North American Journal of Fisheries Management 38:96–103, 2018

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1002/nafm.10034

MANAGEMENT BRIEF

Tag Effects on Prespawn Mortality of Chinook Salmon: A Field Experiment Using Passive Integrated Transponder Tags, Radio Transmitters, and Untagged Controls

George P. Naughton,* Matthew L. Keefer, Tami S. Clabough, Matthew J. Knoff,[1] Timothy J. Blubaugh, and Christopher C. Caudill
Department of Fish and Wildlife Sciences, College of Natural Resources, University of Idaho, 875 Perimeter Drive, Moscow, Idaho 83844-1136, USA

Abstract
We conducted a field experiment to test the hypothesis that intragastric radio-tagging contributed to increased prespawn mortality (PSM) of adult Chinook Salmon *Oncorhynchus tshawytscha* after collection and transport to spawning sites above high-head hydroelectric dams. We assessed PSM rates of 970 wild and hatchery Chinook Salmon collected during trap-and-haul operations that were released untagged, tagged with passive integrated transponder (PIT) tags only, or double tagged with PIT tags and radio transmitters, and then recovered as carcasses in two Willamette River, Oregon, tributaries from 2009 to 2015. Results revealed no evidence that PSM rates were higher in PIT-tagged samples than in untagged (but not unhandled) control samples. The PSM rates in double-tagged samples were variable among years and between locations and indicated that radio-tagging effects were absent or small in effect size, on average, within each population. While we did not detect a consistent negative double-tagging effect across locations and years, results suggest that the potential for radio-tagging effects should be incorporated in study planning and design. We recommend that researchers use experimental designs that include control groups for directly evaluating tagging and handling effects on study outcomes.

Radiotelemetry has been successfully used to study migration behaviors, passage times, and survival of adult Pacific salmon *Oncorhynchus* spp. in rivers throughout the Pacific Northwest (Keefer et al. 2005; Naughton et al. 2005; Cooke et al. 2008; Eiler et al. 2015). Most radiotelemetry studies on adult salmonids use gastric implantation rather than surgical implantation because the gastric method minimizes handling and recovery times and most adults have ceased feeding (McCleave et al. 1978; Gray and Haynes 1979; Cooke et al. 2005, 2011). An inherent assumption of these studies is that radio-tagging does not affect fish behavior and ultimately survival. Concerns about fish tagging and handling effects are well documented and include delayed migration or downstream movement after release (e.g., Burger et al. 1985; Bendock and Alexandersdottir 1993; Bernard et al. 1999), transmitter regurgitation (Smith et al. 1998; Keefer et al. 2004), stomach rupture (Smith et al. 2009; Corbett et al. 2012), and delayed mortality (Naughton et al. 2005; Keefer et al. 2008). The timing and location of collection and tagging are also a concern because adult salmonid tissues degenerate as they sexually mature during their migration and mature fish may be more susceptible to tagging-related injuries (Corbett et al. 2012).

In this study, we tested whether intragastric radio-tagging of adult Chinook Salmon *Oncorhynchus tshawytscha* contributed to increased prespawn mortality (PSM) in Oregon's Willamette River basin. Spring-run Chinook Salmon in the Willamette River were listed as threatened under the U.S. Endangered Species Act (NMFS 1999), in part because construction of high-head hydroelectric dams has blocked access to historic spawning sites. An adult salmonid trap-and-haul program was initiated in the 1990s at Willamette Valley Project dams to use surplus hatchery broodstock to restore a source of marine-derived nutrients and supplement the prey base of native resident fish and

*Corresponding author: naughton@uidaho.edu
[1]Present address: BioSonics Telemetry LP, 4027 Leary Way Northwest, Seattle, Washington 98107, USA.
Received June 28, 2017; accepted October 19, 2017

wildlife, including other threatened species (i.e., Bull Trout *Salvelinus confluentus*) (Beidler and Knapp 2005; Schroeder et al. 2007). In recent years, the trap-and-haul program has focused on facilitating natural spawning of salmonid populations above the dams and is part of a reintroduction and reestablishment program (e.g., Evans et al. 2016). Unfortunately, there has been high PSM of Chinook Salmon observed in some years since the start of the trap-and-haul program (e.g., Keefer et al. 2010; Bowerman et al. 2016; DeWeber et al. 2017), prompting a series of radiotelemetry and passive integrated transponder (PIT) tag studies to evaluate potential causes of PSM in adult Chinook Salmon. Here, we test the hypothesis that radio-tagging contributed to increased PSM by comparing the survival of radio-tagged, PIT-tagged, and untagged wild and hatchery Chinook Salmon following trap-and-haul operations using a multiyear experiment in two Willamette River tributaries. We predicted that PSM rates of double-tagged fish would be higher than rates for PIT-tagged fish and rates for PIT-tagged fish would be higher than for unmarked fish.

METHODS

Study system.— Adult spring-run Chinook Salmon begin entering the Columbia River estuary in late winter and early spring and ascend the Columbia River and most major tributaries from March to July; spawning typically occurs in tributaries during August and September. Chinook Salmon from Oregon's Willamette River basin exhibit a similar pattern and migrate through a corridor that includes dense urban areas and irrigated agricultural lands before reaching their natal tributaries.

