Notes

An Evaluation of Rearing Densities to Improve Growth and Survival of Hatchery Spring Chinook Salmon

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Abstract

We evaluated growth and survival of spring Chinook salmon *Oncorhynchus tshawytscha* reared at varying densities at Warm Springs National Fish Hatchery, Oregon. For three consecutive brood years, density treatments consisted of low, medium, and high groups in 57.8-m^3 raceways with approximately 16,000, 24,000, and 32,000 fish/raceway, respectively. Fish were volitionally released in both the autumn and spring to mimic the downstream migration timing of the endemic wild spring Chinook salmon stock. Just prior to the autumn release, the rearing density estimate was 4.24 kg/m^3 for the low-density group, 6.27 kg/m^3 for the medium-density group, and 8.42 kg/m^3 for the high-density group. While weight gain did not differ among density treatments ($P = 0.72$), significant differences were found in median fork length ($P < 0.001$) for fish reared at different densities. Fish reared at high density exhibited the highest on-hatchery mortality rate during two brood years; however, differences in mortality rate among densities were not significant ($P = 0.20$). In one brood year, adult recovery rates appeared to support the hypothesis that lower initial densities improved postrelease survival ($P < 0.01$). All rearing densities utilized in this evaluation were relatively low and may partially explain why more differences were not readily apparent among density groups. In addition, the volitional release was a confounding factor in our study because we were unable to quantify the number of fish released in the autumn.

Keywords: Chinook salmon; growth; hatchery; rearing density; survival; temperature; volitional release

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Introduction

As part of hatchery reform in the Pacific Northwest, managers of salmon and steelhead trout *Oncorhynchus* spp. hatcheries are encouraged to manage their brood stock as either segregated from, or integrated with, wild fish (Mobrand et al. 2005). Warm Springs National Fish Hatchery (NFH) is an example of an integrated brood stock that periodically incorporates genetic components of the wild spring Chinook salmon *Oncorhynchus tshawytscha* population in the Warm Springs River (USFWS 2006). One of the tenets of the integrated hatchery management strategy is to maintain similar life-history characteristics between the hatchery and wild population. The release strategy at Warm Springs NFH was designed to mimic the downstream migration pattern of wild spring Chinook salmon and consists of an autumn and a spring volitional release (Olson et al. 2004).

In addition to retaining wild salmon genetics and their migratory phenotypes in hatchery fish, managers strive

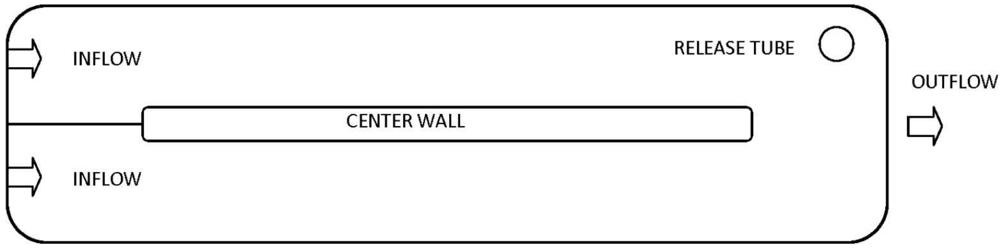

Figure 1. Schematic representation of the U-shaped design of the modified Burrows raceway at Warm Springs National Fish Hatchery, Oregon, where we evaluated growth and survival of spring Chinook salmon *Oncorhynchus tshawytscha* produced from brood years 2000 through 2002. The head end is closed to create two 22.86-m raceways with the water flowing in through vertical header pipes and out through screens at the tail end of the raceway. Each half of the raceway is 2.43 m wide and maintained with a 52-cm water depth with 57.8 m^3 total water volume/"U"-shaped container (2,000 ft^3/"U"-shaped container).

to improve growth and survival of hatchery fish. Previous studies have found that lower rearing densities can increase growth and survival with decreased mortality from disease (Banks 1994; Ewing et al. 1998); however, because each facility can be configured differently and has different factors affecting production, it is recommended that each facility determine its own optimum rearing density (Ewing and Ewing 1995; Integrated Hatchery Operations Team 1995).

