

Effects of Passive Integrated Transponder Tags on Smolt-to-Adult Recruit Survival, Growth, and Behavior of Hatchery Spring Chinook Salmon

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Abstract.—We tagged juvenile upper Yakima River hatchery spring Chinook salmon *Oncorhynchus tshawytscha* with passive integrated transponder (PIT) and coded wire snout tags in a double-tag study to test the assumptions that tags are not lost and do not affect postrelease survival, behavior, or growth. The average loss of PIT tags was 2.0% (95% confidence interval [CI] = 0.7–3.2%) in juveniles before release and 18.4% in recaptures returning 6 months to 4 years after release (95% CI = 17.2–19.5%). Adult tag losses were not significantly correlated with age of return (analysis of covariance, $P = 0.40$), indicating that the majority of PIT tag loss had occurred within the first 6 months after release. Smolt-to-adult recruit survival (SARS) of PIT-tagged fish was significantly lower ($P < 0.05$) than that of non-PIT-tagged (NPT) fish because of tag loss and reduced survival, resulting in an average underestimate of SARS of 25.0%. After correcting for tag loss, we estimated PIT tag-induced mortality to be as great as 33.3% with a mean of 10.3% over all brood years ($P < 0.05$). Mean lengths and weights of PIT-tagged adults were less than those of NPT adults in all age comparisons. However, only age-4 PIT-tagged adults were significantly smaller than NPT fish of the same age (mean length difference = 1.1 cm; mean body weight difference = 0.1 kg; analysis of variance, $P < 0.05$). There was no significant difference between migration timing of PIT-tagged and NPT adults within the upper Yakima River (Mann–Whitney test, $P > 0.09$). Given the widespread and increasing use of PIT tags, and their use in calculating critical estimators related to salmonid life history of Endangered Species Act populations, the effects of using PIT tags must be quantitatively considered under actual study conditions and, if necessary, be accounted for.

The use of tags and marks in fish studies has a long history, dating from at least the 1800s (see review in McFarlane et al. 1990). Techniques employing marks and tags have been developed to estimate fish population size, rates of emigration and migration, exploitation rates, gear selectivity, natural and fishing mortality, growth, age, reproduction, and physiology (Ricker 1975; Seber 1982; Burnham et al. 1987). Two critical assumptions are typically made in studies using tags: (1) tag loss does not occur, and (2) tags do not cause mortality. In addition, tags are usually assumed

to have no significant effect on growth or behavior. Major violations of these assumptions can bias study results (Robson and Regier 1966; Arnason and Mills 1981; Seber 1982; McDonald et al. 2003; Rotella and Hines 2005) and make invalid an extrapolation of results to the untagged portion of the population. Because all artificial tags and marks violate some study assumptions to a greater or lesser degree, one must understand the strengths and limitations of any tagging technique to select the tag violating the fewest or the least important assumptions in the proposed research (Seber 1982; Krebs 1998) and to be able to correct for tag-induced bias.

Estimating postrelease tag loss and tag effects occurring one or more years after release is difficult

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TABLE 1.—The number of juvenile hatchery spring Chinook salmon that were passive integrated transponder (PIT) and snout coded wire (CW) tagged, the number of non-PIT-tagged (NPT) fish, the total release, and the percentages of PIT-tagged fish released by brood year. All fish released were adipose fin clipped.

| Juvenile release | Brood year | | | | |
|-----------------------|------------|---------|---------|---------|---------|
| | 1997 | 1998 | 1999 | 2000 | 2001 |
| PIT/CW tagged | 39,892 | 37,385 | 38,791 | 37,580 | 40,020 |
| NPT | 346,156 | 552,298 | 719,998 | 796,705 | 334,358 |
| Total released | 386,048 | 589,683 | 758,789 | 834,285 | 374,378 |
| Percent PIT/CW tagged | 10.33% | 6.34% | 5.11% | 4.50% | 10.69% |

and often expensive. To estimate long-term tag loss, investigators must ensure that marked fish experience the types of stresses and challenges of a free-ranging life experienced by all fish within the population of interest, rather than maintain the fish studied in a protected, unnatural environment. Beverton and Holt (1957) and Seber (1982) suggest using a double-tagging design and releasing fish under actual study conditions to help estimate postrelease loss of tags and mortality effects for each proposed tag type.

With the development of the passive integrated transponder (PIT) tag in the late 1980s (Prentice et al. 1990), researchers could uniquely mark individuals in large quantities and recover tag codes without necessarily handling fish. More sophisticated individual-based models for data analysis were also developed (Burnham et al. 1987) and applied, using PIT tags, to monitor juvenile salmonid survival and migration timing in the Columbia River basin (Skalski et al. 1998; Muir et al. 2001; Budy et al. 2002). More recently, PIT tags have been used to estimate adult salmonid survivals in the Columbia River (Berggren et al. 2003, 2005; Williams et al. 2005; Copeland et al. 2007). Often these studies test PIT tag loss and survival effects by holding tagged fish for a few days to a few weeks in net pens. However, little rigorous research on the long-term (>1 year) effects of PIT tags on Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* has been conducted under actual study conditions, and the little that has been done is mentioned only in gray literature (e.g., Prentice et al. 1993, 1994).

In this study, we estimate the rate of loss of PIT and coded wire (CW) tags in upper Yakima River hatchery spring Chinook salmon *O. tshawytscha* returning approximately 6 months to 4 years after tagging. We also estimate whether PIT tags affect smolt-to-adult recruit survival (SARS), size-at-age, and timing of adult in-river migration.

