × release date × brood year), the interactions rearing density × release date and brood year × release date are significant ($P \leq 0.05$). Analysis of rearing density and release date effects is therefore confined to a two-way ANOVA (rearing density × release date) within individual broods. Within broods, means for rearing density and release date without a letter in common are significantly different ($P \leq 0.05$).

Release date	Initial rearing density (fish per pond)				Mean across densities	Brood year mean
	91,000	182,000	273,000	364,000		
1989 brood year						
16 Mar 1990	3.8 (0.1)	3.8 (0.1)	3.8 (0.0)	3.8 (0.1)	3.8 (0.0) z	
18 Apr 1990	7.4 (0.2)	6.8 (0.1)	7.0 (0.1)	7.0 (0.2)	7.0 (0.1) y	
17 May 1990	11.2 (0.2)	10.1 (0.5)	10.0 (0.0)	10.4 (0.1)	10.4 (0.2) x	
Mean across releases	7.5 (1.3) z	6.9 (1.2) y	6.9 (1.1) y	7.0 (1.2) y		7.1 (0.6)
1990 brood year						
21 Mar 1991	3.5 (0.0)	3.6 (0.1)	3.4 (0.0)	3.5 (0.1)	3.5 (0.0) z	
18 Apr 1991	6.6 (0.1)	6.8 (0.2)	6.3 (0.1)	6.5 (0.1)	6.5 (0.1) y	
16 May 1991	11.7 (0.0)	11.8 (0.1)	11.2 (0.2)	11.2 (0.2)	11.4 (0.1) x	
Mean across releases	7.3 (1.5) z	7.4 (1.5) z	7.0 (1.4) y	7.0 (1.4) y		7.1 (0.7)
1991 brood year						
5 Mar 1992	4.1 (0.2)	4.0 (0.0)	4.1 (0.2)	3.7 (0.3)	4.0 (0.1) z	
16 Apr 1992	8.6 (0.2)	7.9 (0.3)	8.1 (0.3)	8.0 (0.4)	8.1 (0.2) y	
21 May 1992	13.8 (0.7)	13.3 (0.7)	12.9 (0.7)	12.7 (0.3)	13.1 (0.3) x	
Mean across releases	8.8 (1.8) z	8.4 (1.7) z	8.3 (1.6) z	8.1 (1.7) z		8.4 (0.8)
1992 brood year						
18 Mar 1993	3.5 (0.1)	3.3 (0.1)	3.3 (0.1)	3.3 (0.1)	3.3 (0.0) z	
15 Apr 1993	6.0 (0.2)	5.5 (0.2)	5.6 (0.3)	5.4 (0.1)	5.6 (0.1) y	
20 May 1993	11.6 (0.1)	10.4 (0.4)	10.4 (0.6)	10.2 (0.3)	10.6 (0.2) x	
Mean across releases	7.0 (1.5) z	6.3 (1.3) y	6.4 (1.3) y	6.3 (1.3) y		6.5 (0.6)
Combined broods						
Mar	3.7 (0.1)	3.6 (0.1)	3.6 (0.1)	3.6 (0.1)	3.6 (0.1)	
Apr	7.1 (0.4)	6.7 (0.3)	6.7 (0.4)	6.7 (0.4)	6.8 (0.2)	
May	12.1 (0.4)	11.4 (0.5)	11.1 (0.4)	11.1 (0.4)	11.4 (0.2)	
Mean across releases	7.6 (0.7)	7.2 (0.7)	7.1 (0.7)	7.1 (0.7)		

[a] Mean weights at stocking were 0.35, 0.40, 0.37, and 0.38 g/fish for the 1989, 1990, 1991, and 1992 broods, respectively. About one-third of the initial populations in each pond was released in each of the March and April releases. All remaining fish were released in May.

reared at the other three densities. Fish reared at the two lowest densities were significantly larger at release of the 1990 brood than those reared at the two highest densities. Within the 1991 brood, there was no difference in mean weight at release. Overall, there was an inverse relationship between growth and increased rearing densities ($R = -0.868$).