Chinook Salmon collection and tagging took place in 2009–2015 at two trap-and-haul locations in the Middle Fork Willamette River, southeast of Eugene, Oregon (Figure 1). The first was at Fall Creek Dam (river kilometer [rkm] 493, measured from the mouth of the Columbia River) on Fall Creek, a Middle Fork Willamette River tributary. The second was at Dexter Dam (rkm 491) on the Middle Fork Willamette River. Dexter Dam regulates the outflow from Lookout Point Dam just upstream (rkm 496).

Salmon collection and transport protocols.— The Fall Creek adult fish trap included a short ladder that led to a finger weir in front of a collection pool at the head of the fishway. The finger weir prevents fish from dropping out of the collection pool. U.S. Army Corps of Engineers (USACE) personnel operated a mechanical sweep to crowd fish into a holding tank. The tank was lifted using an overhead crane and placed on the ground, where USACE personnel anesthetized fish with approximately 60 mg/L eugenol. Tagging (see details below) was conducted by University of Idaho personnel twice per week (the trap was not cleared other days of the week) in approximate proportion to the run timing and number of fish collected from May to July each year. Tagging and handling times were approximately 2–3 min per fish. Tagged and untagged fish were then transported by the USACE to a site approximately 3 km upstream from the head of Fall Creek Reservoir and released at rkm 505.4 for a total transport distance of ~10 km (transport time ~15 min).

The Dexter trap was operated by the Oregon Department of Fish and Wildlife (ODFW), and sampled fish were provided to the University of Idaho tagging crew by the ODFW. The ODFW primarily uses the Dexter facility to collect broodstock for the Willamette Hatchery in Oakridge, Oregon. In all years, a fish ladder led to a weir at the entrance to a holding raceway. At the time of sorting, Chinook Salmon were mechanically crowded into an elevator that lifted them to an anesthetic tank containing either CO_2 (approximately 10 mg/L for 5 min) in 2009–2014 or AQUI-S 20E (17 mg/L; AquaTactics Fish Health, Kirkland, Washington) in 2015, following ODFW protocols. After fish were sedated, they were scanned for a coded wire tag, placed in a secondary tank with fresh river water to recover, and then transferred to a second anesthetic tank for assessment and tagging. Tagging anesthesia was tricaine methanesulfonate (MS-222; Argent Chemical Laboratories, Ferndale, Washington) at approximately 50 ppm in 2009–2013 and was AQUI-S 20E at 5–17 mg/L in 2014–2015. Tagging and handling times were similar to those at Fall Creek (approximately 2–3 min per fish). Following tagging, fish were transferred to a transportation truck containing fresh river water for recovery and then hauled above Lookout Point Dam to the North Fork Middle Fork Willamette River (NFMF) at rkm 558 (~67 km transport distance and ~1.5 h transport time). Sampling was approximately uniform through each season, with ~25 fish tagged each week because outplanting was secondary to collection of Chinook Salmon for broodstock and other ODFW obligations; consequently, outplanting densities were not in proportion to seasonal collection timing in several years. Remaining individuals that were not used for broodstock or other obligations were also transported.

Radio- and PIT-tagging protocols.— At Fall Creek Dam, a total of 1,482 wild (i.e., with intact fins) Chinook Salmon were collected and tagged from 2009 to 2012. The experimental sample included 215 that were double tagged with a PIT tag (Biomark, Boise, Idaho; model HPT12) and a radio transmitter, 502 with only a PIT tag, and 765 that were not tagged (Table 1). At Dexter Dam, where all Chinook Salmon were presumed to be of hatchery origin (i.e., clipped adipose fin), 360 were double tagged, 907 were tagged with only a PIT tag, and 9,879 were not tagged, for a total of 11,146 Chinook Salmon from 2009

