Assessing the Utility of Tributary PIT-Tag Arrays in Monitoring Snake River Salmonid Recovery

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Abstract

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Passive integrated transponder (PIT) tag technology is used in the Columbia River basin to monitor migration of threatened and endangered salmonid populations. From 2010 to 2018, the number of tag detection arrays installed in tributaries almost tripled, increasing the range of the PIT-tag detection network and its potential use in evaluating mitigation operations for salmonids. This study used PIT-tag arrays in upper Snake River tributaries to assess how adult dam passage and smolt transportation affect upstream migration success and concluded that there is minimal evidence that adult homing success is related to dam passage or juvenile transportation history. This thesis also compared smolt-to-adult return (SAR) ratios calculated with coded wire tags and PIT-tags and concluded that using PIT-tag recovery data to estimate SARs in the basin is preferred given that they capture more of the natural variability.

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Introduction

Habitat fragmentation and impaired migration of aquatic organisms have been attributed to hydrologic alteration from dam construction worldwide (Grill 2015). The Federal Columbia River Power System (FCRPS) is one of the largest hydroelectric systems in the world, comprising 31 hydroelectric facilities in the Pacific Northwest (BPA 2001) that include 13 major dams on the mainstem of the Columbia and lower Snake Rivers passable to migratory fishes (USACE et al. 2017). These river reaches are migratory corridors for economically and culturally important populations of anadromous salmonids *Oncorhynchus* spp. as they migrate downstream to sea and upstream to spawning grounds (NRC 1996), as well as other members of the aquatic community.

Thirteen salmon and steelhead stocks in the Columbia River basin are listed as “threatened” or “endangered” under the U.S. Endangered Species Act (ESA; USACE et al. 2017). Although initial population declines pre-date hydroelectric development, dams likely exacerbated downward population trends and hinder subsequent recovery (National Research Council 1996; Kareiva et al. 2000). Efforts to study the impacts of the hydrosystem on salmonids date back to the 1930s and mitigation operations began in the 1960s (Williams et al. 2005). Mitigation techniques in the basin include barging smolts to bypass dams, increasing spill to improve out-migrant survival, construction of dam passage facilities, hatchery supplementation, and restoration to improve spawning and rearing habitat (Leonard et al. 2015). There are also major monitoring efforts in place to evaluate these operations, including tagging juvenile and adult salmonids to monitor movement (NPCC 2014), and trapping to collect biological information (Harmon 2003) and hatchery broodstock (Ogden 2016). As a result, research and recovery efforts handle hundreds of thousands of salmonids annually. However, current evaluation measures for these practices do not always take advantage of the latest technology and need reassessment to ensure mitigation efforts are meeting species recovery goals and monitoring efforts are cost effective, sensitive to change, and do not hinder the populations being monitored.

Current evaluation measures in the Columbia River basin estimate juvenile out-migrant success (Widener et al. 2018), smolt-to-adult returns (McCann et al. 2017), adult dam passage survival (NOAA Fisheries 2011), and adult return abundance (Northwest Fisheries Science Center 2015) to assess recovery status and mitigation actions. These measures rely on batch tagging and subsequent recovery or detection to monitor salmonid movement and estimate survival through the hydrosystem. Coded wire tags (CWTs) and passive integrated transponder (PIT) tags are the most widely used for monitoring salmonids in the basin, with approximately 100 million CWTs (Cook-Tabor 2017) and two million PIT-tags released annually (Morris et al. 2018). Although there are fewer PIT-tags in the system than CWTs, their recovery is nonlethal and sequential detection their data can be retrieved in near real-time. This thesis studies the current use of PIT-tag technology in the Columbia River basin and assesses how it can be used to re-evaluate assumptions and improve mitigation and monitoring practices.

History of PIT-tags.—Used in the Columbia River basin since 1987, passive integrated transponder (PIT) tags are typically implanted in the abdominal cavity of salmonids and require nonlethal electronic detection for recovery (Prentice et al. 1990). Out-migrating juveniles and returning adults may be given a PIT-tag, and their migration monitored with detection arrays across the basin. Tag detection and recovery data are uploaded to the Columbia River PIT Tag Information System (PTAGIS; www.ptagis.org), a publicly accessible centralized database for movement of tagged fish in the Columbia Basin.

The PIT-tag detection network in the Columbia River basin is unparalleled globally. In 2017, there were 307 active PIT-tag interrogation sites across the basin. PIT-tag arrays are installed and operational at hatchery facilities and most major passable dams in the basin, with an increasing number of arrays deployed in tributaries. For example, there were 78 tributary arrays across the Columbia River basin at the end of 2010. This number nearly tripled by the end of 2017, with 210 active tributary arrays basin-wide. The expansion of the tag detection network into tributaries was initiated by the 2008 FCRPS Biological Opinion, which specifically earmarked funds to expand PIT-tag detection beyond mainstem rivers to further monitor population survival and better evaluate tributary habitat restoration (NMFS 2008). However, many projects utilizing these arrays are done in isolation and their results are rarely published in the scientific literature. Additionally, despite the proliferation of tributary arrays, evaluation of central mitigation and monitoring techniques like trapping and barging have yet to incorporate these data, instead relying on detectors installed at major dams (Clabough et al. 2014; McCann et al. 2017). As a result, data on salmonid life histories are truncated to that which occurs in mainstem rivers.

To utilize PIT-tag data more thoroughly, it is important to assess what information can be extracted from tributary arrays. Tributary arrays have the potential to improve our understanding of early juvenile survival and outmigration success as well as en route adult mortality. In doing so, we should gain a better understanding of the efficacy of the smolt transportation program and the migration effects of adult trapping at dams (Murauskas et al. 2014; McCann et al. 2017). Furthermore, by assessing what information can be extracted from tributary arrays, we can also identify what information is lacking and address necessary changes to best capture those data.

The Upper Snake River.—Tributary arrays in the upper Snake River represent a third of all instream arrays in the Columbia River basin. The number of instream arrays located in the upper Snake, Clearwater, Grande Ronde, Imnaha, and Salmon River subbasins increased from 27 to 63 between 2010 to 2017. As a result, the survival of an increasing number of fish stocks can be monitored from natal rearing site to spawning grounds across their multi-year life cycle. However, smolt-to-adult return and homing of upper Snake River salmonids continue to be evaluated solely within the hydrosystem. These evaluation metrics truncate life history consideration to Lower Granite Dam, the uppermost passable dam on the Snake River, although an individual's spawning grounds may be 50 to >700 km further upstream (Keefer et al. 2008).

This thesis explores how PIT-tag arrays in upper Snake River tributaries can be used more holistically for salmonid research and recovery. To do so, I identified PIT-tag arrays capable of detecting an individual adult migrant to "home" from 2012 to 2017, defined as a PIT-tag array or series of arrays near and downstream of an adult migrant's mark/release locations in its year of adult return.

Each chapter of this thesis uses this "home array catalog" to examine the current and potential role of PIT-tag arrays in upper Snake River tributaries for evaluating monitoring and mitigation operations for salmonids. In Chapter 1, a rare change in adult ladder operation at Lower Granite Dam provided the opportunity to examine the relationship between adult ladder passage and subsequent homing success, adding to the scant literature on this subject. In Chapter 2, I assess tributary homing success in the context of smolt transportation to verify if the current evaluation framework for smolt transportation program is adequate. In Chapter 3, I evaluate how smolt-to-adult return ratios estimated with PIT-tags compare to that of coded wire tags, the current standard for the basin. This work is timely given a potential upcoming decade-long study of hydrosystem survival that will depend on tag recovery data. In the discussion, I consider what information is currently lacking in the upper Snake River PIT-tag detection network, how to address it, and other questions yet to be answered.

The themes of this thesis are accountability and progress. Tributary arrays in the upper Snake River basin increase the resolution of salmonid migration data and expand the scope of inquiry for these ESA-listed stocks. This thesis examines the current and potential use of these arrays and explores the holistic power of the tributary array network. As we move forward in our efforts to recover upper Snake River salmonids, we must account for the data the tributary array network provides and use them in our evaluation of mitigation and monitoring practices.

Chapter 1: The effects of adult ladder passage at Lower Granite Dam on Snake River salmonid migration

Abstract

Lower Granite Dam is the last dam federally-protected Snake River salmonids *Oncorhynchus* spp. must ascend during their spawning migration to the upper Snake River basin. The dam has an adult fish ladder equipped with a trapping system to facilitate fisheries research and hatchery broodstock collection. There are three possible passage routes through the adult ladder: trapped, shunted, and free passage. During the adult trapping season, all fish must swim through 12-inch shunt pipes outfitted with PIT-tag arrays to select fish for trapping. Selected fish use the “trapped” route and are kept in a holding area for up to 20 h before being sampled and returned to the ladder. Unselected fish use the “shunted” route and immediately resume migration after swimming through the pipes. When the trap is not in operation, the shunted route is inaccessible and all fish use the “free passage” route to ascend the ladder without additional impediment. In 2016, a temporary change in ladder operations permitted free passage for a portion of the trapping season. My study used this rare opportunity to evaluate how different passage routes affect in-ladder transit time and upstream homing success for five salmonid stocks: Sockeye Salmon, steelhead, and spring-, summer-, and fall-run Chinook Salmon. In 2016, only Sockeye Salmon and spring- and summer-run Chinook Salmon were given access to free passage and I found limited evidence that free passage increased subsequent detection at natal sites upstream. I also compared homing success for trapped and shunted adult migrants for 2012–2015, when free passage did not exist. For all five stocks, I found that homing success did not differ between trapped and shunted fish across 2012–2016. To minimize risks of mortality in this final stage of

adult migration, I suggest continued opportunities for free passage at the Lower Granite Dam adult ladder and the modification of trapping operations to reduce holding times.

Introduction

Fish passage facilities for adult salmonids at dams serve primarily as mitigation for upstream passage blocked by hydroelectric projects. When paired with tag technology and entrapment, these facilities also provide opportunities for research and data collection (McCutcheon et al. 1994; Harmon 2003). Although adult fish passage facility design (Clay 1995; Larinier 2001; Williams et al. 2012) and adult passage behavior and performance have been studied at length (Roscoe and Hinch 2010), limitations in monitoring upstream migration have hindered evaluations of the post-passage effects of passage route through these facilities (Roscoe and Hinch 2010) or interception and handling at these facilities (Murauskas et al. 2014).

Passage through adult fish facilities, or fishways, can inhibit migration success by disorienting and delaying migrants. Disorientation from complex fishway designs can induce dam fallback, where an upstream migrant reverses course after successfully ascending a fishway, falling back over the dam (Reischel and Bjornn 2003; Naughton et al. 2006). Fallback increases risk of injury or mortality as a fish passes over dam structures (Wagner and Hillson 1993) and can delay migration timing (Keefer et al. 2004) and decrease homing success to spawning grounds (Boggs et al. 2004). Fishways can also delay migration for hours to days as adult migrants seek entrances and favorable routes of passage (Bjornn and Peery 1992; Naughton et al. 2007; Burnett et al. 2014), as well as retreat from high water temperatures in the passageway (Caudill et al. 2013).

Trapping salmonids for research purposes can also inhibit subsequent migration success by delaying and stressing migrants. Daily trap operations at Ice Harbor Dam modestly delayed migrating adult Chinook Salmon (Clabough et al. 2014), while intensive trapping rates at Tumwater Dam substantially delayed or altogether precluded Wenatchee River Basin Sockeye

Salmon *Oncorhynchus nerka* from migrating to spawning grounds (Murauskas et al. 2014). On the Yukon River, trap holding time at an in-river fish wheel reduced upstream migration success for Chum Salmon *O. keta* (Bromaghin et al. 2007), likely due to stress from capture and handling (Underwood et al. 2004). Trapping wild pre-spawning Rainbow Trout *O. mykiss* at an in-river site in New Zealand induced a significant stress response, delaying upstream migration until fish sufficiently recovered (Clements et al. 2002).