Methods and Materials

PIT and CW tag loss.—We used a double-tag study design (Seber 1982), applying two marks or tags to each fish in the study population: a PIT tag (12×2.1

mm) injected into the body cavity with a hand-held injector (Prentice et al. 1990) and a CW tag injected into the snout (Jefferts et al. 1963). Beginning in 1998 and continuing until 2002, 37,000–40,000 age-1 hatchery-origin spring Chinook salmon (fish in their first year posthatching) were marked with double tags at the Cle Elum Supplementation and Research Facility (CESRF) annually between October and December (Table 1) under similar environmental conditions. Each year an equal proportion of the fish in each raceway, varying between approximately 5% and 10% over the study (Table 1), was PIT and snout CW tagged and reared in common with fish CW tagged in other body areas (e.g., base of the pectoral fin, anterior insertion of the dorsal fin, or cheek muscle). In February, the fish in each raceway were transferred by truck to a raceway at one of three acclimation sites (Clark Flats, Easton, and Jack Creek; Figure 1), held for approximately 1.5 additional months, and then allowed to volitionally emigrate as age-2 smolts (~18 months after fertilization) between March 15 and May 30. Thus, fish were held for between 70 and 125 d after being tagged before volitional releases began. Non-PIT-tagged (NPT) fish were marked with a combination of two other marks and an adipose fin clip. Because all hatchery fish were marked with an adipose fin clip, quick visual identification and enumeration were possible. The PIT-tagged fish were separated from the NPT fish on the basis of other unique marks (presence/absence), PIT tags, or snout CW tags (presence/absence).

For the first brood (1997), the number of PIT-tagged fish released from each acclimation raceway was calculated as the number of fish initially PIT-tagged after adjustment for observed prerelease mortalities (mortalities with PIT tags). Beginning with the 1998 brood, improved tag technology and installation of detection equipment at the acclimation sites allowed the number of PIT-tagged fish released to be based on tag detections at raceway outlets. PIT tag detection efficiency at the acclimation sites after brood year 1997 was estimated to be greater than 99% (Fast et al. 2008).

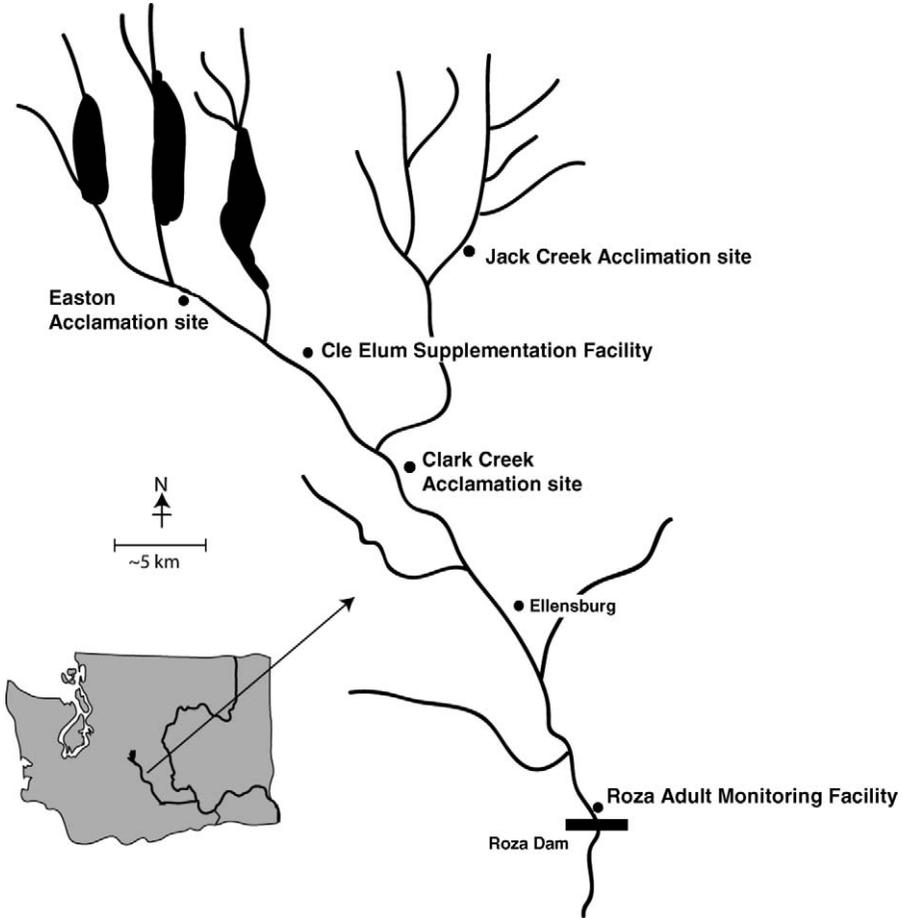


FIGURE 1.—Map of the Yakima River basin, Washington, showing the Roza Adult Monitoring Facility and Cle Elum Supplementation and Research Facility.

The total numbers of PIT-tagged and NPT hatchery juveniles released by brood year are given in Table 1.

Quality control samples were collected from juveniles 1–2 months posttagging and the number of fish with both tags, only a PIT, or only a snout CW tag were counted. These data were used to estimate tag losses before release, using the same methods applied to adult recaptures and described in detail below. Brood year 1997 juveniles, the first year of releases, were not sampled in a manner that allowed estimation of prerelease tag losses.

During the postrelease period, juvenile fish migrated downstream below the Roza Adult Monitoring Facility (RAMF; Figure 1) through the Yakima and Columbia rivers to the Pacific Ocean, where they reared for 1–3 years, eventually returning to the upper Yakima River as maturing fish (age 3, 4, or 5) to spawn between September and October. Age-2 fish, called precocious males, mature approximately 6 months after release

and many do not migrate downstream of RAMF (Pearsons et al. 2004). Returning anadromous adult fish (\geq age 3) were examined for marks 18 months to 4 years after release. All fish passing upstream at RAMF were examined daily, and hatchery-origin fish were identified by an adipose fin clip. Hatchery-origin fish were diverted into a short-term holding tank, anesthetized with tricaine methanesulfonate (MS-222; Bell 1964), and examined for marks and tags. The PIT tags were detected with a hand-held PIT tag detector; CW tags in the snout and at other body sites were detected with a hand-held CW tag detector; and the number of fish retaining a PIT tag, a snout CW tag, or both, was recorded. Postorbital hypural plate (POHP) body length, body weights, and passage date were also recorded. Fish without PIT tags were scale-sampled to determine their age and brood year. Upstream adult fish passage and sampling at RAMF began in late April and continued through early September.