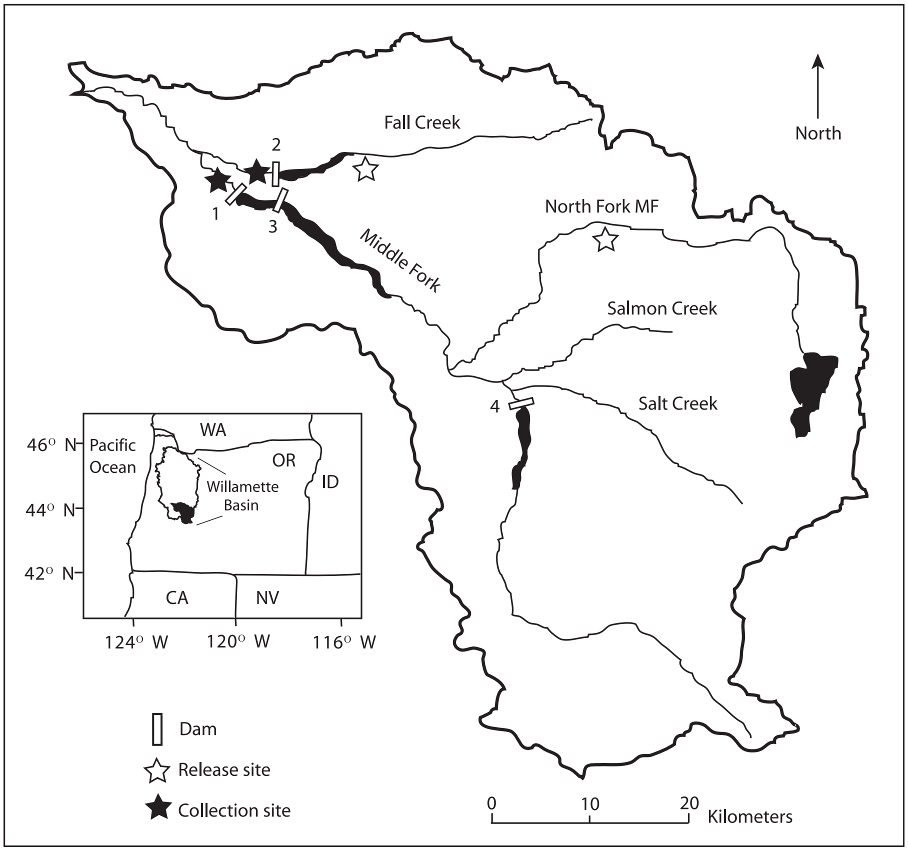

FIGURE 1. Map of the Middle Fork Willamette River basin showing Chinook Salmon collection and outplant sites. Dams are numbered as follows: 1 = Dexter Dam, 2 = Fall Creek Dam, 3 = Lookout Point Dam, and 4 = Hills Creek Dam.

TABLE 1. Numbers of adult Chinook Salmon released, females recovered, and female prespawn mortality (PSM) by tag treatment (PIT tags only, double tagged with PIT tags and radio transmitters, or unmarked) in Fall Creek (wild salmon) and the North Fork Middle Fork Willamette River (NFMF; hatchery salmon), 2009–2015. Numbers include both PSM and successful spawners.

		Number released			Females recovered			Female PSM (%)		
Site and total or mean	Year	PIT	Double	Unmarked	PIT	Double	Unmarked	PIT	Double	Unmarked
Fall Creek	2009	175	25	103	10	6	15	80.0	100.0	86.7
	2010	124	75	342	12	15	46	41.7	66.7	43.5
	2011	125	75	128	12	9	13	16.7	44.4	53.8
	2012	78	40	192	11	5	28	0.0	20.0	17.9
Total sample or mean PSM		502	215	765	45	35	102	34.6	57.8	50.5
NFMF	2009	124	12	981	3	1	19	0.0	100.0	47.4
	2010	148	43	1,231	15	3	102	46.7	66.7	63.7
	2011	109	71	1,366	5	5	98	0.0	60.0	37.8
	2012	104	50	2,441	10	6	192	10.0	16.7	22.9
	2013	106	59	2,031	6	3	143	50.0	33.3	30.8
	2014	150	50	865	17	3	74	23.5	0.0	9.5
	2015	166	75	964	4	3	76	75.0	33.3	35.5
Total sample or mean PSM		907	360	9,879	60	24	704	29.3	44.3	33.5

to 2015. Fish were PIT-tagged in the dorsal sinus, near the back of the dorsal fin in an effort to increase tag retention on scavenged carcasses (Dieterman and Hoxmeier 2009). Double-tagged fish were tagged with a 3-V transmitter (Lotek Wireless, Newmarket, Ontario; model MCFT2–3A, 16-mm diameter × 46-mm length, 16 g in air) that was inserted gastrically through the mouth. A silicone band was placed on each transmitter to reduce regurgitation, as described by Keefer et al. (2004). The objectives of radio-tagging were to verify that fish were moving upstream after release, to determine instream distribution during prespawn holding (Naughton et al. 2011; Roumasset 2012), and to help evaluate fish residence time and fate. The use of radio transmitters also aided in carcass collection for PSM assessments. Double-tagged, PIT-tagged, and untagged fish were typically released at the same time at each location.

Prespawn mortality surveys.— Carcass surveys were conducted by the University of Idaho and ODFW approximately 1–2 times per week from the beginning of releases through the spawning period (May through early October). Chinook Salmon collected during spawning ground surveys were inspected by University of Idaho and/or ODFW personnel for radio and PIT tags, and spawning status was assessed by inspecting the gonads and estimating the proportion of gametes remaining. Analyses were restricted to females, and a successfully spawned female was defined as having less than 25% of gametes remaining in the body cavity; those with more than 25% remaining were considered a PSM (Pinson 2005; Bowerman et al. 2016). We note that the large majority of inspected carcasses had either 0% or 100% of gametes (i.e., partially spawned carcasses were rare). The general condition of each carcass was also scored, including an estimate of how recently it died, obvious wounds, fungus levels, or other apparent visual cues to what may have caused mortality. Substantially scavenged carcasses were excluded from analyses.