Based on operational experience since 1978, production rearing at Warm Springs NFH was set at relatively low densities of approximately 30,000 fish/raceway (9–12 kg/m^3 at release). These low rearing densities are utilized at the hatchery in part because one of the factors limiting production at Warm Springs NFH is high summer water temperature, often reaching 21°C in July (USFWS 2006). At these temperatures, Chinook salmon can experience increased mortality from disease, decreased growth rates, impaired smoltification, and increased vulnerability to predation (Antonio and Hedrick 1995; Marine and Cech 2004). Building upon previous rearing-density evaluations at national fish hatcheries in the Columbia River basin (Banks 1992,1994; Olson 1997; Banks and LaMotte 2002), along with recognizing the fish culture challenges when rearing spring Chinook salmon in high summer water temperature, we designed a study to determine the effects of rearing density on growth and survival of spring Chinook salmon at Warm Springs NFH. We evaluated fish reared at three densities (approximately 16,000, 24,000 and 32,000 fish/raceway) with the highest density most closely representing normal production loading. We evaluated the effect of initial rearing density on fish growth and survival from time of raceway loading (May) to just prior to the autumn release in November, or approximately one-half of the total rearing duration. We also compared fish survival from total release (autumn and spring combined) with adult recovery.

Methods

Warm Springs NFH is located at river kilometer 16 on the Warm Springs River, within lands managed by the Confederated Tribes of the Warm Springs Reservation of Oregon. The Warm Springs River enters the Deschutes River at river km 135 in north-central Oregon, which enters the Columbia River 330 km from the Pacific Ocean upstream of Bonneville Dam (river km 235) and The Dalles Dam (river km 308).

Juvenile spring Chinook salmon produced from brood years 2000 through 2002 were sampled for this study. Spawning occurred from late August to mid-September over a 3–5-wk period. All three broods were from Warm Springs River hatchery stock and all eggs and juvenile fish were reared at Warm Springs NFH per standard procedures across years and among raceways within years (Integrated Hatchery Operations Team 1996).

Fry were moved from the indoor nursery to three outdoor Burrows raceways in mid- to late March, depending on temperature and fish size. Each Burrows raceway was modified to a "U"-shaped rearing container so that the head end was closed with the water flowing in through vertical header pipes and out through screens at the tail end of the raceway (Figure 1), with a total rearing volume of 57.77 m^3 (2,000 ft^3/"U"-shaped container). Water was pumped directly from the Warm Springs River to the raceways at approximately 1,500 L/min/raceway during winter and 2,268 L/min/raceway during summer rearing. Ambient water temperature during the rearing cycle was recorded on an hourly schedule.

We reported rearing density of fish as kg/m^3. We also reported density and flow indices, using standard English measurements (Piper et al. 1982). All normal fish culture activities (i.e., raceway cleaning, time of feeding, sample counting, etc.) were undertaken as equally as possible throughout all three density groups. Mortalities were collected daily and recorded.

Spring Chinook salmon used in this study had their adipose fins clipped and were tagged with coded-wire tags (CWT) from late April to early May of their first year. For brood years 2000 and 2001, the low-density group was marked (fin-clipped and tagged) first and the high-density group was marked last. For brood year 2002, marking progressed from high-to-low-to-medium density groups. Three replicate raceways were used for each density group during each of the 3 y. Each density and brood year was represented by a unique CWT. Densities were rotated annually so that no raceway was used more than once for a specific density group. In addition, for brood year 2002, each raceway of fish received a unique CWT. Fish from brood years 2000 and 2002 were marked manually in trailers using scissors and Mark IV tag injectors (Northwest Marine Technology, Inc.) and brood year 2001 fish were marked using an automated trailer (Hand et al. 2010; VanderHaegen et al. 2012). Average fish weight at time of marking ranged from 3.0 to 3.7 g (124–150 fish/lb). After marking, the number of fish per density group was: 16,000 for the low-density group; 24,000 for the medium-density group; and 32,000 fish/raceway for the high-density group (normal production density).