Chinook salmon double-tagged as juveniles and subsequently recaptured fall into one of four categories: (1) PIT-tagged/snout CW tag/Adipose fin (Ad)-clipped (both tags retained), (2) snout CW tag/Ad-clipped (lost PIT tag), (3) PIT-tagged/Ad-clipped (lost snout CW tag), or (4) Ad-clipped only (lost both PIT and snout CW tags). Captured wild-origin Chinook salmon were identified by an intact adipose fin and excluded from the study. Recaptured PIT-tagged fish falling into categories (1) through (3) could be identified unambiguously. However, recaptures that have lost both PIT tag and CW tag (category 4) cannot be distinguished from other adipose fin clipped hatchery recoveries that have also lost both their marks. Estimating tag loss and identifying category 4 fish in double-mark studies is a common problem. We used a method developed by Seber (1982: 94–96) for this purpose.

Assuming tags are lost within fish independently, that is, losing a PIT tag does not influence whether a fish loses or retains its snout CW tag, we can calculate the following from tagged fish recovered at RAMF:

R_{cwt} = the total number of fish within a brood year retaining only a snout CW tag,

R_{pit} = the total number of fish within a brood year retaining only a PIT tag, and

$R_{pit,cwt}$ = the total number of fish within a brood year retaining both a PIT and snout CW tag.

R is the total number of recovered adults tagged as juveniles within a brood year and is calculated as

$$R = R_{cwt} + R_{pit} + R_{pit,cwt} + (\text{number of fish losing both tags}).$$

R' is the total number of tagged fish within a brood year retaining one or more tags:

$$R' = R_{cwt} + R_{pit} + R_{pit,cwt}.$$

Using the methodology of Seber (1982), we can then estimate the probability of PIT and snout CW tag loss within a brood year as:

$$\begin{aligned} \hat{Pr}_{pit} &= (\text{probability of losing a PIT tag}) \\ &= \frac{R_{cwt}}{R_{cwt} + R_{pit,cwt}} \quad \text{and} \end{aligned}$$

$$\begin{aligned} \hat{Pr}_{cwt} &= (\text{probability of losing a snout CW tag}) \\ &= \frac{R_{pit}}{R_{pit} + R_{pit,cwt}}. \end{aligned}$$

To correct R for missed category 4 recoveries and

estimate the total number of captures, \hat{R} , we used a correction factor developed by Seber (1982). This involves adjusting the observed tag recoveries for fish losing both tags by the correction factor c , where

$$c = \left[1 - \frac{R_{cwt} \times R_{pit}}{(R_{cwt} + R_{pit,cwt})(R_{pit} + R_{pit,cwt})} \right]^{-1},$$

which is the inverse of 1 minus the joint probability of losing both tags. An estimate of the total number of PIT recaptures, including fish losing both tags, is

$$\hat{R} = c(R_{cwt} + R_{pit} + R_{pit,cwt}).$$

We estimated \hat{Pr}_{pit} and \hat{Pr}_{cwt} , the proportion of fish losing both PIT and snout CW tags, by brood year. The 95% confidence interval (CI) for a proportion, \hat{p} , is then (from Scheaffer et al. 1979)

$$\hat{p} \text{ 95\% CI} = z_{\alpha/2} \sqrt{\frac{\hat{p}(1-\hat{p})}{n-1} \left(\frac{N-n}{N} \right)},$$

where N is the total population size, n is the observed sample size, and $(N-n)/N$ is a finite population correction factor. When $n=N$, the entire population is sampled and \hat{p} is known, making the 95% CI = 0. We sampled all the hatchery fish in our study. However, n , the number of fish observed with tags, will equal N only if all PIT and CW tags are retained. We expect that in each brood year some fish will lose both tags; these numbers would be estimated as described above. This will result in variation in the proportion of tags lost because of the error in estimating the number of fish losing both tags. However, if the estimated number of double-tags lost is very small, then the error introduced will also be very small. Using \hat{Pr}_{pit} as an example,

$$\hat{Pr}_{PIT} \text{ 95\% CI} = 1.96 \sqrt{\frac{\hat{Pr}_{PIT}(1-\hat{Pr}_{PIT})}{R'-1} (\hat{R} - R'\hat{R})},$$

where \hat{Pr}_{PIT} is substituted for \hat{p} , R' (the total number of fish with at least a PIT tag or snout CWT) is substituted for n , the total number of fish PIT-tagged (including fish losing both tags, \hat{R}) is substituted for N , and 1.96 for $z_{\alpha/2}$ (the z -score corresponding to a two-tailed 95% CI). These CIs apply only to the population of fish actually tagged.

Mean \hat{Pr}_{cwt} and \hat{Pr}_{pit} values across brood years were calculated and a nonparametric bootstrapping technique (Efron and Tibshirani 1993) was used to estimate an across-brood year 95% CI. This was done by randomly sampling with replacement n brood year values, where $n=4$ for prerelease juveniles and $n=5$ for adult recaptures, from the respective tag loss

distribution, and then calculating the mean of the selected values. This process was repeated 10,000 times and the estimated means sorted from lowest to highest. The values at the 2.5% and 97.5% points in the sorted distributions represent the lower and upper limits of the 95%CI, respectively.

We also examined trends in loss by age. If tag loss is a continuous process over time, then one would expect tag loss to increase with age. We used an analysis of covariance (ANCOVA) to compare trends in mean tag loss over age (2, 3, 4, and 5 years) by tag type (PIT and CW) and tested whether mean adjusted tag loss rates were equal. We assumed that the age-2 fish recovered at RAMF experienced a rate of tag loss similar to that of the age-2 fish (minijacks) remaining upstream of RAMF (nonmigratory) and did not sample these groups.