Biomass per unit of rearing space and per unit of water inflow (Table 3) reached three peaks during the 5-month rearing period from December to May because of the thinning releases in March and April and the final release in May. Pond weight loads were consistently highest just prior to the April release. Biomass at release ranged from 3.4 to 20.7 kg of fish/m^3 of rearing space and from 0.11 to 0.72 kg of fish/L of water inflow.min^{-1}. The density index ranged from 0.46 to 2.11 and the flow index from 0.015 to 0.071.

Dissolved oxygen in pond influents on the afternoon before smolt release ranged from 10.9 to 11.7 mg/L (Table 4). Oxygen concentrations in pond effluents reflected the different rearing density levels. In general, effluent dissolved oxygen was about 2.3 mg/L lower in ponds with the highest densities than in ponds with the lowest densities. The lowest oxygen levels were measured in pond effluents just prior to the second release of fish of the 1991 brood. These appeared to be related to higher pond weight loads.

Mortality was low throughout test rearing of all broods (Table 5). Losses varied from only 1% for fish of the 1989 brood to 1.5% for fish of the 1992 brood. Although rearing losses decreased significantly as the fish increased in size from the first through the final rearing period, significant treatment effects from rearing density were not found. Mortality did not differ during rearing of the 1989, 1990, and 1991 broods but was significantly higher during rearing of the 1992 brood. Losses through-

TABLE 3.—Pond densities and loadings at release of four broods of Tule fall chinook salmon smolts reared in 91.2-m^3 ponds with water inflows of 2,725 L/min. Values are the means of paired ponds. The density index [$W/(LV)$] and flow index [$W/(LF)$] are from Piper et al. (1982); W = weight of fish (kg), L = length of fish (cm), V = rearing space (m^3), and F = water inflow (L/min). At stocking, density indexes averaged 0.104, 0.210, 0.318, and 0.420 in ponds with 91,000, 182,000, 273,000, and 364,000 fish, respectively; flow indexes averaged 0.007, 0.014, 0.022, and 0.029.

Brood year	Release date	Initial rearing density (fish per pond)			
		91,000	182,000	273,000	364,000
		Fish weight/rearing space; (density index)			
1989	16 Mar 1990	3.5 (0.47)	7.4 (0.96)	11.1 (1.44)	14.6 (1.92)
	18 Apr 1990	4.8 (0.50)	8.8 (0.95)	13.6 (1.45)	18.1 (1.93)
	17 May 1990	3.7 (0.33)	6.6 (0.62)	9.9 (0.93)	13.5 (1.26)
1990	21 Mar 1991	3.4 (0.46)	6.9 (0.91)	9.8 (1.33)	13.3 (1.79)
	18 Apr 1991	4.3 (0.47)	8.8 (0.95)	12.4 (1.36)	17.0 (1.85)
	16 May 1991	3.9 (0.34)	7.7 (0.69)	10.9 (1.00)	14.6 (1.33)
1991	5 Mar 1992	4.0 (0.51)	8.5 (1.09)	9.9 (1.27)	14.4 (1.88)
	16 Apr 1992	5.6 (0.56)	10.3 (1.05)	16.0 (1.63)	20.7 (2.11)
	21 May 1992	4.5 (0.38)	8.7 (0.74)	12.7 (1.09)	16.7 (1.45)
1992	18 Mar 1993	3.4 (0.44)	6.3 (0.86)	9.5 (1.30)	12.7 (1.73)
	15 Apr 1993	3.9 (0.43)	7.2 (0.83)	10.9 (1.25)	13.8 (1.61)
	20 May 1993	3.8 (0.34)	6.7 (0.63)	10.1 (0.94)	13.3 (1.24)
		Fish weight/water flow; (flow index)			
1989	16 Mar 1990	0.12 (0.016)	0.25 (0.032)	0.38 (0.048)	0.51 (0.064)
	18 Apr 1990	0.17 (0.017)	0.26 (0.032)	0.47 (0.049)	0.62 (0.065)
	17 May 1990	0.13 (0.011)	0.23 (0.021)	0.34 (0.031)	0.47 (0.042)
1990	21 Mar 1991	0.12 (0.015)	0.24 (0.031)	0.34 (0.044)	0.46 (0.060)
	18 Apr 1991	0.14 (0.016)	0.30 (0.032)	0.42 (0.045)	0.59 (0.062)
	16 May 1991	0.13 (0.011)	0.27 (0.023)	0.38 (0.033)	0.50 (0.044)
1991	5 Mar 1992	0.14 (0.017)	0.30 (0.037)	0.41 (0.043)	0.50 (0.063)
	16 Apr 1992	0.19 (0.019)	0.35 (0.035)	0.55 (0.54)	0.72 (0.071)
	21 May 1992	0.16 (0.013)	0.30 (0.025)	0.43 (0.037)	0.57 (0.048)
1992	18 Mar 1993	0.11 (0.015)	0.22 (0.029)	0.33 (0.044)	0.44 (0.058)
	15 Apr 1993	0.13 (0.015)	0.25 (0.028)	0.37 (0.042)	0.48 (0.054)
	20 May 1993	0.13 (0.014)	0.23 (0.021)	0.35 (0.032)	0.46 (0.042)