Long-distance migration is energetically demanding (Quinn 2005) and stress and delayed passage can deplete energy reserves (Brown et al. 2006; Caudill et al. 2007). Energy depletion can reduce reproductive success via mortality en route to and at spawning grounds (Gilhousen 1990; Geist et al. 2000; Cooke et al. 2006). Even if a delayed migrant survives to spawn, migration timing is an important aspect in mate and redd selection (Seamons et al. 2004; Quinn 2005) and contributes to reproductive success in *Oncorhynchus* spp. (Dickerson et al. 2002; Hruska et al. 2011).

In general, managers seek to minimize the in-situ and post-passage effects of fishway use (Schilt 2007; Williams et al. 2012). In addition to structural modifications, this can be achieved by limiting migration delay (Castro-Santos et al. 2009) and exercising caution when trapping and handling adult migrants (Clements et al. 2002; Murauskas et al. 2014). This is especially critical in the Columbia River basin, where 13 Pacific salmonid populations are listed as “threatened” or “endangered” under the U.S. Endangered Species Act (NMFS 2016) and must pass up to eight mainstem dams before reaching spawning grounds. Although environmental conditions can also inhibit migration success and survival (Hinch et al. 2012; Fenkes et al. 2016; Bowerman et al. 2018), changing trapping operations to address premature mortality is an inexpensive mitigation action that can be readily pursued.

The passive integrated transponder (PIT) tag network in the Columbia River basin provides the ability to monitor migration at dams and in tributaries. Paired with the extensive PIT-tagging programs already in place at hatcheries and wild streams, the recent expansion of PIT-tag detection arrays into tributaries in the upper Snake River basin grants researchers the opportunity to study post-passage effects of the Lower Granite Dam adult fish ladder. In 2016, a temporary change in operation at the Lower Granite Dam adult fishway permitted access to a simplified route of passage not usually accessible during the migration season. This change in operation offered a rare opportunity to directly compare migration success of adult salmonids that used different passage routes with varying degrees of complexity and fish handling.

In this study, I used PIT-tag data to examine the relationship between passage route in the Lower Granite Dam adult ladder and detection to natal site for adult Sockeye Salmon, steelhead *O. mykiss*, and spring-, summer-, and fall-run Chinook Salmon *O. tshawytscha*. My primary objectives were to: (1) identify mean transit time through the ladder for each route of passage and (2) investigate the relationship between passage route and homing success. I hypothesized that transit time would increase and homing success would decrease with increasing passage route complexity.

Study site.—Lower Granite Dam (LGR) is located 695 river kilometers from the mouth of the Columbia River and has remained the uppermost passable dam by salmonids on the Snake River since its completion in 1975. LGR is the last of eight dams adult salmonids must ascend during their spawning migrations to the upper Snake, Clearwater, Grande Ronde, and Salmon River basins. Since 1975, an off-ladder adult fish trap has been operated by the National Marine Fisheries Service (NMFS) and maintained by the U.S. Army Corp of Engineers (USACE) to facilitate fisheries research and broodstock collection (Ogden 2016). At the request of NMFS, the trapping facility was remodeled in 1995 and again in 2006 to meet increasing adult sampling demand, minimize stress to fish, and maximize sampling efficiency (Harmon 2003; Ogden 2016). Off-ladder adult fish traps are routinely operated for similar purposes at two other mainstem dams in the Columbia River basin, Bonneville Dam (USACE 2017) and Priest Rapids Dam (Grant County Public Utility District 2018), and an in-ladder trap is operated on a limited basis at Ice Harbor Dam (USACE 2017). However, the adult trapping operations at LGR are unique given the magnitude of PIT-tagged, known-source migrants routed through the trap and the practice of holding a proportion of adult migrants overnight. Additionally, migrants ascending the LGR adult fish ladder have limited access to an uninhibited route of passage compared to the other dams in the Columbia River basin.

There are three possible passage routes for fish ascending the LGR adult ladder: free passage, shunted, and trapped (Figure 1.1). When trapping is inactive, all fish use the “free passage” route and swim from the ladder entrance to exit without additional impediment. During the trapping season (March to November), a gate is placed between the ladder entrance and exit to facilitate selection of fish for trapping (Harmon 2003). All fish are routed to an attraction pool, ascend a false weir, and are shunted through one of two 12-in pipes equipped with PIT-tag detectors that are programmed with a sort-by-code loop for trap selection and diversion. After exiting the shunt pipes, fish enter flumes with diversion gates. Tagged fish are diverted to the pre-trap holding area if the PIT-tag detectors in the shunt pipes identify a code as preselected for trapping (Harmon 2003). Fish can also be diverted to the holding area if a diversion gate is activated by predetermined random sampling rates to sample the run-at-large, allowing both tagged and untagged fish to be sampled at the trap (Ogden 2016). Fish diverted outside of trap operation hours, generally 1500 to 0700 PDT, are kept in the holding area until trapping operations resume the next morning. Trapped fish are anesthetized, measured, examined for tags and injury, and may be tagged, sampled for genetic and/or age analysis, and/or removed for hatchery broodstock collection (Ogden 2016). After collecting the requisite data, trapped fish are returned to the ladder for continued ascension. Fish that are not selected for trapping and handling use the "shunted" route. After passing through the shunt pipes, these fish continue through the flumes and return to the ladder to resume their spawning migration (Ogden 2016).

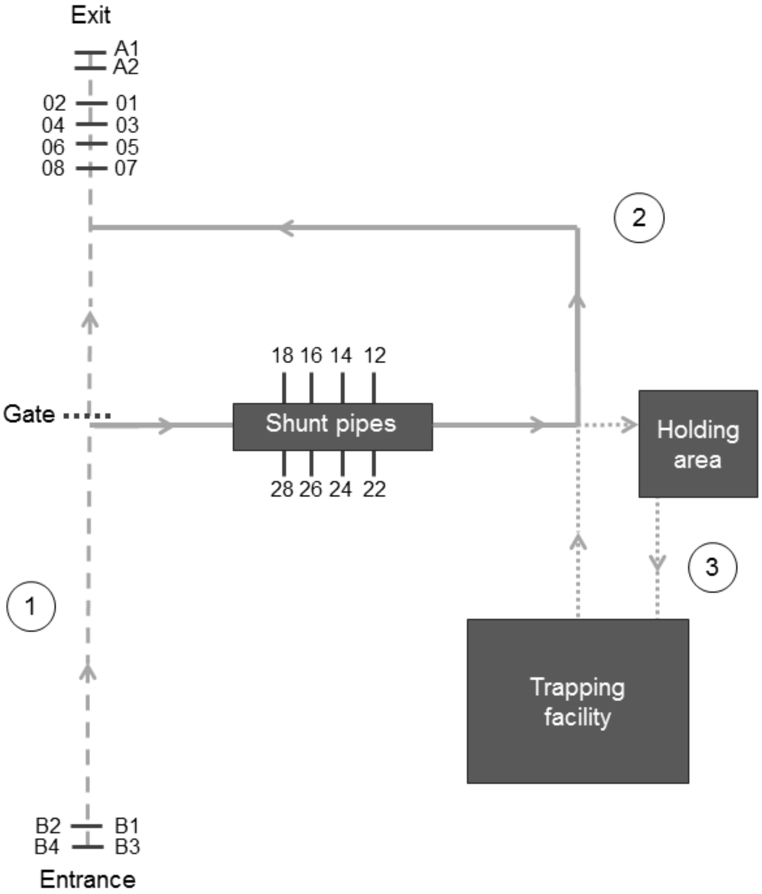

FIGURE 1.1—A schematic of the Lower Granite Dam adult fish ladder in 2016 (not to scale). Black bars represent PIT-tag detection arrays. Route 1 is free passage, noted by dashed lines. Route 2 is shunted, noted by solid lines. Route 3 is trapped, noted by dotted lines.

Prior to 2016, the gate directing fish to the shunt pipes remained in place for the duration of the trapping season. The gate was removed when the trapping season ended and when the trap was closed due to long periods of high water temperatures, per handling protocol (Harmon 2003; Ogden 2016). In 2016, the gate was intentionally opened on weekends to allow free passage across the trapping season (Anchor QEA LLC et al. 2017). Harmon (2003) provides a more detailed description of the trapping facility and its general operations; NMFS releases an annual report on adult trap operations at LGR (e.g. Ogden 2016).

Methods

Study population.—This study included known-source hatchery- and wild-origin steelhead, Sockeye Salmon, and spring-, summer-, and fall-run Chinook Salmon that met the following requirements: (1) ascended LGR during the 2012–2016 trapping seasons, (2) were released above LGR as tagged juveniles, and (3) were detected at the LGR ladder weir or exit as an adult, thereby indicating successful ascension of the ladder. For the homing success analysis, there was the additional requirement that after ascending LGR, the study fish must have had access to a PIT-tag array or recapture mechanism at or near at least one of its juvenile mark- or release-sites. All tagging data were retrieved from the publicly accessible Columbia River Basin PIT Tag Information System (PTAGIS; www.ptagis.org) and trapping time data were retrieved from the Lower Granite Dam Adult Fish Trap database, with access from NMFS.

PIT-tag detection within the LGR ladder was used to classify individuals by passage route. Fish detected at the entrance (arrays: B1, B2, B3, B4) and weir (arrays: 01, 02, 03, 04, 05, 06, 07, 08) or exit arrays (arrays: A1, A2) were classified as "free passage." Fish with an additional detection at the shunt pipes (arrays: 12, 14, 16, 18 and 22, 24, 26, 28) were classified as “shunted.” Shunted fish listed in the recapture file at LGR and reported as released at the LGR adult ladder were classified as “trapped.” Trapped fish were further categorized by their holding time. Holding time was calculated as the elapsed time between the last detection in the shunt pipes (PTAGIS, adjusted for daylight savings) and the time sampled in the trap (NMFS). For the homing success analysis, if a fish fell back and ascended LGR multiple times in a trapping season, it was assigned to the most complex passage route taken. Free passage was considered the least complex route and trapped as the most complex route, with shunted as the intermediate. Fish that were trapped multiple times in a season were eliminated so as not to confound the analysis with multiple handling events. On average, only 1% of trapped fish were trapped multiple times in a season.

Passage route comparisons were only made when passage route use occurred across similar date ranges during the trapping season. In 2012–2015, the gate between the ladder entrance and exit was closed throughout the adult trapping season, thereby precluding free passage. Thus, only comparisons between shunted and trapped passage routes were possible for all fish stocks in those years. Given the dates of free passage ladder operations and the arrival distributions of different fish stocks in 2016, homing success comparisons across all three passage routes (free passage, shunted, and trapped) were only possible for Sockeye Salmon and spring- and summer-run Chinook Salmon (Figure 1.2). For steelhead and fall-run Chinook Salmon, only comparisons between shunted and trapped passage routes were possible.