Survival, migration timing, and body size comparisons.—For these analyses, we used recovered adult returns that were PIT-tagged as juveniles and compared them with adult recoveries from the same cohort that were not PIT-tagged. We did not use age-2 returns as they were sampled in a less rigorous manner over the course of the run; moreover, many were not sampled because they remained upstream of our trapping facility at RAMF. After being PIT-tagged as juveniles, fish were returned to their respective raceways and reared together with NPT fish. Raceways were volitionally released and therefore both PIT-tagged and NPT fish within a cohort had the opportunity to experience the same out-migration and postrelease rearing conditions. Thus, body size, timing distribution of adult migrations, and SARS rates of PIT-tagged and NPT fish from a cohort can be compared, and differences should reflect the effects of PIT tags.

Two methods were used to estimate SARS by brood year. The SARS of PIT-tagged fish was first calculated by dividing the number of observed adult PIT-tagged fish recovered (R') by the number of juvenile PIT-tagged fish released to get the uncorrected SARS. The corrected SARS was calculated by dividing \hat{R} , the corrected number of PIT-tagged fish recovered, by the number of PIT tag releases. Uncorrected NPT SARS was calculated as the number of NPT adults (fish with an adipose fin clip, but no PIT tag or snout CW tag) recovered by the number of juvenile NPT fish released. To calculate the corrected NPT SARS, we subtracted from the NPT recovered population the number of fish estimated to have lost both tags. Because all hatchery fish were examined for tags, there was a complete census of recoveries.

We assumed a linear model for PIT tag-induced effects (PIT_{effect}) on NPT SARS:

TABLE 2.—Sample sizes by brood year and age for observed recoveries of passive integrated transponder (PIT) tagged juvenile Chinook salmon and non-PIT-tagged (NPT) fish, used to compare migration timing, postorbital hypural plate length, and body weight distributions.

| Brood year | Age | PIT-tagged recoveries | NPT recoveries |
|------------|-----|-----------------------|----------------|
| 1997 | 3 | 0 | 0 |
| | 4 | 190 | 1,795 |
| | 5 | 18 | 18 |
| 1998 | 3 | 16 | 289 |
| | 4 | 432 | 1,196 |
| | 5 | 41 | 179 |
| 1999 | 3 | 0 | 0 |
| | 4 | 25 | 231 |
| | 5 | 0 | 0 |
| 2000 | 3 | 38 | 357 |
| | 4 | 148 | 334 |
| | 5 | 0 | 0 |
| 2001 | 3 | 27 | 25 |
| | 4 | 69 | 155 |
| | 5 | 0 | 0 |

$$SARS_{PIT} = PIT_{effect} \times SARS_{NPT}.$$

Thus, PIT_{effect} is the slope of the regression of $SARS_{PIT}$ versus $SARS_{NPT}$ over the five brood years. If there is no PIT_{effect} , then the slope of the regression equals 1. Our null hypothesis was that the slope was not equal to 1 (two-tailed test). The PIT_{effect} 95% CIs from the regression that did not include 1.0 were considered significant ($P < 0.05$).

When regressed SARS values are not corrected for tag loss, then PIT_{effect} is a product of both PIT tag loss and tag mortality. When SARS values have been corrected for tag loss, then PIT_{effect} is the result of PIT tag mortality only. We forced the slope of the SARS regression through the origin, reasoning that both estimates of SARS are ratios and should approach the origin as they decrease.

Because all returning fish passing RAMF were monitored on a daily basis, all returning hatchery fish were identified as to date of passage. These data were transformed to ordinal numbers representing the day of the year; that is, January 1 was represented by 1 and December 31 by 365. The distributions of ordinal passage dates of PIT-tagged and NPT fish recoveries were compared by age within each brood year with use of a Mann-Whitney test (Table 2; Zar 1999). Ages and brood years were treated separately because both have been shown to significantly affect the timing of the upstream passage of adult spring Chinook salmon at RAMF (Knudsen et al. 2006a).

Body weight and length distributions collected at RAMF were compared by using a two-way analysis of variance (ANOVA) examining tag type (PIT-tagged versus NPT) and brood year effects with interactions. We analyzed data representing returns at ages 3, 4, and

TABLE 3.—Estimates of tag loss prior to release by brood year for juvenile spring Chinook salmon. Definitions of passive integrated transponder (PIT) tag loss (\hat{Pr}_{pit}) and coded wire (CW) tag loss (\hat{Pr}_{cwt}) loss and R_{cwt} , R_{pit} and $R_{pit,cwt}$ are given in Methods. Within brood years, confidence intervals (95% CIs) for tag loss are given in parentheses. Mean among-brood year tag loss with bootstrapped 95% CIs is given in the last row.

| Brood year | R_{cwt} | PIT tag loss (\hat{Pr}_{pit}) | R_{pit} | CW tag loss (\hat{Pr}_{cwt}) | $R_{pit,cwt}$ |
|-------------------------|-----------|-----------------------------------|-----------|----------------------------------|---------------|
| 1998 | 2 | 0.8% (0.8–0.8) | 12 | 4.5% (4.5–4.5) | 257 |
| 1999 | 6 | 2.7% (2.7–2.7) | 2 | 0.9% (0.9–0.9) | 220 |
| 2000 | 5 | 3.7% (3.6–3.8) | 2 | 1.5% (1.5–1.5) | 129 |
| 2001 | 2 | 0.7% (0.7–0.7) | 22 | 6.8% (6.7–6.9) | 303 |
| Mean (bootstrap 95% CI) | | 2.0% (0.7–3.2) | | 3.4% (1.2–5.6) | |

5 but did not include any age-class or tag-type cell represented by fewer than 10 recoveries within a year. The age-4 group represents greater than 80% of hatchery returns each year (Knudsen et al. 2006a) and was the only age-class represented in all five brood years (1997–2001). Age-3 recoveries were represented in brood years 1998, 2000, and 2001, age-5 recoveries in brood years 1997 and 1998.