Feeding rates were adjusted to achieve similar size at release for all density groups within a brood year. Erythromycin thiocyanate (Aquamycin 100) was incorporated in the diet during May and September of each year to prevent problems associated with bacterial kidney disease. Although the feed type varied through the years, all three density groups were always fed the same diets for the same number of days.

Approximately 5 mo after the initial marking (late April or early May) and prior to autumn release, we sampled fish in early October from each CWT group (approximately 300 fish/raceway) to determine tag retention and fish weight (No. of fish/kg). We calculated average fish weight (g) from each raceway's aggregate weight sample (Piper et al. 1982). On 3 October 2002 (brood year 2001) and 22 March 2004 (brood year 2002), we sampled a minimum of 300 fish/raceway to determine fork length (mm).

Fish were released into the Warm Springs River during an autumn volitional and spring volitional–forced release. The autumn volitional release of subyearling fish occurred in October and November of the first year of rearing. The spring volitional release of yearling fish occurred between late March and mid-late April of the following year; any fish remaining thereafter were forced out. The total number released each brood year was estimated by subtracting the observed mortalities from the total number of fish tagged and correcting for an estimate of tag retention. Releases were reported to the Regional Mark Processing Center (www.rmpc.org) following standard practices.

Adult fish from each release were recovered in ocean and freshwater fisheries, and at the hatchery after spending 1–3 y in the Pacific Ocean (2002–2007). Observed and expanded adult fish recoveries were obtained from Pacific States Regional Mark Processing Center (www.rmpc.org; 7 February 2011). We used expanded recoveries to estimate total recovery of a group of fish and calculated them as $R_T = aR_O$, where R_T is the estimated total recovery of tags bearing the release group's code, a is the sampling expansion factor, and R_O is the observed number of tag recoveries during sampling (Johnson 1990). The use of expanded recoveries for rearing-density evaluations is an accepted standard (Ewing and Ewing 1995; Banks 1992, 1994; Banks and LaMotte 2002).

We performed both parametric and nonparametric tests (Zar 1999) to analyze juvenile fish weight, length, mortality, and adult recovery data by density and brood year. We performed parametric analysis of variance (ANOVA) when tests were passed for normality and equal variance; otherwise, we performed nonparametric analyses on ranked data (Sigma Plot 11.2, Systat Software, Inc., San Jose, California). We performed Tukey or Dunn's multiple-comparison tests if statistical significance was found during ANOVA. In addition, we performed χ^2analyses to conduct comparisons among density groups within brood years for assessment of release to adult recovery. We reported significance of statistical analysis at the $P < 0.05$ level. Weight, length, and mortality data are archived in the Dryad repository (*Archived Material*; http://dx.doi.org/10.5061/dryad.h5nc8).

Results

During autumn sampling, density (and flow) indices were approximately 0.06 (0.19) for the low-density group, 0.09 (0.28) for the medium-density group, and 0.11 (0.39) for the high-density group. The low-rearing-density group averaged 4.24 kg/m^3 (0.47 kg/m^3 SD), the medium-density group averaged 6.27 kg/m^3 (0.52 kg/m^3 SD), and the high-density group averaged 8.42 kg/m^3 (0.64 kg/m^3 SD). Water temperatures fluctuated daily by season, ranging from a low of 0°C in winter to a high of 22.8°C in summer (Figure 2).

Across all densities and brood years, fish increased in average weight from 3.3g (0.2 SD) at the start of the study in late April or early May to 15.4g (1.3 SD) in early October. We found no significant differences in fish weight gain across densities ($P = 0.72$), after controlling for significant differences among brood years ($P < 0.001$). We found significant differences in fork length ($P < 0.001$) for fish reared at different densities in the one brood year (2001) during which length was measured in the autumn. Brood year 2001 median fork lengths were 107 mm, 105 mm, and 103 mm for the low, medium, and high densities, respectively. Dunn's multiple-comparison test indicated significant differences ($P < 0.05$) in fork length between the low and high densities, as well as between the medium and high densities, in that year (2001).