out the study could not be attributed to any particular disease organism.

Treatment Effects after Release

A total of 729,735 coded-wire-tagged fish were released from the hatchery during the 4 years of test rearing. An estimated 1,090 fish were caught in various marine and freshwater fisheries on the Pacific Coast, and 467 fish returned as adults to the Spring Creek hatchery holding facility. About 10% of the hatchery returns were 2-year-old males, 65% were 3-year-old fish, 24% were 4 years old, and less than 1% were 5 years old.

Analysis of percentage recovery data from coded-wire-tagged adults captured in the various fisheries and at the hatchery holding pond indicated a significant factor interaction between rearing density and brood year (Table 6). The analysis, therefore, was limited to a one-way ANOVA within individual brood years. Within the 1989 brood, the percentage recovery of coded-wire-tagged adults was significantly higher in fish reared at the lowest density. Within the 1990 and 1991 broods, however, differences in percent recovery across densities were not significant. Within the 1992 brood, percent recovery between fish reared at the highest and lowest densities was not significantly different, but both were significantly higher than recovery rates of fish reared at either of the intermediate densities. Within this brood, recovery rates of fish reared at the two intermediate densities did not differ significantly from each other. Overall, percent survival after release was not strongly affected by rearing density.

Rearing density levels of 91,000, 182,000, 273,000, and 364,000 fish per pond resulted in overall mean adult yields of 240, 314, 515, and 691 fish per pond, respectively (Table 7). A significant factor interaction (rearing density × brood year) was found when the combined data for all broods was analyzed using ANOVA. Within the 1989 brood, adult yield from smolts reared at the two lowest densities did not differ significantly from each other, but both were significantly lower than yields from fish reared at the two highest densities. Adult yield from the highest density treatment was significantly higher than that from smolts reared at a density of 273,000 fish per pond.

TABLE 4.—Water temperature and dissolved oxygen (mg/L) in pond influents and effluents on the afternoon before release of four broods of Tule fall chinook salmon smolts. Fish were reared in 91.2-m^3 ponds at four densities with water inflows of 2,725 L/min. Values for dissolved oxygen are the means of paired ponds.

Brood year	Release date	Temperature (°C)	Influent oxygen	Effluent oxygen at initial rearing density (fish per pond)			
				91,000	182,000	273,000	364,000
1989	16 Mar 1990	9.0	11.2	11.1	10.2	9.5	8.8
	18 Apr 1990	10.0	11.2	11.1	10.2	9.4	8.3
	17 May 1990	10.0	11.1	11.0	9.7	8.7	7.6
1990	21 Mar 1991	9.5	11.4	10.9	10.0	9.4	8.6
	18 Apr 1991	9.6	11.4	10.9	10.0	9.3	8.6
	16 May 1991	9.5	11.5	11.5	10.9	10.2	9.6
1991	5 Mar 1992	8.9	11.6	11.4	10.5	10.0	9.3
	16 Apr 1992	10.5	10.9	9.1	8.3	7.4	6.4
	21 May 1992	11.1	11.3	11.2	10.6	9.8	9.2
1992	18 Mar 1993	9.0	11.7	11.5	10.8	10.1	9.4
	15 Apr 1993	9.5	11.3	11.0	10.3	9.4	8.9
	20 May 1993	10.6	11.2	11.1	10.6	10.0	9.5