Results

PIT and CW Tag Loss

Estimated prerelease losses of PIT and CW tags are presented in Table 3. Average prerelease PIT tag loss was 2.0% (95% CI = 0.7–3.2%) and 3.4% (95% CI = 1.2–5.6%) for CW tags.

From April through September, maturing hatchery fish moved upstream past RAMF and were recaptured and examined for tags. A total of 265 fish had lost their PIT tag, 66 had lost their snout CW tag, and 1,202 had retained both their PIT and CW tags (Table 4). Across brood years, PIT tag losses ranged from 16.3 to 19.8%, averaging 18.4% (bootstrapped 95% CI = 17.2–19.5%) and from 0.7 to 13.6% for CW tags, averaging 6.7% (bootstrapped 95% CI = 3.5–9.9%). Estimates of the number of fish losing both tags ($\hat{R} - R'$) within brood years ranged from 0 to 7 fish and represented between 0% and 2% of the total marked recoveries (\hat{R}). Thus,

the loss of both tags had a negligible effect on the observed rates of tag loss.

We estimated tag retention of CW and PIT tags by age for each brood year (Figure 2); using ANCOVA, we found no significant trend as fish increased in age (H_0 : slopes = 0; $P = 0.40$), indicating that tag loss did not change significantly over time. However, overall CW and PIT tag loss rates differed significantly: PIT tags were lost at almost three times the rate of CW tags (equality of means in ANCOVA, $P < 0.001$).

Effects of PIT Tags on Survival of Tagged Fish

In Table 5 we present SARS of PIT-tagged and NPT fish based on uncorrected and corrected adult recoveries by brood year. For uncorrected recoveries, the estimated PIT_{effect} was 0.750 (Figure 3; 95% CI = 0.713–0.787; $r^2 = 0.998$; $P < 0.05$), indicating that NPT fish survival was reduced by 25.0% on average (range = 17.1–44.9%) by a combination of tag mortality and loss. After recoveries were corrected for PIT tag loss, the PIT_{effect} was 0.897 (Figure 3; 95% CI = 0.851–0.944; $r^2 = 0.998$; $P < 0.05$), indicating that SARS of PIT-tagged fish was significantly lower than NPT recoveries by an average of 10.3% (range = –4.4% to 33.3%).

The estimate of PIT tag-induced mortality is not a generic “tagging/handling mortality” because all hatchery fish were marked with more than one tag

TABLE 4.—Recoveries of tagged spring Chinook salmon by brood year for adults (\geq age 3) originally double marked with passive integrated transponder (PIT) and snout coded wire (CW) tags as juveniles. Definitions of the column values for PIT tag loss (\hat{Pr}_{pit}) and CW tag loss (\hat{Pr}_{cwt}) loss percentages, R_{cwt} , R_{pit} , $R_{pit,cwt}$, \hat{R} , and R' are given in Methods. $\hat{R} - R'$ is the estimated number of fish losing both their PIT and CW tags. Within brood years, confidence intervals (95% CIs) for tag loss are given in parentheses. The total number of hatchery fish recovered (both PIT and non-PIT tagged) is given in the last column, and mean tag loss over brood years with bootstrapped 95% CIs is given in the last row.

| Brood year | R_{cwt} | PIT tag loss (\hat{Pr}_{pit}) | R_{pit} | CW tag loss (\hat{Pr}_{cwt}) | $R_{pit,cwt}$ | \hat{R} | $\hat{R} - R'$ | Total recoveries |
|-------------------------|-----------|-----------------------------------|-----------|----------------------------------|---------------|-----------|----------------|------------------|
| 1997 | 112 | 16.3 (16.1–16.5) | 26 | 4.3 (4.2–4.4) | 574 | 716.9 | 5.1 | 7,004 |
| 1998 | 95 | 19.8 (19.4–20.2) | 30 | 7.3 (7.0–7.6) | 384 | 517.0 | 7.4 | 7,678 |
| 1999 | 4 | 17.4 (15.2–19.6) | 3 | 13.6 (11.6–15.6) | 19 | 26.5 | 0.6 | 724 |
| 2000 | 37 | 19.7 (19.5–19.9) | 1 | 0.7 (0.7–0.7) | 151 | 189.3 | 0.2 | 4,160 |
| 2001 | 17 | 18.7 (17.9–19.8) | 6 | 7.5 (6.9–8.1) | 74 | 98.4 | 1.4 | 887 |
| Total | 265 | | 66 | | 1,202 | | | 20,453 |
| Mean (bootstrap 95% CI) | | 18.4 (17.2–19.5) | | 6.7 (3.5–9.9) | | | | |

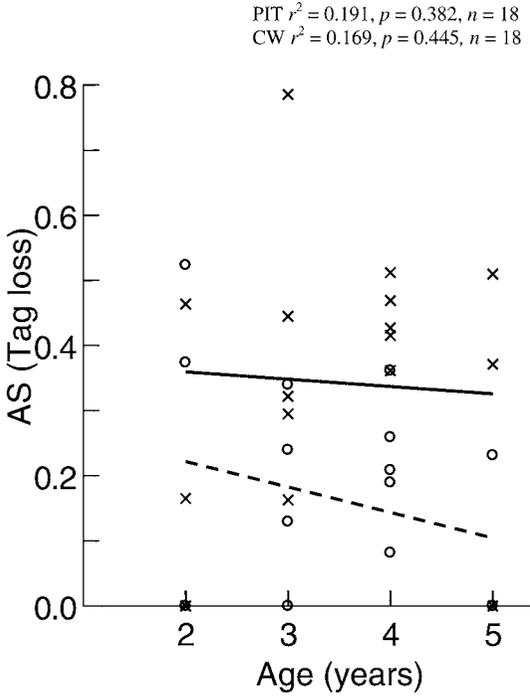


FIGURE 2.—Linear regression of arcsine-square-root (AS)-transformed tag loss proportions of passive integrated transponder tags (solid line; x-symbols) and snout coded wire tags (dashed line; circles) by age for Chinook salmon brood years 1997 to 2001.