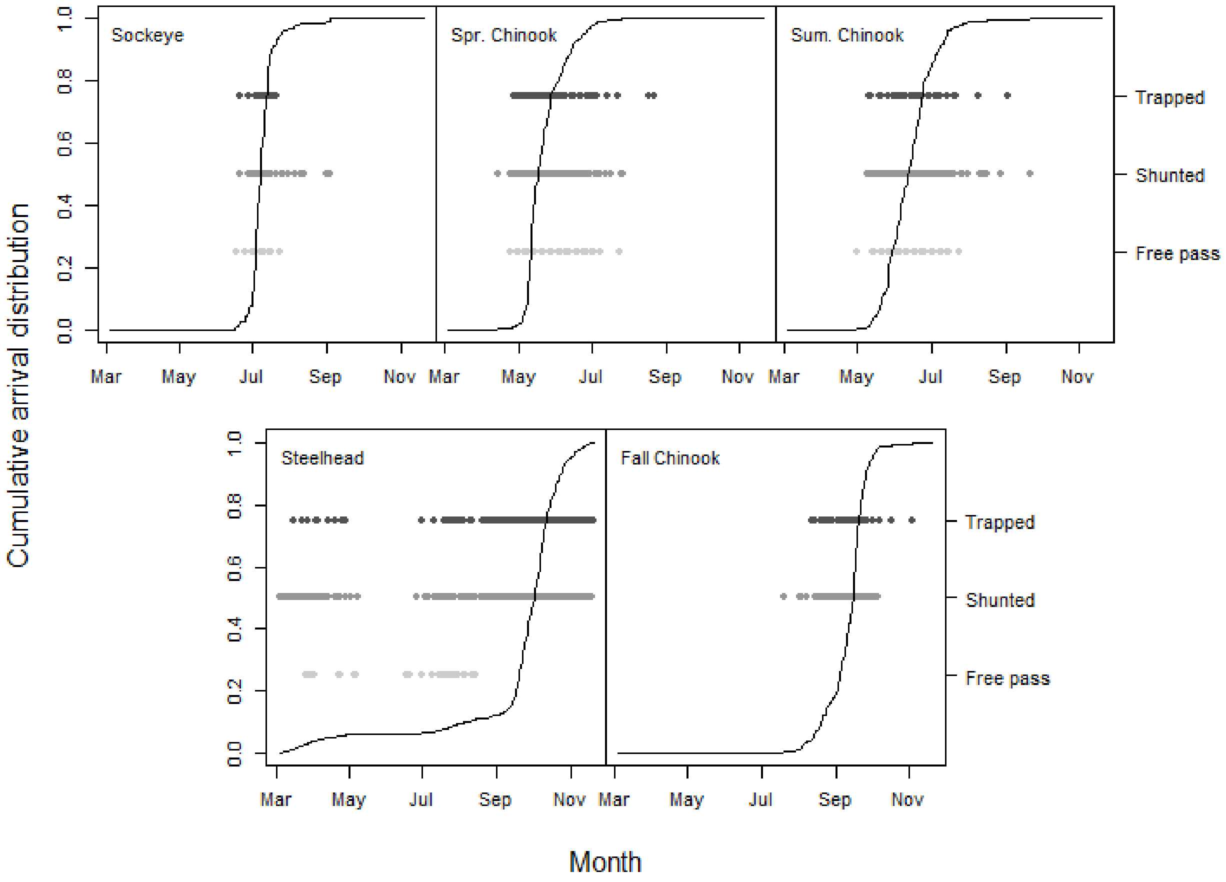

FIGURE 1.2.—Cumulative arrival distribution and dates of passage by route for a given fish stock that ascended Lower Granite Dam during the 2016 trapping season. The Lower Granite Dam adult trap was operated from March 4 to November 20 2016.

Statistical analyses.— The year 2016 was the first year both entrance and exit PIT-tag arrays existed at LGR, allowing measurement of through-ladder transit time. Transit times within the ladder were calculated as the elapsed time between the first detection at the LGR adult ladder entrance and the last detection at the ladder weir or exit. For each fish stock (e.g. spring-run Chinook Salmon), arithmetic mean transit times by passage route within the LGR ladder were estimated. In addition, transit times were compared between passage routes using generalized linear models based on a gamma distribution and inverse link (McCullagh and Nelder 1989). Comparisons tested the hypothesis that transit time increased with route complexity (i.e. free passage < shunted < trapped). Within each stock, critical values α were corrected for multiple comparisons using the Bonferroni correction α/m, where α was set to 0.10 and m is the number of comparisons. Given that the capability to compute an individual's transit time through the ladder is independent of upstream detection and recapture capabilities, transit times were based on all known-source Snake River salmonids ascending the LGR adult ladder. Additionally, for fish that fell back and ascended multiple times, only the time of the first passage attempt was recorded so as not to confound passage time with the effects of possible exhaustion from multiple passage attempts.

To compare homing success probability across passage route use, an index of homing success was derived based on PIT-tag detection histories at tributaries and hatcheries above LGR, queried from the trapping season start date to May 31 of the following year. Homing was classified as successful if a fish was either recaptured or detected at one or more PIT-tag arrays near and downstream of either of its respective juvenile mark- or release-sites. Homing was classified as unsuccessful if a fish was detected elsewhere upstream or not detected at all. On average, 98% of fish classified as homing unsuccessfully were undetected after ascending LGR.

Homing success probabilities by stock of a given rear-type (i.e. hatchery or wild) were estimated by binomial proportions and one-tailed t-tests were used to compare homing success probabilities of fish classified by passage route at the LGR adult ladder. Comparisons tested the hypothesis that estimated probabilities of homing success decreased with route complexity (i.e.

free passage > shunted > trapped). Within each stock of a given rear-type, critical values α were also corrected for multiple comparisons using the Bonferroni correction. Because access to the various passage routes in the LGR ladder varied across the adult migration season and depended on sampling goals for target populations (e.g. stock from a given hatchery), adult detections within a given stock and rear-type were pooled across mark-sites (i.e. where a fish was initially tagged as a juvenile) if passage route proportions were similar in a given year (based on chi-square tests of homogeneity; Zar 2010). Weighted averages were computed across heterogeneous groups for each stock of a given rear-type. Averages were weighted inversely proportional to the variance of the binomial estimates of homing success. It is important to note that the indices of homing success should not be compared across fish stocks because migration distances, access to detection facilities, and detection probabilities at these facilities vary across the Snake River basin.

Fish were included in the homing success analysis only if at least one of their juvenile mark- or release-sites had a PIT-tag array or mechanism for recapture installed and operational. Sometimes large proportions of known-source fish were excluded from this analysis because neither their juvenile mark- nor release-site had a tag detection or recovery mechanism in place (i.e. they could not be detected to home). Although the proportion of spring-run Chinook Salmon without home detection or recovery mechanisms steadily decreased from 17.9% in 2012 to 7.9% in 2016, larger proportions of steelhead and fall-run Chinook Salmon lacked the potential for upstream detection (Table 1.1). Between the years 2012 to 2015, a quarter of steelhead and over half of fall-run Chinook Salmon were excluded from this analysis because they were unable to be detected to home (Table 1.1). These proportions increased in 2016 with 36.7% of steelhead and 93.8% of fall-run Chinook Salmon undetectable to home (Table 1.1).

TABLE 1.1.—The total number of known-source, PIT-tagged adult salmonids that ascended Lower Granite Dam by year and stock. The table reports the percent of a given stock excluded from this analysis because neither its mark- nor release- site were equipped for tag detection or recapture.

	Stock											
	Sockeye		Spr. Chinook		Sum. Chinook		Steelhead		Fall Chinook		Total	
Year	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
2012	61	0.0	1,338	17.9	397	0.0	1,841	26.8	1,995	52.2	5,632	31.5
2013	55	0.0	985	17.0	444	0.0	1,295	17.5	1,064	49.7	3,843	24.0
2014	41	0.0	1,403	16.0	479	0.0	2,213	24.0	1,703	61.4	5,839	30.8
2015	3	0.0	1,643	4.9	372	0.0	1,983	21.8	1,004	50.4	5,005	20.4
2016	122	0.0	838	7.9	361	0.0	1,364	36.8	177	93.8	2,862	25.7
Total	282	0.0	6,207	12.5	2,053	0.0	8,696	25.1	5,943	56.0	23,181	27.1

Results

Transit time through ladder.—During the 2016 trapping season, 2,440 tagged known-source adult Snake River salmonids ascended LGR. Mean transit time from ladder entry to exit was significantly longer for trapped fish of every stock (P < 0.01) and ranged from 13.57 ($\widehat{SE}$ = 1.6) to 20.08 ($\widehat{SE}$ = 2.72) h (Table 1.2). Differences between shunted and free-passed transit times varied by stock. Free-passed Sockeye Salmon had a longer transit time compared to shunted fish (P = 0.91; Table 1.2). Free-passed and shunted summer-run Chinook Salmon had similar mean transit times and were not significantly different (P = 0.48; Table 1.2). However, free-passed spring-run Chinook Salmon had a significantly shorter transit time compared to shunted as well as trapped fish (P < 0.01). Mean transit times for free-passed, shunted, and trapped spring-run Chinook Salmon were 2.70 ($\widehat{SE}$ = 0.17), 3.71 ($\widehat{SE}$ = 0.20), and 18.75 ($\widehat{SE}$ = 1.42) h, respectively (Table 1.2).

TABLE 1.2.—Time from first detection at the entrance to last detection at the exit in LGR adult ladder, by passage route and fish stock (hatchery- and wild-origin fish pooled) in 2016. Standard error for the mean is reported parenthetically. I tested three hypotheses: H_0: free passage (FP) ≥ trapped (T) vs. H_A: free passage < trapped, H_0: free passage ≥ shunted (S) vs. H_A: free passage < shunted, and H_0: shunted ≥ trapped vs. H_A: shunted < trapped.

					P-value		
Stock	Route	*n*	Median (h)	Mean (h)	$FP \geq T$	$FP \geq S$	$S \geq T$
Sockeye	Free pass	31	4.77	6.70 (0.72)	**2.09e-7**	0.91	**1.51e-12**
	Shunted	57	4.66	5.69 (0.37)			
	Trapped	26	15.41	16.63 (2.20)			
Spr. Chinook	Free pass	234	1.88	2.70 (0.17)	**7.11e-33**	**2.30e-4**	**4.44e-45**
	Shunted	414	2.40	3.71 (0.20)			
	Trapped	149	16.86	18.75 (1.42)			
Sum. Chinook	Free pass	107	2.06	4.35 (0.73)	**3.02e-7**	0.48	**2.49e-10**
	Shunted	179	2.36	4.38 (0.51)			
	Trapped	64	20.66	20.08 (2.72)			
Steelhead	Shunted	528	3.01	5.74 (0.57)	N/A	N/A	**2.18e-12**
	Trapped	496	9.32	14.51 (0.78)			
Fall Chinook	Shunted	101	2.90	4.27 (0.4)	N/A	N/A	**7.25e-11**
	Trapped	54	7.96	13.57 (1.60)			

However, reporting mean transit times for trapped fish is deceptive because of the bimodal distributions created from overnight holding (Figure 1.3). Fish diverted to the trap during daytime sampling operations had a mean transit time of 13.22 ($\widehat{SE}$ = 0.67) h, while fish captured outside of daily sampling operations (i.e., 1500 to 0700 PDT) and held until the next day had a mean transit time of 19.67 ($\widehat{SE}$ = 1.11) h. On average, 25.7% of the trapped salmonids at LGR were caught after daytime sampling operations and held overnight (i.e., 2012–2016).