Mean mortality of fish at the hatchery (0.15% SE), from time of marking in April to September, was 1.50, 1.64, and 1.89% for the low-, medium-, and high-density groups, respectively. These differences were not statistically significant ($P = 0.20$) after controlling for significant differences among brood years ($P = 0.01$). Tukey multiple comparisons indicated a near significant ($P = 0.05$) difference in mortality between the low- and high-density groups for brood year 2002 (Figure 3). Elevated mortalities often occurred in July, especially for the high-density groups in brood years 2001 and 2002 (42 and 61% of all mortalities for the year, respectively).

Although raceway densities were unknown after the autumn release and prior to the spring release, we detected differences in median fish length among raceways in brood year 2002 ($P = 0.001$). Median fork lengths were 121 mm, 123 mm, and 120 mm for the low, medium, and high densities, respectively. Dunn's multiple-comparison test indicated significant differences ($P < 0.05$) in fork length between fish from the medium- and

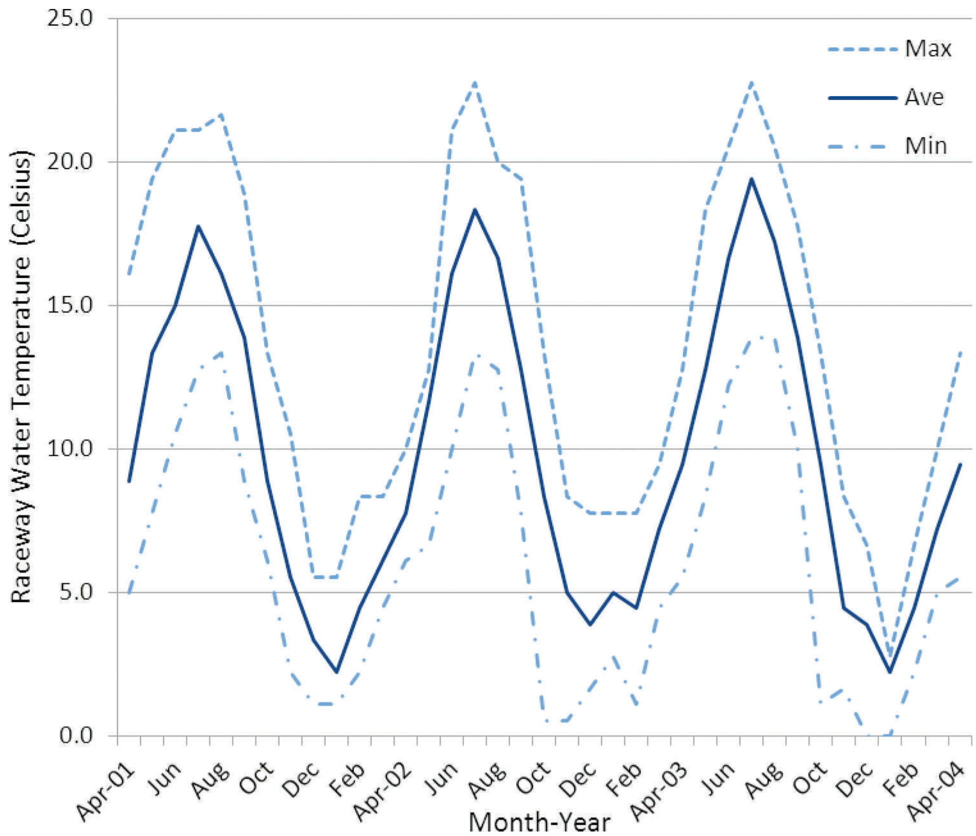

Figure 2. Monthly water temperature (°C) during rearing of spring Chinook salmon *Oncorhynchus tshawytscha* produced at Warm Springs National Fish Hatchery, Oregon, 2001–2004.

high-density raceways, as well as between the medium- and low-density raceways.