TABLE 5.—Smolt-to-adult-recruit survival rates for passive integrated transponder (PIT) tagged ($SARS_{PIT}$) and non-PIT-tagged ($SARS_{NPT}$) spring Chinook salmon by brood year. Uncorrected values are biased by PIT tag loss; corrected values have been adjusted to account for PIT tag loss.

| Brood year | $SARS_{PIT}$ | | $SARS_{NPT}$ | |
|------------|--------------|-----------|--------------|-----------|
| | Uncorrected | Corrected | Uncorrected | Corrected |
| 1997 | 0.0150 | 0.0180 | 0.0206 | 0.0205 |
| 1998 | 0.0111 | 0.0130 | 0.0141 | 0.0139 |
| 1999 | 0.0006 | 0.0007 | 0.0010 | 0.0010 |
| 2000 | 0.0040 | 0.0050 | 0.0053 | 0.0052 |
| 2001 | 0.0020 | 0.0025 | 0.0024 | 0.0024 |
| Mean | 0.0066 | 0.0078 | 0.0087 | 0.0086 |

under the same general environmental conditions, were reared in common raceways, and experienced similar conditions throughout release and migration.

Migration Rate Comparison

We found no difference between passage timing of age-3, -4, and -5 PIT-tagged and NPT fish at RAMF over brood years 1997 to 2001 (Figure 4). Results of Mann-Whitney tests showed that in the 10 age-brood year comparisons all *P*-values were greater than 0.09.

Body Size Comparisons

In all age-brood year comparisons, PIT-tagged fish were smaller than NPT fish (Figures 5, 6). Analyses of POHP length and body weight distributions by two-

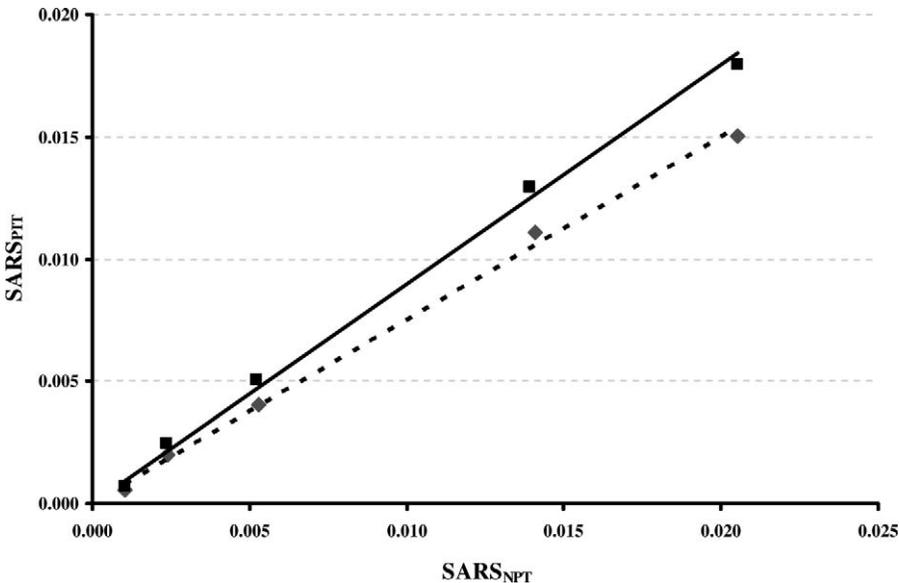


FIGURE 3.—Regression of smolt-to-adult recruit survival ($SARS$; forced through the origin) of passive integrated transponder (PIT) tagged and non-PIT-tagged (NPT) Chinook salmon over the five brood years. The $SARS$ are based on recoveries that were either uncorrected (diamonds; dashed line) or corrected (squares; solid line) for PIT tag loss.

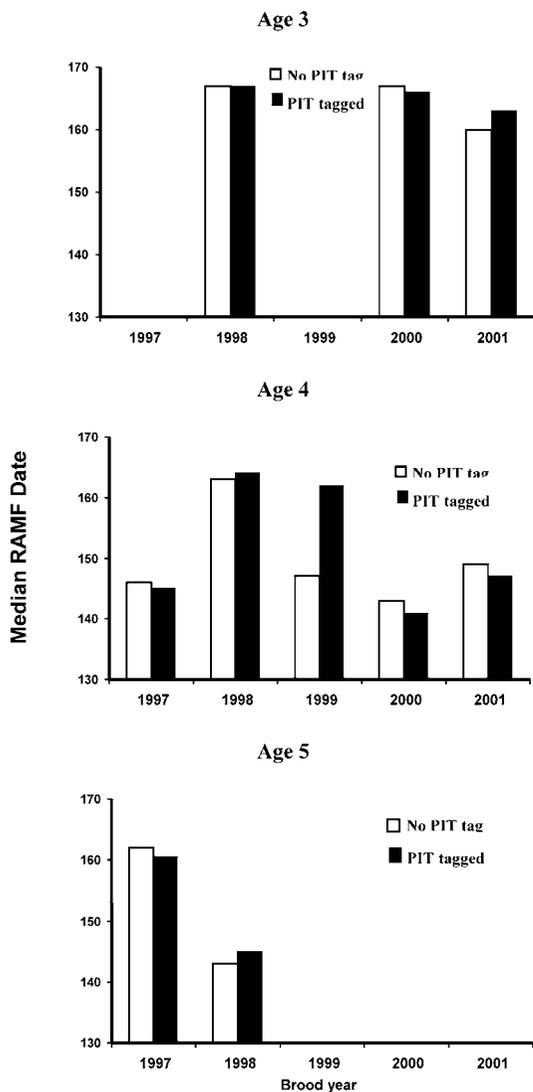


FIGURE 4.—Median ordinal date of passage at Roza Adult Monitoring Facility (RAMF) for adult spring Chinook salmon (ages 3, 4, and 5) with (dark bars) and without (white bars) passive integrated transponder (PIT) tags, returning over brood years 1997 to 2001.

way ANOVA (tag, brood year, and interaction effects) showed significant differences in age-4 returns (POHP tag effect, $P = 0.024$; body weight tag effect, $P = 0.043$), but not in age-3 (POHP tag effect, $P = 0.174$; body weight tag effect, $P = 0.601$) or age-5 (POHP tag effect, $P = 0.203$; body weight tag effect, $P = 0.429$) returns. Differences in age-4 fish were driven to a large extent by the large differences in brood year 1999. There were no significant tag \times brood year interactions in any ANOVA (all interaction $P > 0.43$).