Statistical analysis.— We used logistic regression to test for associations between PSM and tagging treatment across years. Separate models were compared for the Fall Creek and Dexter samples because origin (natural versus hatchery origin) and PSM patterns were markedly different between sites. Predictor variables were tag type and year for both locations. We also tested the interaction of tag type and year in preliminary models, but the interactions were not significant ($P > 0.68$) and were dropped from the final models.

We used a general linear model to test whether there were differences in elapsed time from release to carcass recovery, with tag treatment, year, and PSM (y,n) as covariates. We expected that double-tagged fish would be discovered more rapidly because radio transmitters facilitated collection (i.e., there would be an overall mean effect of treatment on recovery time). We further tested for more rapid death in double-tagged samples using a tag treatment × PSM interaction term in the model and by assuming additive effects. The analysis was limited to PIT- and double-tagged females because release dates were unknown for control treatment fish. General linear models were conducted separately for all females in each population. All analyses were performed in SAS 9.2 (SAS Institute, Cary, North Carolina).

RESULTS

Female Carcass Recovery and Prespawn Mortality Estimates

We recovered and assessed PSM in a total of 182 female Chinook Salmon at Fall Creek and 788 females in the NFMF over the 6-year study. The PSM rates in Fall Creek were highly variable among years for all treatments, with mean annual rates of 34.6% (range = 0–80%) for PIT-tagged, 57.8% (range = 20–100%) for double-tagged, and 50.5% (range = 17.9–86.7%) for untagged female Chinook Salmon (Table 1). Mean PSM rates for females in the NFMF were 29.3% (range = 0–75%) for PIT-tagged, 44.3% (range = 0–66.7%) for double-tagged, and 33.5% (range = 9.5–63.7%) for unmarked treatments (Table 1).

Tagging Treatment Effects

Comparison of PSM rates among tagging treatments (PIT, double, none) revealed some differences among treatments within year, but these differences were not consistent across years. After controlling for year effects at Fall Creek, the PIT-only samples had the lowest PSM rates and double-tagged Chinook Salmon had significantly higher PSM than the PIT-only group (Pearson's $\chi^2 = 6.4$, df = 2, $P = 0.040$) (Figure 2). Year was a significant predictor ($P < 0.001$) but was largely driven by high PSM rates for PIT-tagged (80.0%), double-tagged (100%), and untagged (86.7%) fish in 2009, when water temperatures

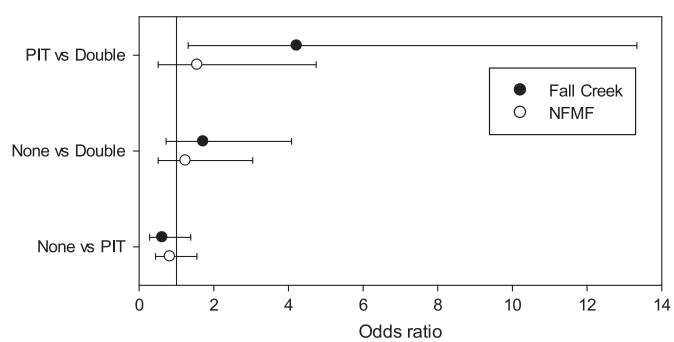

FIGURE 2. Comparison of odds ratios of prespawn mortality for tagged (PIT tags only or double tagged with PIT tags and radio transmitters) and untagged female Chinook Salmon recovered in Fall Creek (wild salmon) and the North Fork Middle Fork (NFMF) of the Willamette River (hatchery salmon) in 2009–2015. Ratios are expressed as the reciprocal of point estimates and 95% confidence intervals of odds ratios. Ratios > 1 indicate an increased probability of being classified as a prespawn mortality in the response group (second term in each pairing) compared with the reference treatment (first term).

were very warm (see Discussion). The odds of PSM were 4.2 times more likely (95% CI = 1.3–13.3, $P = 0.016$) for double-tagged than PIT-only fish at Fall Creek. The point estimate of odds ratio also indicated higher PSM in double-tagged than untagged fish, but the 95% confidence interval included 1.0 (point estimate = 1.7, 95% CI = 0.7–4.1, $P = 0.726$).

In the NFMF sample, there were no consistent year-to-year differences in PSM rates among untagged, PIT-only, or double-tagged treatments. Treatment was not a significant predictor of PSM rates ($\chi^2 = 0.6$, df = 2, $P = 0.729$) in multinomial logistic regression after controlling for year effects ($P < 0.001$).

Time to Carcass Recovery

The general linear model for Fall Creek female carcasses indicated that only PSM status was statistically associated with time to recovery, with fish that died prematurely being collected sooner than successful spawners (Table 2). Year, treatment, and the treatment × PSM terms had $P \geq 0.310$. In contrast, the general linear model for the NFMF showed that PSM status, year, and the treatment × PSM terms were statistically significant ($P < 0.001$). Mean times to recovery were 12.9 d (double-tagged PSM fish), 34.8 d (PIT-tagged PSM fish), 70.1 d (successful PIT-tagged fish), and 95.2 d (successful double-tagged fish) (Table 2).