Although adult yield appeared to be related to rearing density within the 1990 brood, no statistically significant differences were found. Analysis of adult contribution in the 1991 brood revealed no significant differences in adult yield between the two lowest density treatments and between the three highest density treatments but a significant increase in yield at the highest two densities over adult yield at the lowest density. Within the 1992 brood, adult contribution was not significantly dif-

TABLE 5.—Percent rearing mortality in four broods of Tule fall chinook salmon smolts reared in 91.2-m^3 ponds at four densities with water inflows of 2,725 L/min. Cell values are the means of paired ponds; standard errors are given in parentheses. The mean values of percent mortality are not significantly different for rearing density. For the combined broods, the mean values for release dates without a letter in common are significantly different ($P \leq 0.05$); as are the mean values of percent mortality for brood years.

Release date	Initial rearing density (fish per pond)				Mean across densities	Brood year mean
	91,000	182,000	273,000	364,000		
1989 brood year						
16 Mar 1990	2.9 (0.3)	2.4 (0.2)	2.5 (0.1)	2.7 (0.1)	2.6 (0.1)	
18 Apr 1990	0.3 (0.1)	0.2 (0.1)	0.2 (0.0)	0.3 (0.0)	0.3 (0.0)	
17 May 1990	0.2 (0.1)	0.3 (0.1)	0.4 (0.1)	0.4 (0.1)	0.3 (0.0)	
Mean across releases	1.1 (0.6)	1.0 (0.5)	1.0 (0.5)	1.1 (0.5)		1.0 (0.2) y
1990 brood year						
21 Mar 1991	2.9 (0.2)	3.4 (1.2)	3.1 (0.1)	2.9 (0.2)	3.1 (0.3)	
18 Apr 1991	0.3 (0.0)	0.3 (0.1)	0.4 (0.1)	0.5 (0.1)	0.4 (0.1)	
16 May 1991	0.2 (0.0)	0.2 (0.1)	0.2 (0.0)	0.2 (0.1)	0.2 (0.0)	
Mean across releases	1.1 (0.6)	1.3 (0.7)	1.2 (0.6)	1.2 (0.6)		1.2 (0.3) y
1991 brood year						
5 Mar 1992	1.9 (0.3)	2.1 (0.2)	3.3 (0.3)	3.3 (0.5)	2.7 (0.3)	
16 Apr 1992	0.4 (0.1)	0.8 (0.5)	0.6 (0.0)	0.7 (0.0)	0.6 (0.1)	
21 May 1992	0.2 (0.1)	0.3 (0.1)	0.4 (0.1)	0.3 (0.2)	0.3 (0.0)	
Mean across releases	0.8 (0.4)	1.1 (0.4)	1.4 (0.6)	1.4 (0.6)		1.2 (0.2) y
1992 brood year						
18 Mar 1993	3.4 (0.3)	3.1 (0.3)	3.1 (0.1)	2.6 (0.3)	3.1 (0.1)	
15 Apr 1993	0.6 (0.1)	0.7 (0.0)	1.0 (0.2)	1.4 (0.3)	0.9 (0.1)	
20 May 1993	0.4 (0.0)	0.5 (0.2)	0.6 (0.2)	0.8 (0.1)	0.6 (0.1)	
Mean across releases	1.5 (0.6)	1.4 (0.5)	1.6 (0.5)	1.6 (0.4)		1.5 (0.2) z
Combined broods						
Mar	2.8 (0.2)	2.7 (0.3)	3.0 (0.1)	2.9 (0.2)	2.9 (0.1) x	
Apr	0.4 (0.1)	0.5 (0.1)	0.5 (0.1)	0.7 (0.2)	0.5 (0.1) y	
May	0.2 (0.0)	0.3 (0.1)	0.4 (0.1)	0.4 (0.1)	0.3 (0.0) z	
Mean across releases	1.1 (0.3)	1.2 (0.3)	1.3 (0.3)	1.3 (0.2)		

TABLE 6.—Estimated percentage of Tule fall chinook salmon in four broods that were recovered as adults after release. Fish were reared in 91.2-m^3 ponds at four densities with water inflows of 2,725 L/min. Recoveries include hatchery returns and fishery catch. Cell values are the means of paired ponds; standard errors are given in parentheses. Within the two-way ANOVA model (rearing density × brood year), factor interaction is significant ($P \leq 0.05$). Analysis of rearing density effects, therefore, is confined to a one-way ANOVA within individual broods. Within a row, values without a letter in common are significantly different ($P \leq 0.05$).