In one year (brood year 2001), fish from the low- and medium-density groups had significantly greater adult recovery rates than fish from the high-density group ($P < 0.01$; Table 1). No significant differences in recovery rates among density groups for the other two years were identified. Significant differences ($P < 0.001$) in adult recovery rates by brood year were found (Table 1). Combining all adult fish recovered, 13% were harvested in Columbia River fisheries (<1% ocean fisheries), and the majority were recovered at the hatchery (87%). There was no significant difference in recovery location among densities ($P = 0.13$).

Discussion

Fish growth can be an indicator of health and survival (Beckman et al. 1999); and Ewing et al. (1998) found that growth, final weight, and length were inversely related to rearing density. In our study, we found no significant difference in average fish weight gain by density group prior to autumn release. However, our sampling technique was not a precise measurement of growth. The sampling technique that we utilized for estimating fish weight was a standard method for determining fish size and feeding rates for the general hatchery population, but this technique can also easily have associated errors of weights and fish size ranging from 2 to 20% (Piper et al. 1982; Ewing et al. 1994). In the one year that fish were individually measured for fork length prior to autumn release, we did detect a significant, albeit small difference in median fork length among densities, with fish from the high densities being slightly smaller (103 mm) than fish from the medium (105 mm) or low (107 mm) densities. When a different set of raceways were sampled during the following brood year in the spring, we again found that fish from the raceway with the highest initial density had the smallest median fork length. Although statistically significant, the biological significance of the small difference in median fork length between groups reared at different densities is unknown. In addition, not knowing the final density at spring release complicates the interpretation of the results. Density, growth, weight, and length at spring release and their effect on fish health and survival (Reisenbichler et al. 1982; Martin and Wertheimer 1989; Tipping 1997, 2011) needs further investigation at Warm Springs NFH. To improve confidence in our ability to detect a difference in fish growth by density, we recommend keeping an accurate inventory and that individual weights and lengths are recorded for each replicate group, at the start and end of each study period.

Ewing and Ewing (1995) found that higher juvenile mortalities were often associated with increased rearing density. In our study, fish reared at the highest density had the highest on-hatchery mortality rate 2 out of 3 y; however, the differences in mortality rate among