DISCUSSION

Our tag effects experiment revealed a consistent lack of effect from PIT-tagging and year- and location-specific differences in treatment effects of double tagging. In Fall Creek, double-tagged Chinook Salmon had a statistically higher likelihood of PSM than PIT-tagged fish, but there were no statistical differences between double-tagged fish and untagged fish. The comparison of elapsed time to carcass recovery showed that double-tagged PSM fish were collected more quickly than PIT-tagged PSM fish in the NFMF, as expected given likely differences in detection efficiency for radio- versus PIT-tagged carcasses. Notably, the significant interaction between tag treatment and PSM was consistent with a higher instantaneous mortality rate in the double-tagged group in the NFMF samples. However, our study design could not disentangle tag effects from detection efficiency, and it is possible that the interaction resulted from differences in detection efficiency between tag types related to flow or other factors. Regardless, future studies should consider monitoring mortality rate as a metric of tag effects when detection efficiencies between tag types (and controls) are constant, as in laboratories or hatchery raceways. For example, Corbett et al. (2012) found that 90% of Yakima River, Washington, Chinook Salmon with gastrically implanted radio transmitters died 16–37 d after tagging compared with 10% of the controls and 30% of externally tagged fish held in raceways.

The differences in female PSM and time to carcass recovery between our two study populations and the disparity in results between the Middle Fork Willamette River and Yakima River studies indicate (1) possible population-specific differences in response to methods, (2) differences in prior experience of Chinook Salmon, including exposure to pathogens, toxins, high water temperatures, or other carry-over effects prior to collection and tagging, (3) differences in environment during prespawn holding (e.g., in a hatchery raceway versus in a river), or (4) a combination of these factors. Regardless, our results indicate that carefully executed radio- and PIT-tagging studies can provide reliable estimates of Chinook Salmon PSM in some trap-and-haul populations and that tagging effects in future studies should be evaluated to ensure any effects

TABLE 2. Results of general linear model testing for a relationship between mean elapsed time (d) from release to carcass recovery of PIT-tagged and double-tagged adult female Chinook Salmon in Fall Creek (wild salmon) and the North Fork Middle Fork Willamette River (NFMF; hatchery salmon) and the predictors year, prespawn mortality (PSM), tag treatment, and the interaction of PSM × tag treatment in 2009–2015.

				Elapsed time (d)						
Site	Treatment	PSM	*n*	Mean	SD	Source	df	Type III SS	*F*	*P*
Fall Creek	PIT	No	30	103.4	24.2	Year	3	1,364	0.54	0.655
	PIT	Yes	15	62.9	29.9	PSM	1	22,698	27.06	<0.001
	Double	No	14	104.0	12.5	Treatment	1	574	0.68	0.411
	Double	Yes	21	50.9	39.4	Treatment × PSM	1	875	1.04	0.310
NFMF	PIT	No	42	70.1	23.0	Year	6	14,073	6.18	<0.001
	PIT	Yes	18	34.8	28.7	PSM	1	38,115	100.35	<0.001
	Double	No	15	95.2	21.0	Treatment	1	218	0.57	0.451
	Double	Yes	9	12.9	6.6	Treatment × PSM	1	4,695	12.36	<0.001

that manifest can be accounted for when interpreting results.

Conclusions from any tagging study are predicated on the assumption that tagged fish represent sampled populations and behave similarly to untagged fish. Differences in collection procedures and hauling distances prevented meaningful direct comparison between our two Middle Fork Willamette River populations. Despite these constraints, several lines of evidence suggest that radio-tagging and PIT-tagging did not substantively affect PSM relative to handling with no tagging in most site–years. First, there was no statistical difference in PSM between the double-tagged and untagged treatments in either Fall Creek or the NFMF. Second, radio-tagging times were short (approximately 2–3 min) for both populations and were conducted by experienced personnel across study years and typically added less than 1 min to the overall handling time. Third, our logistic regression models showed that year was an important predictor of PSM rates in Fall Creek, an indication that all treatment groups responded in one or more years to shared environmental factor(s) like water temperature. Prespawn mortality has been positively correlated with water temperature across years in the Willamette basin during this and concurrent studies (Mann et al. 2010, 2011; Roumasset 2012; Bowerman et al. 2018). For example, annual temperature maxima in Fall Creek ranged from 19.8°C in 2011 to 23.6°C in 2009, when PSM was highest across treatments (G. P. Naughton, unpublished data). Temperatures were consistently lower and less variable in the NFMF (annual maxima = 14.0–15.8°C), where PSM estimates were also lower and less variable. Accounting for the effects of environmental factors when testing for tag effects is desirable, and advances in biotelemetry could allow individual environmental histories to be associated with fate. Notably, interactive effects are plausible, especially the manifestation of tag effects at higher temperatures (e.g., in Fall Creek in 2009).

Our combined evidence of a limited radio-tagging effect is consistent with other adult salmonid telemetry research, including on Atlantic Salmon *Salmo salar* (Thorstad et al. 2000; Jokikokko 2002; Rivinoja et al. 2006), Sockeye Salmon *Oncorhynchus nerka* (Ramstad and Woody 2003), and Chinook Salmon in several locations (e.g., Burger et al. 1985; Matter and Sandford 2003). Another concern in adult anadromous fish research, downstream movement following tagging (Bernard et al. 1999; Mäkinen et al. 2000), did not substantively affect our study results because nearly all double-tagged and PIT-tagged fish were recovered upstream from release sites in both study streams and downstream movements by radio-tagged fish were rare based on fixed-site monitoring below release sites.