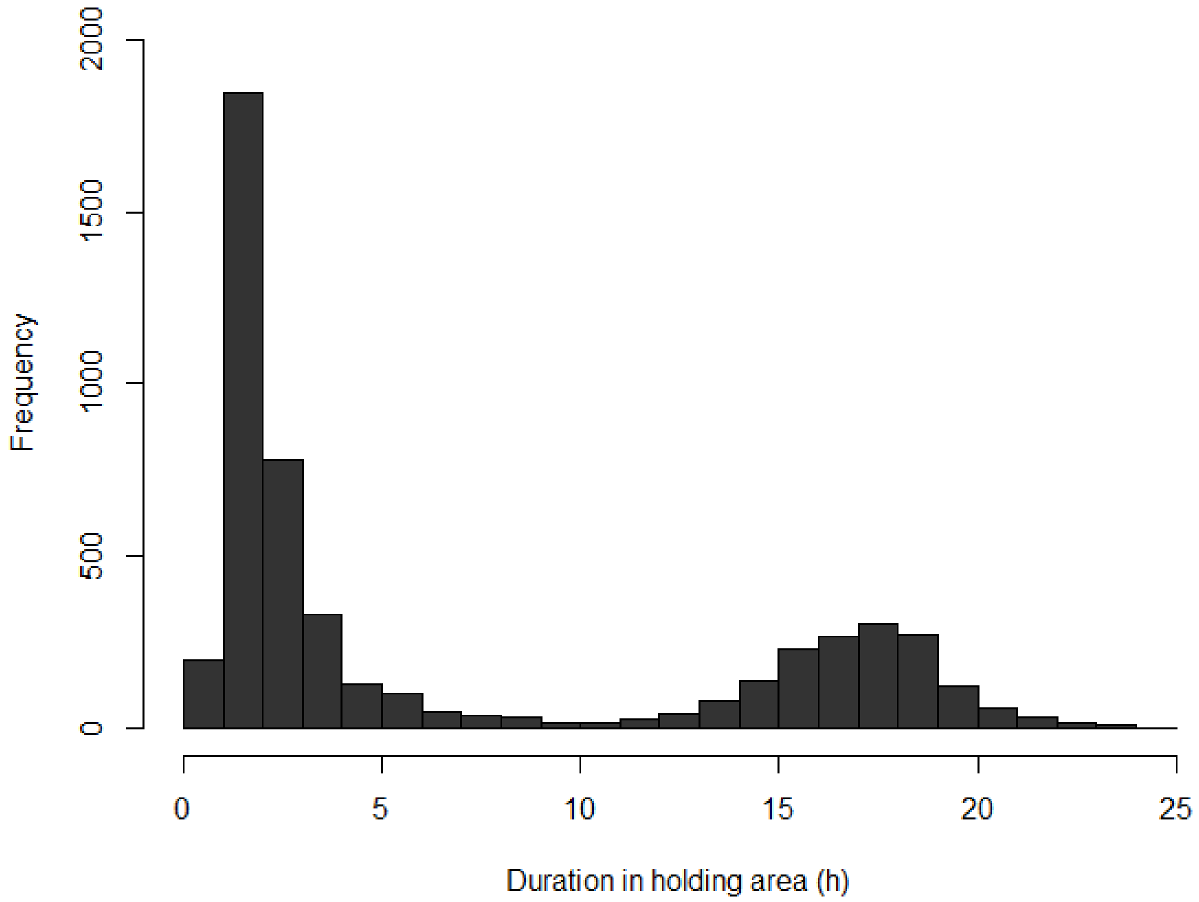

FIGURE 1.3.—Holding time distribution for fish trapped during their ascension of the LGR adult ladder across years 2012–2016.

Homing success.—Given the stark differences in holding time, homing success was compared between free-passed, shunted, and two categories of trapped fish—fish trapped and held for <10 h (short-holdovers) and fish trapped and held for ≥10 h (long-holdovers). Using one-dimensional optimization (Brent 1973), 10 h was identified as the minimum between the bimodal peaks for holdover times pooled across years 2012–2016 (Figure 1.3).

In the 2016 trapping season, 2,102 PIT-tagged adult salmonids that met study requirements ascended LGR. Most of these salmonids were of hatchery-origin (84.6%). Of the three stocks that had access to free passage, minimal evidence supported my hypothesis that homing success decreased with increasing passage route complexity. Only free-passed hatchery-origin summer-run Chinook Salmon and wild-origin spring-run Chinook Salmon demonstrated higher homing success compared to other routes. Hatchery-origin summer-run Chinook Salmon that ascended LGR via free passage had an estimated probability of homing success of 79.2% ($\widehat{SE}$ = 4.1), which was significantly higher than the estimated 61.3% ($\widehat{SE}$ = 8.7) for short-holdover fish (P = 0.02; Table 1.3). Wild-origin spring-run Chinook salmon that ascended LGR via free passage had an estimated homing success probability of 66.7% ($\widehat{SE}$ = 0.3), which was significantly higher than the estimated 33.3% ($\widehat{SE}$ = 25.0) for long-holdover trapped fish (P = 0.01). However, sample size for long-holdover fish was small. Overall, there was no significant difference in estimated probability of homing success between free passage and the two other routes in 2016 (P > 0.025; Table 1.3). Additionally, for all stocks in 2016, weighted averages yielded no significant difference (P > 0.025) in estimated probability of homing success between the two holdover groups of trapped fish (Table 1.3). This was also observed across years 2012–2016 (Table 1.4).

In examining standard operating procedure, where trapped and shunted were the only routes of passage through the LGR adult fish ladder, weighted averages across years 2012–2016 yielded no significant difference (P > 0.033) in average estimated probability of homing success, apart from wild-origin adult steelhead. Across years 2012–2016, shunted wild-origin steelhead had an average estimated probability of homing success of 76.2% ($\widehat{SE}$ = 2.9), which is significantly higher than the 59.0% ($\widehat{SE}$ = 9.1) for short-holdover trapped fish (P = 0.03; Table 1.4).

TABLE 1.3.—For 2016, the total number of adult migrants at LGR by route of passage (n). The table reports weighted averages (%) with standard errors in parenthesis. Trapped$_{\text{Long}}$ is the category for fish that were trapped and held in the holding area for ≥10 h; Trapped$_{\text{Short}}$ were held in the holding area for <10 h. P-values were derived from a one-tailed t-test. I tested four hypotheses: H_0: trapped$_{\text{short}}$ (T_S) ≤ trapped$_{\text{long}}$ (T_L) vs. H_A: trapped$_{\text{short}}$ > trapped$_{\text{long}}$, H_0: free passage (FP) ≤ trapped$_{\text{long}}$ vs. H_A: free passage > trapped$_{\text{long}}$, H_0: free passage ≤ trapped$_{\text{short}}$ vs. H_A: free passage > trapped$_{\text{short}}$, H_0: free passage ≤ shunted (S) vs. H_A: free passage > shunted.

		Trapped$_{\text{Long}}$		Trapped$_{\text{Short}}$		Shunted		Free Passage		*P*-values			
Rear	Stock	*n*	%	*n*	%	*n*	%	*n*	%	$T_S \leq T_L$	$FP \leq T_L$	$FP \leq Ts$	$FP \leq S$
H	Sockeye	12	66.7 (13.6)	16	75.0 (10.8)	58	69.0 (6.1)	34	79.4 (6.9)	0.31	0.19	0.36	0.14
	Spr. Chinook	53	41.3 (9.0)	75	48.3 (10.4)	349	36.8 (0.4)	202	39.4 (17.3)	0.33	0.53	0.67	0.42
	Sum. Chinook	24	66.7 (9.6)	31	61.3 (8.7)	138	68.8 (3.9)	96	79.2 (4.1)	0.66	0.10	**0.02**	0.04
W	Spr. Chinook	4	33.3 (25.0)	13	77.6 (5.1)	43	72.5 (0.5)	32	66.7 (0.3)	0.09	**0.01**	0.96	0.91
	Sum. Chinook	8	87.5 (11.7)	3	100.0 (0.0)	45	84.4 (5.4)	13	100.0 (0.0)	0.26	0.10	1.00	0.07

TABLE 1.4.—Across all years, 2012–2016, the total number of adult migrants at LGR by route of passage (n). The table reports weighted averages (%) with standard errors in parenthesis. P-values were derived from a one-tailed t-test. I tested three hypotheses: H_0: $\text{trapped}_{\text{short}}$ (T_S) $\leq$ $\text{trapped}_{\text{long}}$ (T_L) vs. H_A: $\text{trapped}_{\text{short}} > \text{trapped}_{\text{long}}$, H_0: shunted (S) $\leq$ $\text{trapped}_{\text{long}}$ vs. H_A: shunted $> \text{trapped}_{\text{long}}$, and H_0: shunted $\leq \text{trapped}_{\text{short}}$ vs. H_A: shunted $> \text{trapped}_{\text{short}}$.

Rear	Stock	$\text{Trapped}_{\text{Long}}$		$\text{Trapped}_{\text{Short}}$		Shunted		P-values		
		n	%	*n*	%	*n*	%	$T_S \leq T_L$	$S \leq T_L$	$S \leq T_S$
H	Sockeye	19	61.1 (8.8)	26	65.2 (10.9)	194	69.0 (3.9)	0.40	0.28	0.37
	Spr. Chinook	240	26.4 (6.5)	359	41.1 (5.3)	3931	29.4 (6.6)	0.04	0.43	0.75
	Sum. Chinook	119	83.9 (3.7)	141	89.1 (4.8)	1117	88.4 (2.9)	0.22	0.28	0.55
	Steelhead	462	49.2 (4.2)	884	50.2 (4.7)	3743	50.1 (2.2)	0.44	0.44	0.51
	Fall Chinook	558	6.6 (3.2)	1748	9.2 (3.7)	243	11.3 (5.7)	0.32	0.29	0.40
W	Spr. Chinook	52	74.5 (5.1)	93	80.4 (1.3)	493	81.3 (3.4)	0.10	0.26	0.55
	Sum. Chinook	36	90.6 (0.9)	36	84.8 (1.9)	467	88.8 (1.7)	0.99	0.66	0.24
	Steelhead	89	64.4 (8.7)	178	59.0 (9.1)	1111	76.2 (2.9)	0.66	0.14	**0.03**

Discussion

My study shows that trapping indeed delays transit time over LGR compared to other routes, but I did not find robust evidence that trapping operations at the LGR adult ladder impede adult homing success to upstream tributaries. Additionally, there appears to be no difference between the shunted and free passage routes in terms of transit time and probability of upstream homing success. These findings suggest that passage route over LGR alone does not inhibit homing success at the stock level and that the shunted and free passage routes may not differ in providing an uninhibited, straight-through route of passage. However, my findings do highlight how current operations at the LGR adult fish ladder may be modified to further accommodate migration success. This is especially important as other migration stressors, such as warming water temperature, increase in frequency and magnitude due to climate change (Mote et al. 2003; Stewart et al. 2005; Mantua et al. 2010).

My findings are contrary to other studies examining the relationship between trapping/passage route and subsequent migration success. This may be due to differences in study structure. Other studies investigated trapping effects on a single run of a given stock (e.g. Wenatchee River Basin Sockeye Salmon; Murauskas et al. 2014), but due to sample size inadequacies across passage route use at LGR, my study reported estimates of homing success by averaging across runs of a given stock. Run-specific comparisons of passage route use and homing success may illuminate the differences I hypothesized. Additionally, my study examined homing success of known-source fish PIT-tagged as juveniles whereas similar studies tagged the adult migrants studied (Reischel and Bjornn 2003; Bromaghin et al. 2007; Keefer et al. 2017). Thus, results of decreased migration success because of trapping or passage route complexity may be the result of an interaction between trapping/passage route and adult tagging.

Although I did not find a difference in homing success across passage route use, I did identify how operations at the LGR adult fish ladder and trapping facility can further minimize migration stress and delay. For example, I discovered that the nature of the trapping operations at LGR creates a strong bimodal distribution of holding times (Figure 1.3). Adult salmonids diverted to the trap in the late afternoon and evening are held overnight to be sampled the next morning. Although sampling of trapped adult salmonids officially ceases at 1500 PDT, the holding area may still contain fish at the end of the trapping day during peak migration and when the trap is running under modified protocol. Thus, fish shunted to the holding area as early as 1330 PDT may not be sampled until the following morning (Figure 1.4). This pattern was consistent with previous years, 2012–2015. Albeit this practice did not inhibit the subsequent probability of homing success, it does not align with priorities put forth by managing agencies to reduce passage delay for adult migrants in the Federal Columbia River Power System (USACE et al. 2017). Furthermore, operations that delay migration may indirectly reduce reproductive success via energy depletion (Brown et al. 2006; Caudill et al. 2007), fallback behavior (Boggs et al. 2004), premature mortality (Gilhousen 1990; Geist et al. 2000; Cooke et al. 2006), and stress-induced impairment of gonad development (Pankhurst and Dedualj 1994; Cooke et al. 2006). These risks to reproductive success are compounded in years with high water temperature, when adult migrants are already exposed to stressful hydrosystem passage conditions (Crossin et al. 2008; Keefer et al. 2010; Strange 2012). Trap operators at LGR and other dams in the basin acknowledge this by employing modified trapping protocol when in-ladder water temperatures exceed an established value (USACE 2017). However, decreasing the duration a fish is kept in the holding area is an additional mitigation action that can further accommodate migration success.