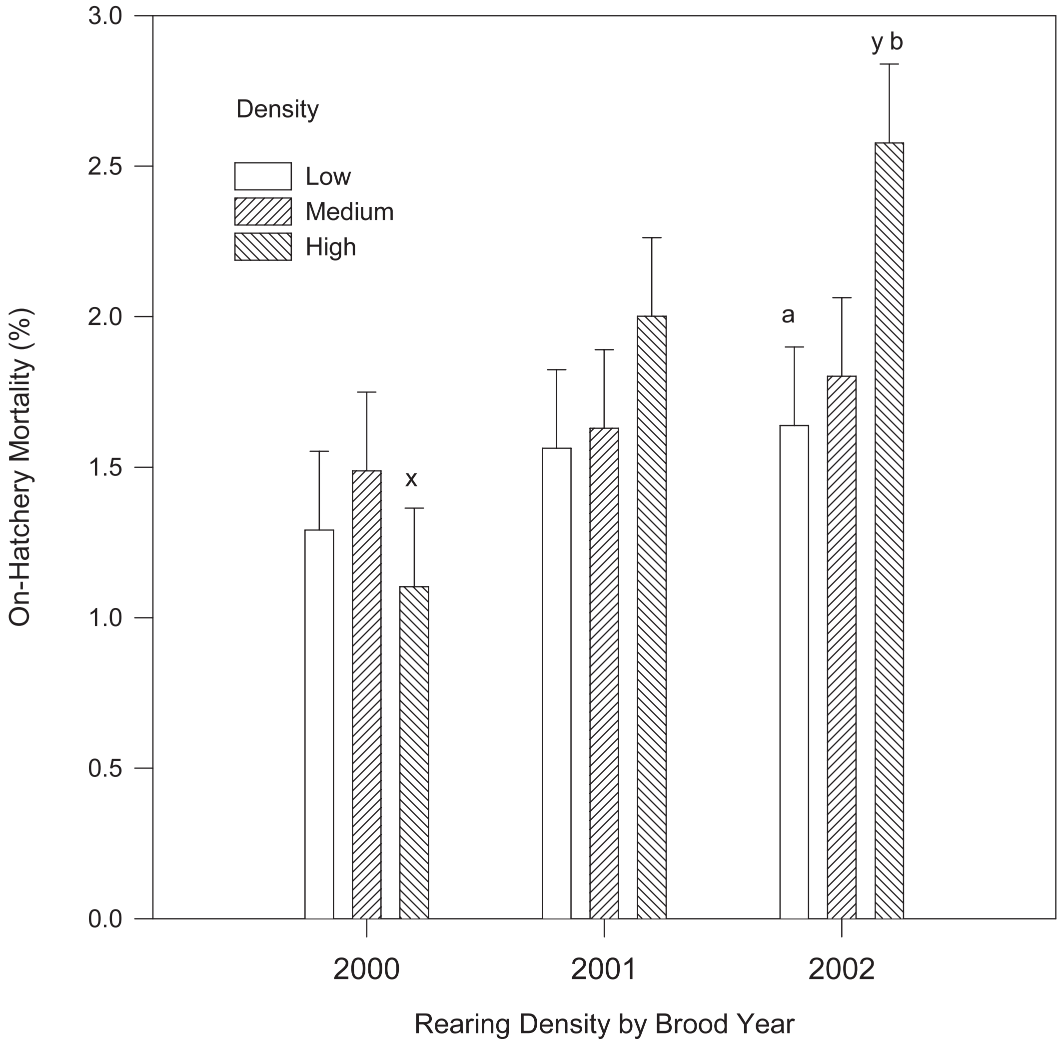

Figure 3. Percent mortality of juvenile spring Chinook salmon *Oncorhynchus tshawytscha* from time of marking in April–May through September, prior to autumn release in October–November for the rearing density study at Warm Springs National Fish Hatchery, Oregon, brood years 2000–2002. At autumn release, the density index was approximately 0.06 for the low-density group (4.24 kg/m^3), 0.09 for the medium-density group (6.27 kg/m^3), and 0.11 for the high-density group (8.42 kg/m^3). Data are expressed as mean (+SE) mortality (%) for density group by brood year. A near significant ($P = 0.05$) difference was detected between the low- and high-density group for brood year 2002 (denoted by the letters *a* and *b*) and brood year 2000 percent mortality was significantly different ($P = 0.002$) from brood year 2002 for the high-density group (denoted by the letters *x* and *y*).

densities were not statistically significant. The rearing densities in our evaluation may partially explain why differences were not readily apparent among densities. In comparison with other density studies (Banks 1990; Ewing and Ewing 1995), all rearing densities in this evaluation would be considered in the low range. Our study was also in general agreement with other studies (Banks 1992, Banks 1994; Ewing et al. 1998), which showed that mortality between brood years can be much larger than mortality within densities. Survival of fish at Warm Springs NFH was comparable to other spring Chinook salmon hatcheries in the Columbia River basin (USFWS 2007).

Previous studies with Chinook salmon have found that postrelease, smolt-to-adult survival rates decreased as rearing density increased, and were generally consistent for all rearing densities, ranging from 4.5 to 44.0 kg/m^3 (Ewing and Ewing 1995). In our study, we estimated density up to the autumn release (4.2–8.4 kg/m^3). Even though we no longer knew the raceway densities at spring release, our study would be considered on the lower range of densities previously evaluated. Because the fish were volitionally released in the autumn and spring, we cannot conclude that the differences we saw in recovery rates were due to initial rearing densities. However, adult recovery rates from brood year 2001 appeared to support the hypothesis that lower initial densities improved survival.