Brood year	Initial rearing density (fish per pond)				Brood year mean
	91,000	182,000	273,000	364,000	
1989	0.45 (0.05) z	0.26 (0.01) y	0.29 (0.00) y	0.32 (0.03) y	0.33 (0.03)
1990	0.22 (0.05) z	0.23 (0.07) z	0.19 (0.06) z	0.08 (0.00) z	0.18 (0.03)
1991	0.20 (0.01) z	0.16 (0.02) z	0.17 (0.03) z	0.13 (0.01) z	0.16 (0.01)
1992	0.23 (0.00) z	0.09 (0.02) y	0.14 (0.02) y	0.26 (0.03) z	0.18 (0.03)
Mean across densities	0.27 (0.04)	0.18 (0.03)	0.20 (0.03)	0.20 (0.04)	

ferent among the three lowest density treatments, but it was significantly higher at the highest density. Overall, there was a positive correlation between increased rearing density and increased adult contribution ($R = 0.985$).

Analysis of adult returns to the hatchery showed no treatment effects on age composition, fork length, or sex ratio.

Discussion

Although significant interactions were found between rearing density and brood year within the experimental model, the effects of increased rearing density on smolt survival and adult contribution seem apparent (Figure 1). Within the range of densities tested, a four-fold increase in rearing density produced a three-fold increase in adult contribution in a relationship close to linearity ($R = 0.985$). About 53 additional adults were recovered for each 1,000-fish increase in stocking density. Little difference in percent survival after release was found in fish reared at the three highest densities. The observed increase in survival rate in fish reared at the lowest density, however, may have been more apparent than real. The increase comes from the survival rates of fish reared at the lowest density within the 1989 brood (Table 6). Survival rates of both pond replicates within this cell are double the rates found in the 1990, 1991, and 1992 brood tests. The reasons for the high survival of these fish are not clear. Fish from this cell were significantly larger at release (Table 2); however, other treatment groups differed significantly in size at release without corresponding differences in survival.

Increased rearing densities produced significant, but inconsistent, reductions in smolt size at release within the 1989, 1990, and 1992 broods. Although not significant, a similar trend was also observed within the 1991 brood. Overall, increased rearing density produced a decrease in smolt size at release ($R = -0.868$). Pond weight loads were consistently greatest just prior to the second release in April because of the nature of the experimental model. Smolts were only a little more than half as large at the second release in April as they were at the final release in May. Two-thirds of the original population, however, was still in residence until the April release. The density index averaged about 0.48 and the flow index about 0.015 at the release of fish from the ponds with the lowest density (91,000 fish). In ponds stocked at the highest

TABLE 7.—Estimated adult contribution per pond from four broods of Tule fall chinook salmon reared in 91.2-m^3 ponds at four densities with water inflows of 2,725 L/min. Recoveries include hatchery returns and fishery catch. Cell values are the means of paired ponds; standard errors are given in parentheses. Within the two-way ANOVA model (rearing density × brood year), factor interaction is significant ($P \leq 0.05$). Analysis of rearing density effects, therefore, is confined to a one-way ANOVA within individual broods. Within a row, values without a letter in common are significantly different ($P \leq 0.05$).

Brood year	Initial rearing density (fish per pond)				Brood year mean
	91,000	182,000	273,000	364,000	
1989	396 (42) x	453 (16) x	765 (0) y	1,123 (108) z	684 (112)
1990	192 (45) z	394 (108) z	490 (136) z	297 (1) z	343 (54)
1991	176 (10) y	266 (27) yz	449 (68) z	443 (5) z	334 (46)
1992	195 (5) y	144 (26) y	356 (47) y	899 (80) z	398 (115)
Mean across densities	240 (36)	314 (50)	515 (65)	691 (129)	