Overall, we conclude that double tagging with PIT tags and radio transmitters had limited additional tagging effects on the probability of PSM compared with PIT tagging only or to handling without tagging in the NFMF. Observed double-tagging and year effects in Fall Creek suggest that double tagging may have increased risk under some circumstances, such as in Fall Creek in 2009 when water temperatures were well above average. We recommend that future investigators carefully weigh the potential for increased mortality and consider adaptive sampling plans to minimize risk (e.g., cessation or reduction of radio-tagging and limited handling at warm temperatures). Moreover, obtaining reliable estimates of tagging effects on PSM in the field will remain a challenge because of small sample sizes and low probability of carcass detection. For example, in the 4 years with all treatments in Fall Creek we recovered 35 double-tagged, 45 PIT-tagged, and 102 untagged females. The statistical power (1-ß; Cohen 1992; Gerow 2007) to detect a 10 percentage point difference in PSM between the double-tagged and untagged groups at $\alpha = 0.05$ would be approximately 0.33 (i.e., $n = 35$ and 102 and PSM = 60% and 50%, respectively). To achieve a power of 0.80, a commonly used benchmark (Cohen 1992), sample sizes would need to increase by a factor of 3.3 ($n = 116$ and 337, respectively) or the PSM rates would need to be 60% and 33%, respectively. Consequently, we may have been unable to detect modest differences in PSM rates among sample groups, and sample size limitations should be considered in future tag effect evaluations.

Previous studies have suggested that fish radio-tagged either later in migration or further upstream can have lower survival rates, but patterns are inconsistent. For example, Corbett et al. (2012) found that Chinook Salmon tagged upstream late in migration exhibited poor survival relative to fish tagged earlier. In the current study, Chinook Salmon tagged later did tend to have higher PSM rates in the NFMF, but the date effect was evident regardless of tag type (Naughton, unpublished data). In contrast, DeWeber et al. (2017) found that Chinook Salmon outplanted in the South Santiam River (another Willamette River tributary) later in the run had lower PSM rates than earlier outplants. The mixed results across the cited studies presumably reflect the complex interactions among individual- and population-level migration timing and distance and concomitant differences in temperature exposure during migration and holding. Disentangling underlying temperature exposure effects from capture, handling, and tagging effects is an ongoing challenge in PSM studies.

Migration distance does not explain differences in PSM estimates between Fall Creek and the NFMF. Both populations were tagged approximately 490 km from the Pacific Ocean and shared the same migration corridor for over 99% of that distance. We note that the Yakima River population studied by Corbett et al. (2012) migrated

~745 km upriver before collection and tagging. Comparisons across populations suggests that run timing and environmental conditions may have stronger effects on PSM than migration distance.

Although we did not detect a strong overall double-tagging effect, our estimated PSM rates for each group must be viewed with some caution. Several studies suggest that radio-tagging may negatively affect salmonid behavior and survival (Gray and Haynes 1979; Burger et al. 1985; Bernard et al. 1999; Corbett et al. 2012). Decisions about tagging methodology ultimately depend on the study objectives. In our study, radiotelemetry was considered necessary to locate concentrations of spawning Chinook Salmon and to assess the extent of postrelease downstream movement, particularly in early study years. Regardless of methods and study objectives, fish welfare must be a primary consideration, and researchers should determine if questions can be answered with the least invasive approach. Specifically, we recommend that potential biases related to tag effects be critically examined during study design prior to tagging and that future studies include control groups for directly evaluating tagging and handling effects when possible.

ACKNOWLEDGMENTS

Many people worked on this project and its successful completion was made possible through their efforts. We would like to thank: Ryan Mann, Charles Erdman, Jeff Garnett, Eric Johnson, Grant Brink, Eric Powell, Dan Joosten, Mike Turner, and Chris Noyes (University of Idaho) for assisting with field work and data collection; Greg Taylor, Doug Garletts, and Chad Helms from the USACE Lookout Point office for field help and project coordination; David Griffith, Rich Piaskowski, Fenton Khan, and Robert Wertheimer (USACE Portland District); and Cameron Sharpe, Dan Peck, Tim Wright, Mike Sinnott, Brian Franklin, Suzette Savoie, and Kevin Stertz (ODFW) for assistance on spawning ground surveys, tagging, and data collection. Carl Schreck, Michael Kent, Mike Colvin, Susan Benda, Courtney Danley, and Rob Chitwood (Oregon State University) provided support. Karen Johnson (University of Idaho) provided administrative support, and Michael Jepson (University of Idaho) assisted with data management and permitting. This study was conducted under Cooperative Ecosystems Study Unit agreement CESU W912HZ-12-2-0004 funded by the USACE Portland District. There is no conflict of interest declared in this article.

REFERENCES

Beidler, W., and S. Knapp. 2005. A synopsis of information relating to the success of adult hatchery Chinook Salmon releases above migration barriers in the Willamette River system. Oregon Department of Fish and Wildlife, Corvallis.