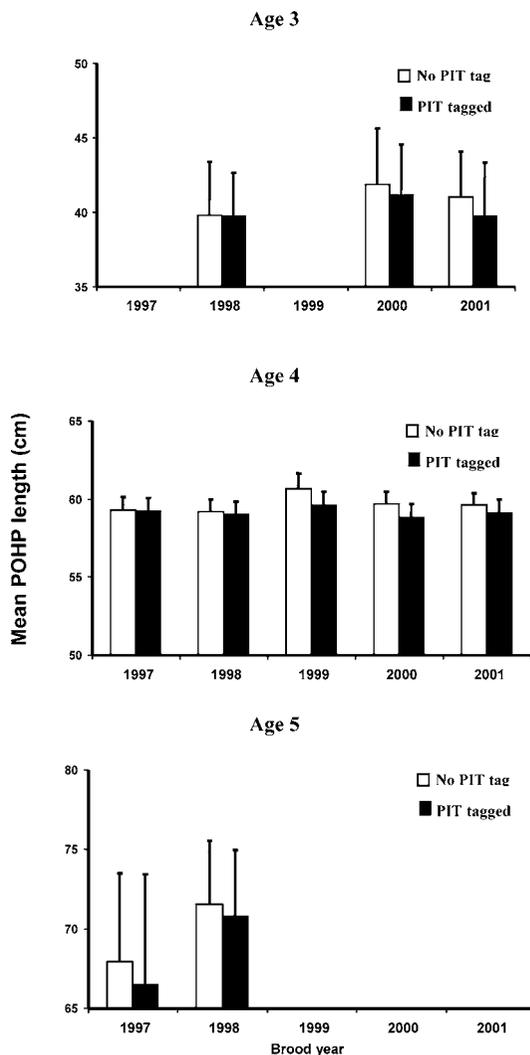


FIGURE 5.—Mean (\pm SD) postorbital hypural plate (POHP) length of adult spring Chinook salmon (ages 3, 4, and 5) with (dark bars) and without (white bars) passive integrated transponder (PIT) tags, returning over brood years 1997 to 2001.

Discussion

Remote monitoring of PIT-tagged adults returning to the Columbia River has recently become possible and analysis of PIT tag movement has been used to examine impacts of flow on Chinook salmon SARS (Berggren et al. 2003, 2005; Williams et al. 2005). However, Williams et al. (2005) and Copeland et al. (2007) have observed that SARS of PIT-tagged salmonids was as much as 50% lower than that of NPT conspecifics. Berggren et al. (2005) had extrapolated their results to the untagged portions of study

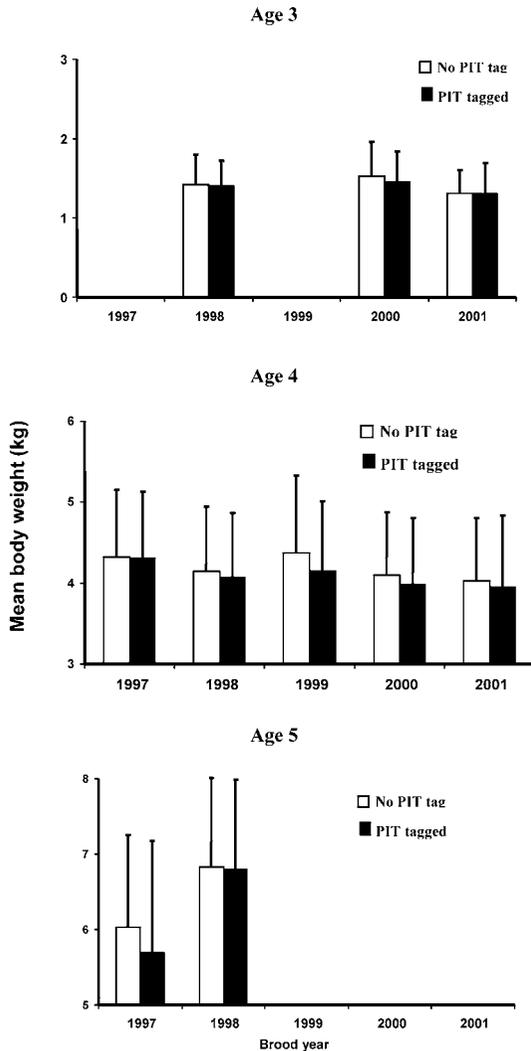


FIGURE 6.—Mean (\pm SD) body weight of adult spring Chinook salmon (ages 3, 4, and 5) with (dark bars) and without (white bars) passive integrated transponder (PIT) tags, returning over brood years 1997 to 2001.

populations, and in response the Independent Science Advisory Board (ISAB) noted that the lower SARS of PIT-tagged fish observed by Williams et al. (2005) “has major implications for all uses of PIT-tagged fish as surrogates for untagged fish” (ISAB 2006). Based on our results, SARS of PIT-tagged fish was underestimated by 25% on average because of a combination of PIT tag loss and tag-induced mortality and could account for much of the estimated survival difference between PIT-tagged and NPT fish noted by Williams et al. (2005) and Copeland et al. (2007).