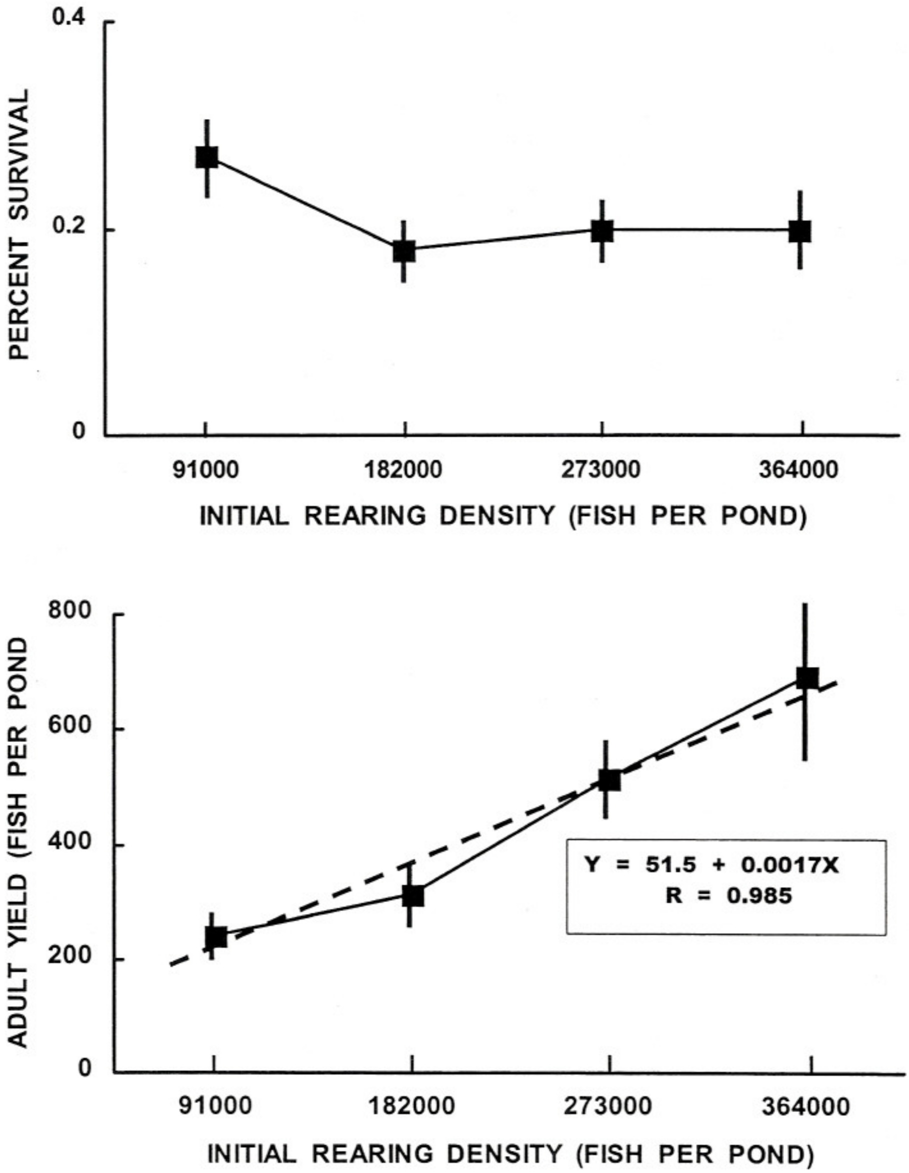

FIGURE 1.—Effects of four levels of hatchery rearing density on survival and adult contribution of Tule fall chinook salmon after release. Vertical bars represent standard errors. About one-third of the original stocked population was randomly released each month from March to May.

density (364,000 fish), the density and flow indices averaged about 1.68 and 0.056, respectively, at time of fish release.

Rearing losses were consistently low and did not appear to be related to rearing density. Significant disease-related problems were not observed during periodic examinations throughout rearing. The dissolved oxygen levels shown in Table 4 are not a representation of overall oxygen concentrations throughout the rearing period. However, they provide a reasonable estimate of oxygen levels in pond effluents at a time (late afternoon) and at a period (just prior to release) when weight loads were at their maximum. There was no evidence that dissolved oxygen levels affected the results of these tests. Oxygen levels at smolt release were well in excess of the lower limits defined by Burrows and Combs (1968) and Westers and Pratt (1977) for salmonid culture.