Bendock, T., and M. Alexandersdottir. 1993. Hooking mortality of Chinook Salmon released in the Kenai River, Alaska. North American Journal Fisheries Management 13:540–549.

Bernard, D. R., J. L. Hasbrouck, and S. J. Fleischman. 1999. Handling-induced delay and downstream movement of adult Chinook Salmon in rivers. Fisheries Research 44:37–46.

Bowerman, T., M. L. Keefer, and C. C. Caudill. 2016. Pacific salmon prespawn mortality: patterns, methods, and study design considerations. Fisheries 41:738–749.

Bowerman, T., A. Roumasset, M. L. Keefer, C. S. Sharpe, and C. C. Caudill. 2018. Prespawn mortality of female Chinook Salmon increases with water temperature and percent hatchery origin. Transactions of the American Fisheries Society 147:31–40.

Burger, C. V., R. L. Wilmot, and D. B. Wangaard. 1985. Comparison of spawning areas and times for two runs of Chinook Salmon (*Oncorhynchus tshawytscha*) in the Kenai River, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 42:693–700.

Cohen, J. 1992. A power primer. Quantitative methods in psychology. Psychological Bulletin 121:155–159.

Cooke, S. J., G. T. Crossin, D. A. Patterson, K. K. English, S. G. Hinch, J. L. Young, R. F. Alexander, M. C. Healey, G. Van Der Kraak, and A. P. Farrell. 2005. Coupling non-invasive physiological assessments with telemetry to understand inter-individual variation in behaviour and survivorship of Sockeye Salmon: development and validation of a technique. Journal of Fish Biology 67:1342–1358.

Cooke, S. J., S. G. Hinch, A. P. Farrell, D. A. Patterson, K. Miller-Saunders, D. W. Welch, M. R. Donaldson, K. C. Hanson, G. T. Crossin, M. T. Mathes, A. G. Lotto, K. A. Hruska, I. C. Olsson, G. N. Wagner, R. Thomson, R. Hourston, K. K. English, S. Larsson, J. M. Shrimpton, and G. Van Der Kraak. 2008. Developing a mechanistic understanding of fish migrations by linking telemetry with physiology, behavior, genomics and experimental biology: an interdisciplinary case study with adult Fraser River Sockeye Salmon. Fisheries 33:321–338.

Cooke, S. J., C. M. Woodley, M. B. Eppard, R. S. Brown, and J. L. Nielsen. 2011. Advancing the surgical implantation of electronic tags in fish: a gap analysis and research agenda based on a review of trends in intracoelimic tagging effects studies. Reviews in Fish Biology and Fisheries 21:127–151.

Corbett, S. C., M. L. Moser, and A. H. Dittman. 2012. Experimental evaluation of adult spring Chinook Salmon radio-tagged during the late stages of spawning migration. North American Journal of Fisheries Management 32:853–858.

DeWeber, J. T., J. T. Peterson, C. Sharpe, M. L. Kent, M. E. Colvin, and C. B. Schreck. 2017. A hidden-process model for estimating prespawn mortality using carcass survey data. North American Journal of Fisheries Management 37:162–175.

Dieterman, D. J., and J. H. Hoxmeier. 2009. Instream evaluation of passive integrated transponder retention in Brook Trout and Brown Trout: effects of season, anatomical placement, and fish length. North American Journal of Fisheries Management 29:109–115.

Eiler, J. H., A. N. Evans, and C. B. Schreck. 2015. Migratory patterns of wild Chinook Salmon *Oncorhynchus tshawytscha* returning to a large, free-flowing river basin. PLOS (Public Library of Science) ONE [online serial] 10:e0123127.

Evans, M. L., M. A. Johnson, D. Jacobson, J. Wang, M. Hogansen, and K. G. O'Malley. 2016. Evaluating a multi-generational reintroduction program for threatened salmon using genetic parentage analysis. Canadian Journal of Fisheries and Aquatic Sciences 73:844–852.

Gerow, K. G. 2007. Power and sample size estimation techniques for fisheries management: assessment and a new computational tool. North American Journal of Fisheries Management 27:397–404.

Gray, R. H., and J. M. Haynes. 1979. Spawning migration of adult Chinook Salmon (*Oncorhynchus tshawytscha*) carrying external and internal transmitters. Journal of the Fisheries Board of Canada 36:1060–1064.

Jokikokko, E. 2002. Migration of wild and reared Atlantic Salmon (*Salmo salar* L.) in the River Simojoki, northern Finland. Fisheries Research 58:15–23.

Keefer, M. L., C. A. Peery, W. R. Daigle, M. A. Jepson, S. R. Lee, C. T. Boggs, K. R. Tolotti, and B. J. Burke. 2005. Escapement, harvest, and unknown loss of radio-tagged adult salmonids in the Columbia River-Snake River hydrosystem. Canadian Journal of Fisheries and Aquatic Sciences 62:930–949.

Keefer, M. L., C. A. Peery, and M. J. Heinrich. 2008. Temperature-mediated en route migration mortality and travel rates of endangered Snake River Sockeye Salmon. Ecology of Freshwater Fish 17:136–145.