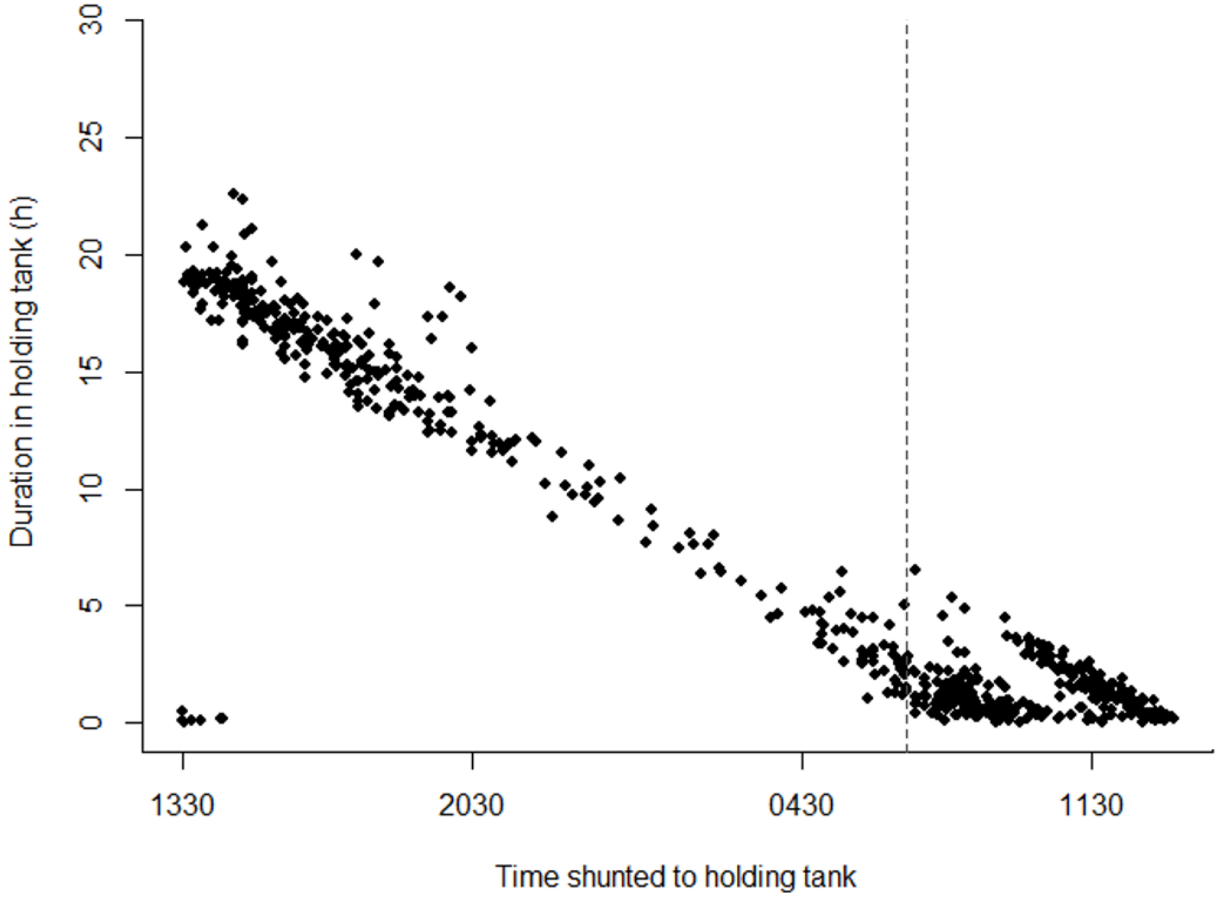

FIGURE 1.4.—Time shunted to the holding area and duration in holding area prior to sampling at the trap for all stocks in 2016. The dashed line delineates 0700 PDT, when daily trap operations begin. This pattern was consistent with previous years, 2012–2015.

In addition to decreasing time in the holding area, maintaining some level of systematic free passage at the LGR adult ladder might be prudent. For example, by allowing 33.2% of summer-run Chinook Salmon free passage over LGR in 2016, the overall homing success of these migrants was 71.3%. Without free passage, the overall estimated probability of homing success would have been closer to 67.4%. Thus, allowing free passage improved the probability of homing success by a factor of 1.06. Given that salmonids likely used multiple migration strategies pre-hydrosystem construction, the Independent Scientific Group (1996) asserted that a "diversity of management schemes should be used to assist migration." In reference to smolt transportation, the Independent Scientific Advisory Board (1998) called for a strategy to "[spread] the risk of negative outcomes across alternative routes of hydroelectric passage." Although there is little evidence that distinguishes the homing success and transit time of shunted and free passage fish, maintaining systematic access to free passage aligns with the "spread the risk" strategy already employed in the Columbia and Snake River basins for downstream passage of juvenile salmonids. While this "spread the risk" strategy primarily refers to spill-transport operations for out-migrating juveniles, it should be applicable to adult strategies as well. Diversifying passage route options at LGR to include a simplified route spreads the risk of mortality and is consistent with salmonid recovery goals in the basin.

Spreading the risk may be especially pertinent for steelhead and fall-run Chinook Salmon that were not given access to free passage in 2016 and have runs with greater targeted sampling frequency at LGR. For example, the proportion of Clearwater Hatchery adult steelhead trapped and released within a given year ranged between 76.2% and 95.3% from 2013 to 2016. The proportion of Dworshak Hatchery fall-run Chinook Salmon trapped and released in a given year ranged between 83.3% to 95.3% from 2012 to 2016. In comparison, the proportion of a given Chinook and Sockeye Salmon run selected for trapping rarely exceeded 20%. Given that handling stress has been documented in *O. mykiss* (Vijayan and Moon 1992; Clements et al. 2002) and both steelhead and fall-run Chinook Salmon experience other migration stressors in the hydrosystem (Keefer et al. 2004; Goniea et al. 2006; Caudill et al. 2007), spreading the risk of negative outcomes from trapping and handling at LGR to include free passage is a reasonable mitigation action. Extending free passage operations beyond the month of July would also allow for upriver migration evaluation of free-passed steelhead and fall-run Chinook Salmon.

Furthermore, maintaining and extending free passage ladder operations will address current data limitations hindering a more thorough analysis. With only one year of data for three of the five stocks studied, my results are not a thorough evaluation of the effects of free passage route use on homing success. Additionally, my results are confounded with a potential year effect as well as the 2016 installation of a water cooling system in the adult fish ladder to mitigate thermally-induced passage delays (Anchor QEA LLC et al. 2017).

However, to take full advantage of free passage ladder operations in evaluating homing success across passage routes, detection capability to home must also be considered when designing PIT-tag studies. The lack of PIT-tag arrays or recapture mechanisms at hatcheries and tributaries historically excluded large proportions of spring-run Chinook Salmon and currently preclude substantial proportions of steelhead and fall-run Chinook Salmon from being analyzed. This issue is prevalent for hatchery-origin fish that are marked at one site and released at another, leading to imperfect detection or recovery capability. I acknowledge that some release-sites, like those in the mainstem Snake River, are not conducive to in-stream PIT-tag array installation and operation. This is a particular issue for detecting homing success of fall-run Chinook Salmon as they are mainstem spawners typically outplanted in the Snake River downstream of Hells Canyon Dam. However, more work can be done to ensure that other mark- and release-sites like hatcheries and hatchery acclimation ponds are equipped for detecting and reporting individual returning migrants. For wild-origin steelhead and spring-run Chinook Salmon, smolt traps in the Clearwater, Grande Ronde, and Salmon Rivers must also be paired with adult detection equipment to monitor return. Designing juvenile PIT-tag studies with adult homing detection in mind will increase the holistic utility of a PIT-tag and expand migration and survival studies beyond the hydrosystem.

Management implications.—Lower Granite Dam (LGR) is the last anthropogenic hurdle for adult salmonids returning to the upper Snake River basin to complete their multi-year migration cycle. LGR is also the last best location to radio-tag adult migrants, sample biological data, and collect broodstock for the upstream hatchery supplementation program in the Snake River basin. Thus, trapping operations at LGR will continue into the foreseeable future. Although I did not conclude that passage route through the LGR adult fish ladder affects homing success for Snake River salmonids, passage route complexity and handling stress may compound with other migration stressors to diminish homing success in the future. Therefore, I encourage maintaining systematic access to free passage as well as decreasing the duration migrants are kept in the holding area prior to sampling. I acknowledge that modifying trap operations may limit sample sizes for research and brood collection (Harmon 2003; Ogden 2016), but the risk of handling and overnight holding must be considered against the benefits of additional data. Considering the adult salmonids at LGR to be the end product of an extensive series of mitigation actions from juvenile to adult, care at this last stop in their migration may be warranted. Such mitigation at the dam would be relatively inexpensive, considering over $0.5B is spent on salmonid recovery in the Columbia and Snake River basins annually (Bonneville Power Administration 2016).

Chapter 2: Should salmonid smolt transportation evaluation consider migration success above Lower Granite Dam?

Abstract

Smolt transportation is a mitigation tool used in the Columbia River basin to increase survival. The efficacy of the downstream transportation program is evaluated using a transport-in-river ratio (TIR) that compares the smolt-to-adult return (SAR) rates of transported smolts to those of in-river smolts. In this evaluation framework, migration success is defined as return to Lower Granite Dam where the transportation program begins, rather than natal sites farther upstream, and is driven by the assumption that transportation does not affect homing ability in river reaches where fish previously migrated in-river. This study used the recently expanded PIT-tag detection network in Snake River tributaries to evaluate this assumption. For hatchery-origin Sockeye Salmon, steelhead, and spring- and summer-run Chinook Salmon across five smolt classes, the average TIR between Lower Granite Dam and natal sites upstream was not significantly different from 1.0, ($\widehat{TIR}$ = 1.04, $\widehat{SE}$ = 0.04). Conclusions for wild-origin steelhead and Chinook Salmon were limited by data resolution, but the mean value for the two stocks analyzed was 1.09 ($\widehat{SE}$ = 0.04). Overall, the current TIR evaluation framework appears adequate for hatchery-origin salmonids, but there was some evidence that the average TIR between Lower Granite Dam and natal sites upstream was significantly greater from 1.0 for wild-origin steelhead and Chinook Salmon. More work should be done to verify this conclusion for these wild-origin fish.

Introduction

In dam-regulated rivers, smolt transportation is a mitigation tool to bypass high-mortality zones and increase out-migration survival (Mills 1991; Ward et al. 1997), with the ultimate goal of increasing adult return (Park 1985). Fisheries researchers have conducted smolt transportation experiments on Atlantic salmon *Salmo salar* in Scotland (Mills 1991, 1994), but smolt transportation is predominantly practiced in the Columbia River basin for Pacific salmonid *Oncorhynchus* spp. recovery (Raymond 1979; Ward et al. 1997). To spread the risk of mortality during juvenile dam passage in the Federal Columbia River Power System, where fish must pass up to eight dams during their migration to sea, federal entities have been transporting salmonid smolts en masse from lower Snake River dams to the base of the hydrosystem since the 1970s (Ebel 1980). Smolts are collected at juvenile bypass facilities, selectively loaded onto barges or trucks, and transported to a release location downstream of Bonneville Dam, the lowermost dam in the system, for subsequent seaward migration (Muir et al. 2006). Smolts that are not transported migrate wholly in-river.