Our estimates of PIT tag loss varied very little over

brood years. Mean PIT tag loss in adults was 18% with a range of only $\pm 2\%$, indicating that tag loss is relatively stable over brood years. Because PIT tag loss in prerelease juveniles averaged only 2%, the vast majority of adult tag loss must occur after release. Our estimates of PIT tag-induced mortality were more variable over brood years, ranging from -4% to 33%. Notably, brood year 1999, in which the relative difference between SARS of NPT and PIT-tagged fish was greatest (Table 5), also had the lowest overall SARS, experienced exceptionally high juvenile in-river mortality probably resulting from low main-stem Columbia River flows in 2001 (Yakama Nation [YN], unpublished data), and also demonstrated the greatest difference between PIT-tagged and NPT adults in body size and migration timing. We hypothesize that the effects of PIT tags on survival and growth will be greatest when fish experience conditions that result in high overall mortality and stress levels, even though rates of PIT tag loss would remain relatively stable.

Our study should be considered a “best case” scenario in terms of the impacts of PIT tagging on postrelease fish because (1) tagged fish were allowed to recover from the stresses of tagging for 70 d or more before being allowed to volitionally emigrate from their raceways; (2) tagging was done during late fall, when water temperatures were relatively low and decreasing; (3) the tagged fish were not experiencing the physiological challenges of smoltification; and (4) the fish were relatively large, averaging fork lengths of 100 mm or greater at tagging. Many field studies are “worst case” scenarios, where tagging is focused on actively migrating smolts captured in situ, often at fork lengths as small as 60 mm, during periods when water temperatures are elevated, and fish are released less than 24 h after tagging. The stress from handling and anesthetizing juvenile Chinook salmon during tagging is significant and has been estimated to take approximately 2 weeks to dissipate (Sharpe et al. 1998). Under this worst case scenario, postrelease stress would be much higher than we experienced, and mortality attributable to PIT tagging could be a more severe and consistent problem than we observed.

Prentice et al. (1994) used a double-tag study design to estimate PIT tag loss in the only published report of which we are aware that estimates smolt-to-adult PIT tag retention in free-ranging adult Pacific salmon. They found that mature adult coho salmon *O. kisutch* PIT-tagged as juveniles lost their tags at high rates before spawning, and they estimated overall tag loss rates of 59% in females and 13% in males. Their results point out the potential for males and females to experience different rates of PIT tag loss, differences that may be related to changes in gamete development at full

maturity. In their study, they estimated mid-term PIT tag loss (8 months after tagging) to be 1% (Prentice et al. 1993). Thus, nearly all of the tag loss documented in Prentice et al. (1994) occurred after release, as in our study, and at some time during the 12 months before spawning. We did not estimate PIT tag losses for males and females separately because our ability to identify the sexes at RAMF is poor. On the basis of fish sexed at RAMF and subsequently examined postmortem during spawning, we were able to identify males and females with approximately 70% and 90% accuracy, respectively (C.M.K., unpublished data). Because fish pass our sampling site at RAMF 1–6 months before reaching full maturity, it is possible that PIT tag loss may continue as gametes, particularly those of females, loosen in the body cavity and allow PIT tags to exit via the cloacae.

Because we did not dissect fish that lost their PIT tags, we cannot rule out that in a few cases a PIT tag may actually have still been present but not functioning. However, earlier work by Prentice et al. (1993), examining PIT tag failure rates in salmonids, found that over periods as long as 3 years failure rates were typically 0–1%. They also found that nearly all failures were observed in the first sample collected within a few months after tagging; after that, the numbers of new failures detected were not significant. Thus, our detections of PIT tag codes in fish voluntarily exiting their raceways more than 70 d after having been placed there should be indicative of viable tags. Because we have no reason to believe that PIT tag failure was greater than average in any of our releases, such failures probably contributed 1% or less to the overall observed PIT tag loss.

We found that PIT-tagged adults were smaller on average than NPT adults. The mean body size differences of 1.1 cm and 0.1 kg in age-4 females would result in a decrease in average fecundity of approximately 172 eggs (4.4%; Knudsen et al. 2006b), directly affecting per capita productivity. However, because only 5–11% of all releases are PIT-tagged, this practice is unlikely to result in a major reduction in population productivity. Prentice et al. (1994), comparing PIT and snout CW tagged adult coho salmon, found that the fork length of PIT-tagged adults was significantly smaller (by 2 cm) than that of the NPT adults. Their previous study (Prentice et al. 1993) compared PIT-tagged and control (untagged) Chinook salmon reared in net pens and found that PIT-tagged fish were 2 cm smaller. Thus, our observations on the effects of PIT tags on adult body size are in line with these earlier study results.

Our results indicate that tag shedding did not increase significantly over time with age. Thus, most

PIT tag loss occurred within the first 6 months after release but before the time when age-3 adults began returning. Estimates of SARS based on observed PIT tag recoveries were significantly underestimated by an average of 25%. After correcting for tag loss, SARS of PIT-tagged fish were still 10% lower than that of NPT fish. We also found that PIT-tagged adults were smaller in length and body weight than the NPT fish, thus reducing per capita productivity directly by 4% through decreased fecundity. Finally, our results indicate timing of adult migration within the upper Yakima River was not significantly affected by the presence of PIT tags.

When study comparisons are restricted to similarly tagged groups, the results should be a valid comparison because tag effects, if present, are experienced equally by both groups. Understanding the performance of PIT tags or any tag or mark under proposed study conditions is critical to ensure that the most appropriate tag for a given situation is applied and that the results can be interpreted correctly in a broader perspective. If tag loss indeed occurs, true survival of tagged groups will be underestimated, but this can be corrected for if the loss has been estimated by using a double-tag study design. When tag-induced mortality occurs or if growth and behavior are affected by tagging, investigators should only cautiously extrapolate study results to the remainder of the untagged population. Given the widespread and increasing use of PIT tags and the reliance on them to obtain critical estimators related to salmonid life history of Endangered Species Act populations (Berggren et al. 2005; Williams et al. 2005; ISAB 2006; Brakensiek and Hankin 2007), it is vital that tag loss and tag-induced mortality be quantitatively considered under actual study conditions.

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