Keefer, M. L., C. A. Peery, R. R. Ringe, and T. C. Bjornn. 2004. Regurgitation rates of intragastric radio transmitters by adult Chinook Salmon and steelhead during upstream migration in the Columbia and Snake rivers. North American Journal of Fisheries Management 24:47–54.

Keefer, M. L., G. A. Taylor, D. F. Garletts, G. A. Gauthier, T. M. Pierce, and C. C. Caudill. 2010. Prespawn mortality in adult spring Chinook Salmon outplanted above barrier dams. Ecology of Freshwater Fish 19:361–372.

Mäkinen, T. S., E. Niemelä, K. Moen, and R. Lindström. 2000. Behaviour of gill-net and rod-captured Atlantic Salmon (*Salmo salar* L.) during upstream migration and following radio tagging. Fisheries Research 45:117–127.

Mann, R. D., C. C. Caudill, M. L. Keefer, C. A. Peery, C. B. Schreck, and M. L. Kent. 2010. Migration behavior and spawning success of spring Chinook Salmon in Fall Creek and the North Fork Middle Fork Willamette River: relationships among fate, fish condition, and environmental factors. Prepared for the U.S. Army Corps of Engineers by the Cooperative Fish and Wildlife Research Unit, University of Idaho, Technical Report 2010-7, Moscow.

Mann, R. D., C. C. Caudill, M. L. Keefer, C. A. Peery, C. B. Schreck, and M. L. Kent. 2011. Migration behavior and spawning success of spring Chinook Salmon in Fall Creek and the North Fork Middle Fork Willamette River: relationships among fate, fish condition, and environmental factors. Prepared for the U.S. Army Corps of Engineers by the Cooperative Fish and Wildlife Research Unit, University of Idaho, Technical Report 2011-8, Moscow.

Matter, A. L., and B. P. Sandford. 2003. A comparison of migration rates of radio- and PIT-tagged adult Snake River Chinook Salmon through the Columbia River hydropower system. North American Journal of Fisheries Management 23:967–973.

McCleave, J. D., J. H. Power, and S. A. Rommel Jr. 1978. Use of radio telemetry for studying upriver migration of adult Atlantic Salmon (*Salmo salar*). Journal of Fish Biology 12:549–558.

Naughton, G. P., C. C. Caudill, T. S. Clabough, M. L. Keefer, M. J. Knoff, and M. A. Jepson. 2011. Migration behavior and spawning success of spring Chinook Salmon in Fall Creek and the North Fork Middle Fork Willamette River: relationships among fate, fish condition, and environmental factors. Prepared for the U.S. Army Corps of Engineers by the Cooperative Fish and Wildlife Research Unit, University of Idaho, Technical Report 2012-2, Moscow.

Naughton, G. P., C. C. Caudill, M. L. Keefer, T. C. Bjornn, L. C. Stuehrenberg, and C. A. Peery. 2005. Late-season mortality during migration of radiotagged adult Sockeye Salmon (*Oncorhynchus nerka*) in the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 62:30–47.

NMFS (National Marine Fisheries Service). 1999. Endangered and threatened species: threatened status for three Chinook Salmon evolutionarily significant units in Washington and Oregon, and endangered status for Chinook Salmon ESU in Washington. Federal Register 64:116(17 June 1999):14517–14528.

Pinson, A. 2005. Energy use, migration time, and spawning success of adult Chinook Salmon returning to the South Fork Salmon River in central Idaho. Master's thesis. University of Idaho, Moscow.

Ramstad, K. M., and C. A. Woody. 2003. Radio tag retention and tag-related mortality among adult Sockeye Salmon. North American Journal of Fisheries Management 23:978–982.

Rivinoja, P., K. Leonardsson, and H. Lundqvist. 2006. Migration success and migration time of gastrically radio-tagged v. PIT-tagged adult Atlantic Salmon. Journal of Fish Biology 69:304–311.

Roumasset, A. G. 2012. Pre-spawn mortality of upper Willamette River spring Chinook Salmon: associations with stream temperature, watershed attributes, and environmental conditions on the spawning grounds. Master's thesis. University of Idaho, Moscow.

Schroeder, R. K., K. R. Kenaston, and L. K. McLaughlin. 2007. Spring Chinook Salmon in the Willamette and Sandy rivers. Oregon Department of Fish and Wildlife, Portland.

Smith, G. W., R. N. B. Campbell, and J. S. MacLaine. 1998. Regurgitation rates of intragastric transmitters by adult Atlantic Salmon (*Salmo salar* L.) during riverine migration. Hydrobiologia 371(372):117–121.

Smith, J. M., M. E. Mather, H. J. Frank, R. M. Muth, J. T. Finn, and S. D. McCormick. 2009. Evaluation of a gastric radio tag insertion technique for anadromous river herring. North American Journal of Fisheries Management 29:367–377.

Thorstad, E. B., F. Økland, and B. Finstad. 2000. Effects of telemetry transmitters on swimming performance of adult Atlantic Salmon. Journal of Fish Biology 57:531–535.