The efficacy of the transportation program is evaluated with a transport-in-river ratio (TIR). TIR—also referred to as T:C (transport-to-control, (Ward et al. 1997), T/I (transport-to-in-river, (Marsh et al. 2005), and T:B (transport-to-bypassed, (Smith et al. 2017)—compares smolt-to-adult return rates of transported smolts to in-river smolts using adult tag detections at Lower Granite Dam (LGR) as the terminus. The gateway into and out of the Snake River hydrosystem, LGR has remained the uppermost passable dam on that river since its completion in 1975 and is the hub for salmonid research and recovery operations. LGR has been a primary location for smolt transportation collection since its construction (Ward et al. 1997) and, historically, was the uppermost location on the Snake River capable of detecting many tagged adults. Although an individual's spawning grounds may be 50 to >700 km farther upstream (Keefer et al. 2008), TIR calculations consider LGR the homing site for Snake River salmonids under the assumption that transportation does not affect homing ability in stream reaches where fish previously migrated in-river (Ebel 1980). This has been perpetuated also in part because of historic tag detection limitations where tags were more easily recovered at dams and hatcheries than on spawning grounds (Ward et al. 1997).

The introduction of passive integrated transponder (PIT) tag technology in upriver tributaries and hatcheries now allows detection of adults at natal sites. Smolts are tagged at their natal sites upstream of LGR and a growing number of these hatchery and release sites are equipped with tag detection arrays or systematic recapture mechanisms—expanding the PIT-tag detection network into upper Snake River tributaries. These detections are remotely uploaded to PTAGIS (www.ptagis.org), a centralized database for PIT-tags in the Columbia River basin, increasing data accessibility. As a result, the fisheries community can now compute adult return rates above LGR for multiple populations and study the effects of transportation on migration success beyond the river reaches through which fish were transported.

Studies have used PIT-tags to study adult migration success within the transported reach (Muir et al. 2006; Keefer et al. 2008) and determined that transportation disrupts the imprinting process across this reach (Bond et al. 2017), and that it reduces homing probability, increases probability of straying, and increases loss below LGR (Keefer et al. 2008). However, the effect of transportation on adult migration success upriver of LGR has not been evaluated with PIT-tag technology. Before PIT-tag technology, previous studies used thermal brands as well as magnetic, coded-wire, dart, and jaw tags to quantify the adult homing success of steelhead *O. mykiss* and Chinook Salmon *O. tshawytscha* to hatcheries and spawning grounds (Ebel et al. 1973; Ebel 1980).

These studies concluded that transportation did not diminish homing success above LGR compared to in-river migration, but they involved adults of unknown origin, required manual tag recovery upstream, and were limited to a few hatchery populations and years. Tag detection efficiency and the number of hatchery populations upstream of LGR have since increased. At the end of 2017, there were 220 active adult PIT-tag interrogation sites at hatcheries and tributaries in the Columbia River basin—61 of which were upstream of LGR.

This study used the recently expanded PIT-tag detection network in Snake River tributaries upstream of LGR to investigate if the current TIR calculation framework—where home is defined as the top of the hydrosystem, rather than natal site—is adequate in assessing the transportation program. More specifically, this study compares the homing success of transported and in-river hatchery- and wild-origin salmonids from LGR to natal sites upstream. If the homing success between these two groups are not equal, as previously assumed, then the current TIR calculation framework used by managers in the basin is not an accurate evaluation metric for the smolt transportation program and must be reconsidered.

Methods

Study population.—All tagging data were retrieved from the publicly accessible Columbia River Basin PIT Tag Information System (PTAGIS; www.ptagis.org), and juvenile transportation histories were determined using data from Columbia River DART (www.cbr.washington.edu/dart). TIRs were retrieved from the Comparative Survival Study 2017 Annual Report (McCann et al. 2017).

Established in 1996, the Comparative Survival Study (CSS) began creating a long-term data set of salmonid migration and survival to assess the efficacy of smolt transportation and in-river migration (McCann et al. 2017). The CSS uses PIT-tag detections paired with bootstrapping estimation to compute TIRs for Major Population Groups (MPGs) in the upper Snake River basin (McCann et al. 2017).

This study included upper Snake River salmonid smolts from 10 hatchery-origin and two wild-origin MPGs from the 2017 CSS Annual Report that migrated in years 2011–2015. The hatchery-origin MPGs represented five populations of spring-run Chinook Salmon three populations of summer-run Chinook Salmon, and one population of Sockeye Salmon and steelhead (Table 2.1). The wild-origin MPGs represented one population each of Chinook Salmon and steelhead (Table 2.1). Consistent with McCann et al. (2017), the adult Chinook Salmon count is the sum of the returning adults that spent 2–4 years at sea and excludes jacks and mini-jacks. The adult counts for steelhead and Sockeye Salmon are the sums of those that spent 1–3 years at sea.

TABLE 2.1. —The Major Population Groups studied, by stock and rear-type.

Rear	Stock	Major Population Group (MPG)
H	Spr. Chinook	Catherine Creek (CATH)
		Clearwater Hatchery (CLWH)
		Dworshak National Fish Hatchery (DWOR)
		Rapid River Hatchery (RAPH)
		Sawtooth Hatchery (SAWT)
	Sum. Chinook	Clearwater Hatchery (CLWH)
		Imnaha Acclimation Pond (IMNAP)[A]
		McCall Hatchery (MCCA)
	Sockeye	Sawtooth Hatchery (SAWT)
	Steelhead	Clearwater River B-Run (CLWR)[B]
W[C]	Chinook	Wild Chinook
	Steelhead	Wild Steelhead

[A] These fish were marked at Lookingglass Hatchery and released at the Imnaha River Weir. The MPG name is consistent with the 2017 Annual CSS Report.

[B] These fish were tagged at Clearwater Hatchery and Dworshak National Fish Hatchery.

[C] Included all wild fish tagged above LGR and detected at LGR during out-migration.

These MPGs were selected because they had an adult detection or recapture mechanism proximal to their mark- and/or release-sites. Some out-migrant classes for a given MPG were excluded from this analysis due to detection capabilities. For example, I excluded the 2014–2015 smolt classes of summer-run Chinook Salmon marked at Clearwater Hatchery because all fish were released at Powell Rearing Pond (POWP), a site with no adult detection capability. Due to more extensive adult detection inconsistencies, I also excluded the 2012 smolt class for spring-run Chinook Salmon marked at Clearwater Hatchery. Clearwater Hatchery spring-run Chinook Salmon were released from four locations from 2011–2015: Clear Creek (CLEARC), Powell Rearing Pond (POWP), Red River Rearing Pond (REDP), and Selway River from its mouth to Moose Creek (km 0-65; SELWY1). Due to detection capability differences by release-site, fish can only be tracked to CLEARC and REDP in all years. Because Clearwater Hatchery is a major rearing source, I did not want to entirely exclude their spring-run Chinook Salmon stock from this analysis. Thus, using a chi-square test, if the proportion of barged to in-river fish were the same for CLEARC and REDP, then I assumed that it was also the same for fish released at POWP and SELWY1. Proportions were not the same in 2012, violating the assumption for POWP and SELWY1 and forcing exclusion from the analysis. I included wild-origin MPGs although up to a third of release groups originated from smolt trap sites lacking proximal adult detection or recovery mechanism.

Statistical analyses.—To address the relationship between barging and the rate of adult return for each MPG with homing detection capability, this study calculated overall TIR with the following equations:

$$\widehat{TIR}_{LGR-LGR} \cdot \widehat{TIR}_{LGR-TRIB} = \widehat{TIR}_{Total} \tag{1}$$

$$\frac{\left(\frac{x_{1T}}{N_T}\right)}{\left(\frac{x_{1R}}{N_R}\right)} \cdot \frac{\left(\frac{x_{2T}}{x_{1T}}\right)}{\left(\frac{x_{2R}}{x_{1R}}\right)} = \frac{\left(\frac{x_{2T}}{N_T}\right)}{\left(\frac{x_{2R}}{N_R}\right)} \tag{2}$$

where N is the number released as smolts, x_1 is the number of returning adults detected at LGR, x_2 is the number of returning adults detected at tributaries upstream of LGR, and the subscripts T and R denote transported and in-river migrants, respectively. Transported fish include fish transported from LGR, Little Goose, and Lower Monumental dams as smolts. $\widehat{TIR}_{LGR-LGR}$ is the TIR computed by CSS and $\widehat{TIR}_{LGR-TRIB}$ is the TIR computed to natal site upstream of LGR. A $\widehat{TIR}_{Total} > 1$ indicates adults barged as smolts return home at a higher rate than in-river migrants, while a $\widehat{TIR}_{Total} < 1$ indicates otherwise. A $\widehat{TIR}_{Total} = 1$ indicates the adult return of transported smolts is equal to the adult return of in-river smolts.

Variance for $\widehat{TIR}_{Total}$ was calculated using Goodman’s exact formula for the variance of a product. CSS reports 90% nonparametric confidence intervals, so standard errors were approximated from the CSS results using the following equation:

$$SE\left(\widehat{TIR}_{LGR-LGR}\right) = \frac{Upper\ bound - lower\ bound}{1.645 * 2} \tag{3}$$

This estimate of standard error assumes the CSS TIRs are normally distributed and the confidence intervals have asymptoted to their normal theory equivalent.

$\widehat{TIR}_{LGR-TRIB}$ is computed based on the maximum likelihood estimates (MLE) from the likelihood model:

$$L = \binom{N_R}{x_R}(p_R)^{x_R}(1-p_R)^{N_R-x_R} \cdot \binom{N_T}{x_T}(p_R \cdot TIR)^{x_T}(1-p_R \cdot TIR)^{N_T-x_T} \quad (4)$$

$$TIR = \frac{p_T}{p_R} \quad (5)$$

$$p_R = \frac{x_R}{N_R} \quad (6)$$

The maximum likelihood estimate of $\widehat{TIR}_{LGR-TRIB}$ is:

$$\widehat{TIR}_{LGR-TRIB} = \frac{x_T \cdot N_R}{x_R \cdot N_T} \quad (7)$$

and its associated variance is:

$$Var\left(\widehat{TIR}_{LGR-TRIB}\right) = (\widehat{TIR}_{LGR-TRIB})^2[CV(p_T)^2 + CV(p_R)^2] \quad (8)$$

where p_T is the recovery fraction of N_T and p_R is the recovery fraction of N_R. The program USER was used to find the MLE and the variance estimate of $\widehat{TIR}_{LGR-TRIB}$. A likelihood ratio test was used to test whether the $\widehat{TIR}_{LGR-TRIB}$ was significantly different from 1.0.

Weighted averages for $\widehat{TIR}_{LGR-LGR}$, $\widehat{TIR}_{LGR-TRIB}$, and $\widehat{TIR}_{Total}$ were computed across all MPGs to summarize results. Weighted regressions were also conducted to examine the effect of out-migration year, MPG, and species on $\widehat{TIR}_{Total}$ and $\widehat{TIR}_{LGR-TRIB}$. Both the average and regressions were weighted by $\frac{1}{CV^2}$ so that variance estimates were no longer a function of TIR (see Equation 8). Lastly, a simple linear regression was conducted to examine the relationship between $\widehat{TIR}_{LGR-LGR}$ and $\widehat{TIR}_{LGR-TRIB}$. This study used a critical value of 0.10 for all comparisons.

Results

Hatchery-origin adult salmonids with different juvenile transportation histories were detected to their natal sites upstream of LGR at similar proportions. The overall weighted average of $\widehat{TIR}_{LGR-TRIB}$ across all hatchery-origin MPGs and out-migrant classes was 1.04 ($\widehat{SE}$ = 0.04) and was not significantly different from 1.0 (P > 0.10; Table 2.2). However, of the 10 hatchery-origin MPGs, one group did have a $\widehat{TIR}_{LGR-TRIB}$ value significantly greater than 1.0 (P < 0.01). Dworshak Hatchery spring-run Chinook Salmon had an across-year weighted average $\widehat{TIR}_{LGR-TRIB}$ value of 1.28 ($\widehat{SE}$ = 0.08; Table 2.3), indicating that transported smolts were detected to home at a greater proportion than those that migrated in-river. This was an exception to the general pattern, however. Overall, I did not find evidence to refute the assumption that juvenile transportation history affects homing success between LGR and natal site for hatchery-origin adult salmonids. However, juvenile transportation history does appear to affect smolt-to-adult return to LGR. The weighted average of $\widehat{TIR}_{LGR-LGR}$, as reported by the CSS, was 1.38 ($\widehat{SE}$ = 0.17; Table 2.2) and significantly greater than 1.0 (P = 0.10). Therefore, the TIR calculation framework for evaluating the smolt transportation program with respect to hatchery-origin salmonids is adequate.