Ewing and Ewing (1995) found support for their hypothesis that stress from higher rearing densities may have the largest negative effects on survival to adulthood during poor ocean conditions; and conversely, during years of favorable ocean conditions, survival may not be adversely affected from higher densities. In our

Table 1. Estimated tagged release (autumn and spring) and adult recovery (harvest plus hatchery escapement) of spring Chinook salmon *Oncorhynchus tshawytscha* from the rearing density study at Warm Springs National Fish Hatchery, Oregon, brood years 2000–2002. Percent recovery is an estimate of total survival, where the expanded recovery is divided by estimated tagged release for each tag code, then multiplied by 100. At autumn release, the density index was approximately 0.06 for the low-density group (4.24 kg/m^3), 0.09 for the medium-density group (6.27 kg/m^3), and 0.11 for the high density group (8.42 kg/m^3). Significant differences ($P < 0.05$) in release to recovery ratios are denoted by different letters. Significant differences were detected between all brood years, denoted by the letters x, y, and z. Significant difference between densities was detected within brood year 2001, denoted by the letters a and b. Release and recovery data were obtained 7 February 2011 from the coded wire tag Regional Mark Processing Center database (www.rmpc.org).

Brood year	Tag code	Estimated tagged release	Observed recovery	Expanded recovery	Percent recovery	Density group
2000 x						
	054930	42,343	149	276	0.65	Low
	054412	63,935	245	453	0.71	Med
	054515	87,338	301	546	0.63	High
2001 y						
	054317	46,688	84	131	0.28	Low a
	054424	70,299	107	166	0.24	Med a
	054448	92,988	94	159	0.17	High b
2002 z						
	051495	14,756	63	97	0.66	Low
	051497	14,486	84	130	0.90	Low
	051498	14,238	74	117	0.82	Low
	053350	21,266	70	122	0.57	Med
	053351	20,491	107	171	0.83	Med
	053352	21,923	121	189	0.86	Med
	054848	29,089	134	210	0.72	High
	054849	28,929	138	213	0.74	High
	054850	28,613	131	210	0.73	High

study, lower densities appeared to give fish the greatest adult survival advantage when fish experienced poor postrelease conditions (i.e., brood year 2001). Fish from brood year 2001 had significantly lower adult recovery rates when compared with the 2000 and 2002 broods and were similar to other nearby spring Chinook hatcheries (Pastor 2010). These data indicated that postrelease factors played an important role in overall survival. Along with ocean productivity (Hare et al. 1999; Peterson et al. 2011), other factors that could lead to poor postrelease survival include disease (Warren 1991 and Moffitt et al. 1998), juvenile (Muir et al. 2001) and adult (Keefer et al. 2004) passage conditions, and predation (Rieman et al. 1991; Collis et al. 2001) in the Columbia River. Ideally, postrelease conditions would be predicted early enough so that rearing densities at hatcheries could be adjusted; unfortunately, this is not practical at this time.

Hatchery evaluation studies are often constrained by the number of fish and number of replicates available in an individual year (Tipping and Zajac 2010). Ewing and Ewing (1995) also noted that experimental study design may affect the ability to detect differences between densities and survival. We found this in our study as well. Three raceways were used during each of the 3 y for each of the three treatments (accommodating a 2-factor ANOVA to assess mortality); however, unique tag codes for individual raceways were only used in 1 of the 3 y. Ideally unique tag codes would have been used for all raceways during all 3 y to accommodate a factorial ANOVA to assess adult recovery rates. Also, the large number of fish in this study required utilizing embryos from multiple spawn periods, over two to three consecutive weekly spawns. Ideally the number of embryos taken from each spawn would have been equalized among density groups, but that was not practical due to the timing and size of the marking program. However, spawn periods were relatively close together for all density groups, and all fish at the start of the study were relatively small (averaged 3.3g [0.2 SD]); therefore, spawn period most likely had a negligible effect on growth and survival among densities.