The results suggest that adult contributions could not be maintained by rearing less than 364,000 fish per pond. There is also evidence that adult contributions might be increased by increasing rearing densities above 364,000 fish per pond as long as multiple releases are used. Anyone who selects this option, however, needs to be aware of the potential for catastrophic losses from diseases such as bacterial gill disease that have been observed in the past in water recycle systems. The cause of gill hyperplasia and bacterial gill disease in fish cultural systems is complex and not well understood. At one time gill damage was thought to be a reflection of un-ionized ammonia, but more recent work suggests that other metabolic waste products in combination with water quality may be involved (Meade 1985). Also, gill damage and gill disease may be related to abrasion from feed particles and other fine solids and may be correlated with levels of dissolved oxygen and total ammonia (J. Colt, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, personal communication). Treatment with chemicals or antibiotics is often impractical in this type of system because the function of the biological filters is often destroyed and, once treated, replacement of system water with fresh water is usually not practical. Premature release of all fingerling stock is often the only management alternative.

The effects of hatchery rearing densities on survival and adult contribution of Tule fall chinook salmon have not been previously reported. This seems surprising in view of their economic importance to the Pacific Northwest. Postrelease effects from different rearing densities have been reported for upriver bright fall chinook salmon reared in freshwater net pens (Beeman and Novotny 1994) and for coastal fall chinook salmon (T. Downey, Oregon Department of Fisheries and Wildlife, unpublished). The effects of rearing density on spring chinook salmon after release have been reported by several investigators (Fagerlund et al. 1987; Denton 1988; Martin and Wertheimer 1989; Banks 1994; C. Hopley, Washington Department of Fisheries and Wildlife, unpublished). Studies of rearing density effects on coho salmon *Oncorhynchus kisutch* after release have been reported by Fagerlund et al. (1983, 1984, 1989), Hill et al. (1989), Banks (1992), Hopley et al. (1993), and in three unpublished studies (K. Sandercock, Canada Department of Fisheries and Oceans; A. Hemmingsen, Oregon Department of Fisheries and Wildlife; and J. Holway, U.S. Fish and Wildlife Service). In general, most studies with coho salmon suggest that increased hatchery rearing densities produce increases in adult contribution. In contrast, chinook salmon fingerlings appear to be less tolerant of crowding in hatcheries. In many cases, studies have found that increased rearing densities result in no increase in adult contribution or a reduction in adult contribution. The results for Tule fall chinook salmon reported herein suggest a response to increased densities similar to that of coho salmon rather than spring chinook salmon, at least within the range of densities tested. However, additional studies at more conventional hatcheries using higher densities are needed to determine the generality of this trend. The fact that two-thirds of the fish in this study were reared for 4 months or less leads to speculation about the outcome if the fish had been reared at similar densities for a year or more, as is common with other species of Pacific salmon at other hatcheries.

In conclusion, the variable results reported in rearing density studies are almost certainly a reflection of the complex relationship between rearing density and the many site-specific factors found at individual hatcheries. The results obtained here again point out the need for an extensive rearing density information base for Pacific salmon if fish culturists are to make informed production management decisions aimed at maximizing the adult contribution from hatcheries.

Acknowledgments

We thank J. Bayman, E. Gunderson, D. Tiffin, M. Woods, S. Zirjacks, and all the other staff members at Spring Creek National Fish Hatchery who reared the test fish, helped with fish stocking and release, and assisted in the bimonthly size sampling efforts. We also thank T. Nielsen, E. Pelton, K. Stone, and P. Trollier of the Lower Columbia River Fish Health Center who performed periodic health examinations of the test fish. J. Edwards, L. Fowler, J. Holmes, and J. Poole from the Abernathy Fish Technology Center also helped with stocking and release activities. We are indebted to all those who worked on the fish tagging crews and to personnel from the Lower Columbia Fishery Resource Office who supervised tagging operations and who recovered and decoded coded wire tags from adult returns to the hatchery. We also appreciate the editorial efforts of L. Fowler, J. Morrison, B. Piper, and four other anonymous reviewers. Funding for this study was provided by the U.S. Fish and Wildlife Service.