TABLE 2.2.—Across-year weighted averages of $\widehat{TIR}_{LGR-LGR}$ as reported by the CSS, $\widehat{TIR}_{LGR-TRIB}$, and $\widehat{TIR}_{Total}$ by Major Population Group. Bolded cells signify values significantly different from 1.0 at $\alpha = 0.10$, using a two-tailed t-test.

Rear type	Major Population Group	$\widehat{TIR}_{LGR-LGR}$	$\widehat{TIR}_{LGR-TRIB}$	$\widehat{TIR}_{Total}$
Hatchery	SAWT Sockeye	**0.73 (0.11)**	1.03 (0.21)	0.81 (0.26)
	CATH Spring Chinook	1.38 (0.31)	0.89 (0.11)	1.13 (0.14)
	CLWH Spring Chinook	0.92 (0.14)	1.06 (0.11)	0.94 (0.07)
	DWOR Spring Chinook	1.03 (0.21)	**1.28 (0.08)**	1.28 (0.21)
	RAPH Spring Chinook	**1.52 (0.23)**	1.01 (0.16)	1.59 (0.38)
	SAWT Spring Chinook	1.71 (0.46)	1.11 (0.13)	2.07 (0.84)
	CLWH Summer Chinook	**0.59 (0.14)**	0.95 (0.10)	**0.55 (0.11)**
	IMNAP Summer Chinook	2.58 (1.25)	1.00 (0.05)	2.72 (1.46)
	MCCA Summer Chinook	1.74 (0.47)	0.98 (0.03)	1.73 (0.48)
	CLWR B-Run Steelhead	1.09 (0.06)	1.06 (0.13)	1.16 (0.16)
	Weighted average	**1.38 (0.17)**	1.04 (0.04)	**1.46 (0.21)**
Wild	Chinook	1.68 (0.57)	1.03 (0.05)	1.65 (0.51)
	Steelhead	**1.59 (0.33)**	**1.17 (0.05)**	**1.84 (0.35)**
	Weighted average	**1.64 (0.33)**	**1.09 (0.04)**	**1.74 (0.31)**

TABLE 2.3.—$\widehat{TIR}_{LGR-TRIB}$ values for hatchery-origin Major Population Groups. Bolded cells denote values significantly different from 1.0 at $\alpha = 0.10$, using a likelihood ratio test for an MPG in a given year and a two-tailed t-test for weighted averages.

Year	SAWT Sockeye	CATH Spring Chinook	CLWH Spring Chinook	DWOR Spring Chinook	RAPH Spring Chinook	SAWT Spring Chinook	CLWH Summer Chinook	IMNAP Summer Chinook	MCCA Summer Chinook	CLWR B-run Steelhead	Weighted average
2011	1.38 (0.58)	1.07 (0.09)	1.29 (0.14)	1.34 (0.62)	1.10 (0.45)	1.09 (0.12)	1.00 (0.32)	0.95 (0.10)	**0.89** **(0.07)**	**1.21** **(0.12)**	**1.13** **(0.05)**
2012	0.94 (0.21)	1.07 (0.06)	N/A	1.15 (0.31)	1.23 (0.50)	0.91 (0.14)	0.77 (0.32)	1.07 (0.08)	1.01 (0.06)	**1.36** **(0.23)**	1.06 (0.06)
2013	**1.62** **(0.46)**	**0.83** **(0.09)**	1.04 (0.20)	1.24 (0.38)	**0.38** **(0.18)**	0.87 (0.11)	1.10 (0.22)	0.99 (0.10)	0.95 (0.06)	0.82 (0.25)	0.98 (0.10)
2014	0.82 (0.14)	N/A[B]	0.75 (0.25)	1.12 (0.36)	1.09 (0.44)	1.07 (0.21)	N/A	**0.83** **(0.09)**	1.06 (0.09)	0.86[C] (0.14)	0.95 (0.05)
2015[A]	**0.40** **(0.33)**	**0.60** **(0.22)**	1.17 (0.08)	1.53 (0.25)	1.28 (0.68)	1.39 (0.44)	N/A	1.14 (0.20)	1.00 (0.08)	N/A	1.09 (0.15)
Weighted average	1.03 (0.21)	0.89 (0.11)	1.06 (0.11)	**1.28** **(0.08)**	1.01 (0.16)	1.11 (0.13)	0.95 (0.10)	1.00 (0.05)	0.98 (0.03)	1.06 (0.13)	1.04 (0.04)
		1.08 (0.06)					0.98 (0.03)				

[A] Incomplete. 2-salt returns through September 15, 2017.

[B] The CSS 2017 Annual Report did not report a 2014 TIR value citing "too few adults in Transport and/or C_0 group to estimate TIR."

[C] Incomplete adult returns until 3-salt returns (if any) occur after September 15, 2017 at Lower Granite Dam.

In contrast to hatchery-origin salmonids, there is some evidence that wild-origin adults with transported juvenile histories have a higher probability of homing success between LGR and natal site compared to those with in-river histories. This is particularly true for steelhead. Although both wild-origin Chinook and steelhead had one out-migrant class with a $\widehat{TIR}_{LGR-TRIB}$ value significantly greater than 1.0 (P < 0.10), only steelhead had an across-year weighted average significantly greater than 1.0 (P = 0.02). Across all years, wild-origin steelhead had a $\widehat{TIR}_{LGR-TRIB}$ value of 1.17 ($\widehat{SE}$ = 0.05; Table 2.4). For wild-origin Chinook and steelhead overall, the weighted average of $\widehat{TIR}_{LGR-TRIB}$ was 1.09 ($\widehat{SE}$ = 0.04; Table 2.2) and was significantly greater than 1.0 (P = 0.04). Given that the weighted average of $\widehat{TIR}_{LGR-LGR}$ as reported by CSS was 1.64 ($\widehat{SE}$ = 0.33; Table 2.2) for these population groups, it appears that transportation increases smolt-to-adult return for wild-origin salmonids.

TABLE 2.4.—$\widehat{TIR}_{LGR-TRIB}$ for wild-origin Major Population Groups. Bolded cells denote values significantly different from 1.0 at $\alpha = 0.10$, using a likelihood ratio test for an MPG in a given year and a two-tailed t-test for weighted averages.

Year	Chinook	Steelhead	Weighted average
2011	1.18 (0.04)	**1.32 (0.05)**	1.25 (0.07)
2012	**1.12 (0.03)**	1.11 (0.10)	1.12 (0.01)
2013	1.00 (0.08)	1.12 (0.11)	1.06 (0.06)
2014	0.92 (0.19)	1.13 (0.14) [B]	1.02 (0.10)
2015	0.94 (0.16) [A]	N/A	N/A
Weighted average	1.03 (0.05)	**1.17 (0.05)**	**1.09 (0.04)**

[A] Incomplete. 2-salt returns through September 15, 2017.

[B] Incomplete until 3-salt returns (if any) occur after September 15, 2017 at Lower Granite Dam.

Lastly, I found no evidence for an association between $\widehat{TIR}_{LGR-LGR}$ and $\widehat{TIR}_{LGR-TRIB}$ for hatchery-origin fish, with an r^2 value of 0.005 (P = 0.64). The same comparison for wild-origin fish had an r^2 value of 0.297 (P = 0.13).

Discussion

For hatchery-origin fish, this study supports the current TIR calculation framework where average migration success is defined as smolt-to-adult return to LGR, rather than to natal site. With $\widehat{TIR}_{LGR-TRIB}$ values approximate to 1.0, this study indicated that transportation does not affect homing ability in upper river reaches where hatchery-origin fish previously migrated in-river and is consistent with previous findings (Ebel et al. 1973; Slatick et al. 1975; Ebel 1980). However, there was statistical evidence suggesting that $\widehat{TIR}_{LGR-TRIB}$ is >1.0 for wild-origin salmonids. Although this might suggest that the current TIR calculation framework reports underestimates, it may also be an issue of data resolution. Limited conclusions can be made from the wild-origin data given the aggregation approach used by the Comparative Survival Study (CSS) to increase the sample size of wild-origin Chinook Salmon and steelhead MPGs. Whereas hatchery-origin MPGs in the CSS were defined by their hatchery of origin (e.g. SAWT Spring Chinook), wild-origin Chinook Salmon and steelhead were not separated by mark-site, stream, or river basin of origin. Instead, due to sample size inadequacies, the CSS reported wild steelhead and Chinook Salmon in aggregate. As a result, heterogeneous proportions of populations are represented across wild fish with transported and in-river juvenile histories. This can lead to inconsistent comparisons.

For example, the upstream homing success of the 2011 out-migrant class of wild steelhead was significantly greater than 1.0, with a $\widehat{TIR}_{LGR-TRIB}$ value of 1.32 ($\widehat{SE}$ = 0.05). However, the populations represented by returning adult steelhead from the 2011 smolt class were not comparably proportional across juvenile histories. For the 2011 smolt class, the transported steelhead returning to LGR as adults were exclusively from the Imnaha River basin, while two-thirds of the in-river steelhead were from the Clearwater River basin. Thus, $\widehat{TIR}_{LGR-TRIB}$ compares smolt-to-adult return of two completely different populations. This was also observed for the 2012 and 2013 out-migrant classes of wild-origin steelhead. Similar heterogeneity across out-migrant categories was also observed for wild-origin Chinook Salmon. Therefore, although there is evidence suggesting that $\widehat{TIR}_{LGR-TRIB}$ may be >1.0 on average for wild-origin fish, I cannot responsibly make this conclusion. Thus, like previous studies, my results for wild-origin fish are inconclusive (Ebel et al. 1973; Slatick et al. 1975; Ebel 1980). In the future, when possible, I recommend the CSS report TIRs for wild-origin fish by river basin (e.g. Clearwater River) and not as conglomerates of unknown proportions.

Moving forward, the current TIR calculation framework remains adequate for hatchery-origin salmonids, the majority of fish in the basin. For wild-origin Chinook Salmon and steelhead, further investigation is warranted on the effects of juvenile transportation history on migration success upstream of LGR. Finally, although this study verified that the traditional approach to evaluating transportation effects is adequate for hatchery-origin fish, managers should regularly reevaluate their assumptions as management practices change and better technologies emerge.

Chapter 3: Comparison of smolt-to-adult return ratios for upper Snake River salmonids using coded wire and passive integrated transponder tags

Abstract

Smolt-to-adult return (SAR) ratios estimate survival of anadromous salmonids *Oncorhynchus* spp. and are an important metric for managing stocks, including those in the Columbia River. However, SAR estimates differ in methodology by reporting group. Agencies and tribal groups in the Columbia River basin estimate SARs using either coded wire tag (CWT) or passive integrated transponder (PIT) tag recovery data and there is a need to standardize estimation methodology across the basin. This study examined the relationship between CWT and PIT-tag SAR estimates for upper Snake River salmonids and found no consistent relationship for 19 hatchery groups across four stocks (i.e. Coho Salmon, steelhead, and spring- and fall-run Chinook Salmon). Available evidence suggests that the two methods of SAR estimates cannot be readily used as surrogates for one another and that relationships between the two estimates may be unique to each hatchery group. A variance component analysis found that while total variability is smaller for CWT SARs than PIT-tag SARs, 38.9% of that variability is attributed to measurement error whereas 21.3% of total error is attributed to measurement error for PIT-tag SARs. Given that PIT-tag SARs are more likely to capture natural variability and that wild-origin fish are primarily PIT-tagged, this study recommends using PIT-tag recovery data to estimate SARs in the basin.