There was no accurate accounting of when fish migrated during the autumn volitional release. Although the autumn volitional release occurred at the same time for the same number of days for all density groups, a variable number of fish could have left each raceway, which would have affected their final density, overwinter to spring survival, and postrelease survival. We attempted a mark–recapture sample with brood year 2002 to quantify the autumn release from each density, but we encountered problems in identifying our mark during sampling. The mark–recapture sample was abandoned. A volitional release evaluation is currently underway at the hatchery using Passive Integrated Transponder tags to quantify the number of fish leaving the hatchery, in both autumn and spring, with subsequent recoveries occurring at Bonneville Dam (juvenile and adult), the Columbia River estuary (juvenile), and at the hatchery (adult). Preliminary estimates from a 3-y evaluation (brood years 2005–2007) indicated that each year was unique in that approximately 16, 29, and 64% of the fish annually exited the raceways during the autumn volitional release (D. Hand, USFWS, personal communication). A spring only release is also being evaluated.

Although not a controlled factor in this study, summer water temperatures are an on-going concern at the hatchery. Summer water temperatures were high and increased each brood year from a July average 17.8°C (21.1°C maximum) for brood year 2000 to 19.4°C (22.8°C maximum) for brood year 2002. High summer water temperatures most likely contributed to high parasite loads experienced by fish among all density groups (S. Gutenberger, USFWS, unpublished data). The elevated summer water temperatures also explain, in part, why on-hatchery mortality increased each brood year and why the highest mortality occurred in brood year 2002, particularly of those fish reared at the highest density. The summer water temperatures at Warm Springs NFH were higher than the 15.6°C for optimum growth of Chinook salmon (Banks et al. 1971), higher than temperatures observed at nearby National Fish Hatcheries (USFWS 2007), higher than natural rearing areas upstream of the hatchery (B. Spateholts, Confederated Tribes of the Warm Springs Reservation, unpublished data), and exceeded the 20°C summer maximum guidance issued by the Environmental Protection Agency to protect salmon and trout in Pacific Northwest streams (ideally not exceeding 16°C; www.epa.gov/r10earth/temperature.htm, accessed 21 April 2011). Furthermore, climate changes along with warming temperature trends in the Pacific Northwest are predicted (Mote and Salathé 2010) and will likely increase challenges for hatchery operations (Hanson and Ostrand 2011), in particular fish health management. Hatcheries will need to account for climate change when determining optimum rearing densities.

Most hatcheries in the Columbia River are limited by availability of water and rearing containers; therefore, each facility needs to determine optimum rearing densities (Integrated Hatchery Operations Team 1995), and Warm Springs NFH is no exception. During a recent hatchery review, the USFWS recommended that the density index at Warm Springs NFH not exceed 0.2 throughout the rearing cycle (0.1 density index preferred) with a flow index of 1.0 or lower, unless specific hatchery evaluations find other values providing higher benefits and lower risks (USFWS 2006). The highest density we evaluated in our study was approximately 0.11 density index (8.42 kg/m^3) and 0.39 flow index prior to autumn release, well within the recommended parameters. As a precautionary management approach, the USFWS preferred density index (0.1 density index) appears to be a reasonable guideline for growth and survival of fish at Warm Springs NFH, especially over the summer rearing period when fish experience high water temperatures.

Supplemental Material

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On hatchery mortality during rearing density study. On hatchery mortality of spring Chinook salmon *Oncorhynchus tshawytscha* during the rearing density evaluation at Warm Springs National Fish Hatchery from the start of the study in April through September, 2000–2002, just prior to autumn release. Data stored in the Columbia River Information System maintained by the Columbia River Fisheries Program Office, Vancouver, WA.

Weight gain by rearing density. Chinook salmon *Oncorhynchus tshawytscha* weight (g) at start of study in April to prior to autumn release in October, 2000–2002, by rearing density and brood year. Data from Columbia River Information System maintained at Columbia River Fisheries Program Office, Vancouver, WA.

Fork Length October. Fork Length (mm) of spring Chinook salmon *Oncorhynchus tshawytscha* at Warm Springs National Fish Hatchery, Warm Springs, OR, on 3 October 2002 (brood year 2001).

Fork Length March. Fork Length (mm) of spring Chinook salmon *Oncorhynchus tshawytscha* at Warm Springs National Fish Hatchery, Warm Springs, OR, on 22 March 2004 (brood year 2002).

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