References

Banks, J. L. 1992. Effects of density and loading on coho salmon during hatchery rearing and after release. Progressive Fish-Culturist 54:137–147.

Banks, J. L. 1994. Raceway density and water flow as factors affecting spring chinook salmon (*Oncorhynchus tshawytscha*) during rearing and after release. Aquaculture 119:201–217.

Beeman, J. W., and J. F. Novotny. 1994. Pen rearing and imprinting of fall chinook salmon. Final Report to Bonneville Power Administration, Project 82–313, Portland, Oregon.

Burrows, R. E., and H. H. Chenoweth. 1970. The rectangular circulating rearing pond. Progressive Fish-Culturist 32:67–80.

Burrows, R. E., and B. D. Combs. 1968. Controlled environments for salmon propagation. Progressive Fish-Culturist 30:123–136.

Denton, C. 1988. Marine survival of chinook salmon, *Oncorhynchus tshawytscha*, reared at three densities. Alaska Department of Fish and Game, FRED Report Number 88, Juneau.

Dixon, W. J., editor. 1990. BMDP statistical software manual volumes 1 and 2 to accompany the 1990 software release. BMDP Statistical Software, Inc., Los Angeles.

Ewing, R. D., and S. K. Ewing. 1995. Review of the effects of rearing density on survival to adulthood for Pacific salmon. Progressive Fish-Culturist 57: 1–25.

Fagerlund, U., J. McBride, B. Dosinjh, and E. Stone. 1987. Culture density and size effects on performance to release of juvenile chinook salmon and subsequent ocean survival. Smolt releases from Capilano Hatchery in 1980 and 1981. Canada Fisheries and Marine Service Technical Report 1572.

Fagerlund, U., J. McBride, B. Dosinjh, E. Stone, and K. Sandercock. 1983. Influence of culture density on juvenile coho salmon production and ocean survival. Smolt releases in 1979 and 1980 from Capilano Hatchery. Canada Fisheries and Marine Service Technical Report 1229.

Fagerlund, U., J. McBride, B. S. Dosanjh, J. Van Tine, and M. Greig. 1989. Effects of culture density and size of juveniles on growth and survival of pond–reared coho salmon released from Quinsam Hatchery in 1983 and 1984. Canada Fisheries and Marine Service Technical Report 1689.

Fagerlund, U., J. R. McBride, B. S. Dosanjh, H. T. Bilton, R. B. Morley, and J. Van Tine. 1984. Density effects on performance to release of three size groups within populations of pond–reared juvenile coho salmon. Smolts released from Quinsam Hatchery in 1983. Canada Fisheries and Marine Service Technical Report 1337.

Hill, J. M., T. Olson, and T. J. Clune. 1989. Evaluation of a low–cost salmon production facility. Bonneville Power Administration, Fishery Research Project 83–364, Portland, Oregon.

Hopley, C. W., S. B. Mathews, A. E. Appleby, A. Rankis, and K. L. Halliday. 1993. Effects of pond stocking rate on coho salmon survival at two Lower Columbia River fish hatcheries. Progressive Fish-Culturist 55:16–28.

Martin, R., and A. Wertheimer. 1989. Adult production of chinook salmon reared at different densities and released as two smolt sizes. Progressive Fish-Culturist 51:194–200.

Meade, J. 1985. Allowable ammonia for fish culture. Progressive Fish-Culturist 47:135–145.

Piper, R., I. McElwain, L. Orme, J. McCraren, L. Fowler, and J. Leonard. 1982. Fish hatchery management. U.S. Fish and Wildlife Service, Washington, D.C.

Snedecor, G. W., and W. Cochran. 1967. Statistical methods, 6th edition. Iowa State University Press, Ames.

Vreeland, R. R. 1989. Evaluation of the contribution of fall chinook salmon reared at Columbia River hatcheries to the Pacific salmon fisheries. Final Report to Bonneville Power Administration, Project 79–2, Portland, Oregon.

Westers, H., and K. M. Pratt. 1977. Rational design of hatcheries for intensive salmonid culture, based on metabolic characteristics. Progressive Fish-Culturist 39:157–165.