Introduction

Smolt-to-adult return (SAR) ratios are used to estimate survival of anadromous salmonids *Oncorhynchus* spp. over a significant proportion of their life cycle and are an important metric for managing stocks and evaluating mitigation efforts. SARs are a ratio of the number of tags recovered from returning adults to the number of tagged juvenile out-migrants. SARs are used to estimate marine survival for commercial Pacific salmonid fisheries (Peterson et al. 2015; Kendall et al. 2017) and in the Columbia River basin, the Northwest Power and Conservation Council (NPCC) uses SARs to assess recovery goals. The NPCC seeks to achieve a minimum SAR ratio of 2% by 2025 for Snake River and upper Columbia salmon and steelhead listed under the Endangered Species Act (NPCC 2014). However, SARs are estimated with two tagging techniques in the Columbia River basin—coded wire tags (CWT) and passive integrated transponder (PIT) tags, complicating comparisons and recovery goal assessment.

Coded wire tags are implanted in the nasal cartilage of juvenile salmonids and require lethal recovery for tag code identification (Jefferts et al. 1963). Tag codes are group specific and do not allow for individual fish identification (Newman 1997). Additionally, tag codes must be retrieved via facial dissection and manually identified under low magnification (Johnson 2004). CWTs have been used in the Columbia River basin since the 1970s to primarily tag hatchery-origin fish and are recovered in hatcheries, spawning ground surveys, and by sampling commercial, recreational, and tribal fishery harvests (Nandor et al. 2010). All CWT release and recovery data for the region are publicly accessible and collected by the Regional Mark Processing Center, managed by the Pacific States Marine Fisheries Commission. These tag recoveries are corrected for sampling rates at each recovery source. Beyond being used for SAR estimation, CWTs are used for stock assessment and stock contribution to a specific fishery (Johnson 2004; Nandor et al. 2010), as well as harvest rates and geographic range of a fish stock (Newman 1997).

In contrast to CWTs, passive integrated transponder (PIT) tags are injected into the abdominal cavity of juvenile and adult salmonids and are recovered with electronic detection rather than in hand (Prentice et al. 1990). PIT-tags have been used in the Columbia River basin since 1987 to tag both hatchery- and wild-origin salmonids (Pacific Marine Fisheries Commission 2009). Individual tag codes are recovered via manually-operated hand wands or in-situ detectors at hydroelectric facilities, tributaries, and hatcheries. However, unlike CWTs, PIT-tags are not routinely recovered from fishery harvests. All PIT-tag release and recovery data for the region are publicly accessible and collected by the PIT Tag Information System (PTAGIS), a project also coordinated by the Pacific States Marine Fisheries Commission.

For upper Snake River salmonids, state and federal agencies and tribal groups may use either CWT or PIT-tag data to estimate SARs. The NPCC uses SARs to monitor status and trends of salmonid recovery, direct management, set quantitative goals, and evaluate mitigation operations in the region (NPCC 2014). In addition to the use of SARs for management and mitigation, there is urgency to standardize SAR methodology given the recently affirmed court order to increase spill over Columbia and Snake River dams (NWF v. NMFS 2017) and a potential upcoming decade-long study to examine subsequent population response (Skalski, pers. comm.). Thus, to make a tag technology recommendation, this study examines the relationship between SARs estimated using CWT recovery and PIT-tag detection and quantifies the sources of error for each type of estimate.

Methods

Study population.—This study included known source hatchery-origin Coho Salmon *O. kisutch*, steelhead *O. mykiss*, and spring- and fall-run Chinook Salmon *O. tshawytscha* released above Lower Granite Dam (LGR) as tagged juveniles. This study compares PIT-tag SARs to CWT SARs as reported by Columbia Basin Research in the DART (Data Analysis in Real Time) public access database (http://www.cbr.washington.edu/trends/index.php). The CWT SARs are reported by brood year, hatchery mark-site, release location, and run-type (Skalski and Townsend 2005). To match the stock identification for CWT SARs, this study queried PIT-tag release and detection data from PTAGIS based on the same attributes. Thus, only fish stocks with equivalent CWT and PIT-tag data were examined. SAR estimates for wild-origin populations primarily use PIT-tag data and were excluded from this analysis. Nineteen unique hatchery:release groups were analyzed (Table 3.1). The number of brood years analyzed per group ranged from three to twenty, with a median of six. Brood years range from 1991 to 2013, with most brood years after 2002 (Table 3.1).

TABLE 3.1.—Hatchery:release groups by run, along with brood years analyzed.

Run	Hatchery site	Release site	Brood years	*n*
Coho	Eagle Creek	Kooskia	2008, 2011-2012	3
	Eagle Creek	Lapwai Creek (Clearwater R)	2007-2008, 2011-2012	4
	Kooskia	Kooskia	2003, 2009, 2011	3
Fall Chinook	Lyons Ferry	Captain Johns Pond	2006-2012	7
	Nez Perce	Nez Perce	2002-2003, 2005-2008, 2010, 2012	8
Spring Chinook	Dworshak	Dworshak	1991-1999, 2002-2012	20
	Kooskia	Clear Creek (Clearwater R)	1994, 1996-1998, 2002, 2004	6
	Kooskia	Kooskia	2005-2012	8
	Lookingglass	Catherine Creek (Grande	2009, 2011-2012	3
	Lookingglass	Imnaha	2002-2012	11
	Lookingglass	Lookingglass	1992, 2006, 2009, 2011-2012	5
	Nez Perce	Newsome Creek (SF	2004-2005, 2008	3
	Nez Perce	Meadow Creek (Selway R)	2002, 2006, 2008-	5
	Nez Perce	Nez Perce	2006, 2008-2009, 2011-2012	5
Steelhead	Dworshak	Clear Creek (Clearwater R)	1995-1996, 2001, 2011-2013	6
	Dworshak	Dworshak	1991, 2009-2013	6
	Hagerman	Sawtooth	1996-1999, 2001, 2003-2005	8
	Irrigon	Big Sheep Creek (Imnaha R)	2001-2004	4
	Irrigon	Little Sheep Creek (Imnaha R)	1999, 2001-2005, 2007-2013	13

Statistical analyses.—CWT SARs were retrieved from the Columbia Basin Research website (http://www.cbr.washington.edu/trends/index.php). PIT-tag SARs were calculated by cohort as a binomial proportion of the number of juveniles released to the number of adults that returned to LGR. Detection to upstream tributaries was examined, but there were few cohorts with CWT SARs and upstream PIT-tag detection capability for a given brood year, limiting sample size. Additionally, almost all (>95%) of fish detected at upstream PIT-tag detection arrays were detected at LGR except for hatchery steelhead that presumably adopted river residency, rather than out-migrating to sea. Compared to tributary arrays, PIT-tag arrays at LGR have high year-round detection probability and a near-guaranteed likelihood of continued maintenance and operation. Thus, this study defined survival as detection at LGR.

A simple linear regression was conducted to examine if there was a 1:1 relationship between PIT-tag and CWT SARs for a given cohort. For hatcheries that released a given run at multiple release locations, pair-wise comparisons were conducted to test for congruity between the release groups. Across all groups, a weighted linear regression was performed, weighting the estimates of SAR inversely proportion to the variance to examine if the relationship between CWT and PIT-tag SARs was consistent between runs. I used a two-tailed t-test to compare the weighted average for CWT and PIT-tag SARs and a critical value of 0.10 for all comparisons.

For each hatchery:release group, proportional contributions of natural variability, σ^2, and average measurement error, $\overline{Var(\widehat{SAR}|SAR)}$, to total interannual variance, s^2, were calculated for CWT and PIT-tag SAR estimates. This allowed for examination of the noise to signal ratio for each tag technique.

Results

Both fall-run Chinook Salmon and steelhead had larger PIT-tag SARs, on average, compared to CWT SARs. For fall-run Chinook Salmon, average CWT and PIT-tag SARs were 0.0003 ($\widehat{SE}$ = 0.0002) and 0.0041 ($\widehat{SE}$ = 0.0009), respectively (P < 0.0001; Table 3.2). For steelhead, average CWT and PIT-tag SARs were 0.0018 ($\widehat{SE}$ = 0.0004) and 0.0038 ($\widehat{SE}$ = 0.0004), respectively (P = 0.06; Table 3.2). Although spring-run Chinook Salmon had larger average CWT SARs compared to PIT-tag SARs with values of 0.0066 ($\widehat{SE}$ = 0.0006) and 0.0046 ($\widehat{SE}$ = 0.0004), respectively, this difference was not statistically significant (P = 0.88; Table 3.2). Coho Salmon were the only run with comparable weighted average values for CWT and PIT-tag SARs with values of 0.0019 ($\widehat{SE}$ = 0.0006) and 0.0024 ($\widehat{SE}$ = 0.0015), respectively (P = 0.79; Table 3.2).

I found that 9 of the 19 hatchery:release groups displayed a relationship between CWT and PIT-tag SARs that differed significantly from 1:1 (P < 0.10; Table 3.3). These nine groups spanned three of the four stocks, excluding fall-run Chinook Salmon. However, these results appeared related to the number of brood years for a given hatchery:release group. Groups with ≥10 years of data had relationships significantly different from 1:1, while groups with <10 years of data had mixed results (Table 3.3). Hence, findings appear to depend on available sample size and statistical power and it is likely most fish stocks had a CWT to PIT-tag SAR relationship other than 1:1.

TABLE 3.2.—Weighted averages for each hatchery:release group, run, and overall. Averages were weighted by the inverse of the standard error squared. Standard errors are reported parenthetically.

Run	Hatchery site	Release site	SAR_{CWT}	SAR_{PIT}	$\overline{SAR_{CWT}}$	$\overline{SAR_{PIT}}$
Coho	Eagle Creek	Kooskia	0.0026 (0.0022)	0.0019 (0.0031)	0.0019 (0.0006)	0.0024 (0.0015)
	Eagle Creek	Lapwai Creek (Clearwater R)	0.0013 (0.0008)	0.0017 (0.0012)		
	Kooskia	Kooskia	0.0041 (0.0010)	0.0118 (0.0068)		
Fall Chinook	Lyons Ferry	Captain Johns Pond	0.0048 (0.0008)	0.0052 (0.0014)	0.0003 (0.0002)	0.0041 (0.0009)
	Nez Perce	Nez Perce	0.0003 (0.0002)	0.0015 (0.0008)		
Spring Chinook	Dworshak	Dworshak	0.0007 (0.0002)	0.0066 (0.0005)	0.0066 (0.0006)	0.0046 (0.0004)
	Kooskia	Clear Creek (Clearwater R)	0.0096 (0.0006)	0.0029 (0.0012)		
	Kooskia	Kooskia	0.0012 (0.0003)	0.0036 (0.0006)		
	Lookingglass	Catherine Creek (Grande Ronde R)	0.0017 (0.0002)	0.0038 (5E-11)		
	Lookingglass	Imnaha	0.0023 (0.0006)	0.0051 (0.0014)		
	Lookingglass	Lookingglass	0.0020 (0.0006)	0.0016 (0.0011)		
	Nez Perce	Newsome Creek (SF Clearwater R)	4E-06 (1E-05)	0.0012 (0.0002)		
	Nez Perce	Meadow Creek (Selway R)	4E-07 (3E-06)	0.0014 (0.0002)		
	Nez Perce	Nez Perce	0.0006 (0.0002)	0.0012 (0.0007)		
Steelhead	Dworshak	Clear Creek (Clearwater R)	0.0004 (0.0003)	0.0049 (0.0009)	0.0018 (0.0004)	0.0038 (0.0004)
	Dworshak	Dworshak	0.0021 (0.0004)	0.0040 (0.0014)		
	Hagerman	Sawtooth	0.0006 (0.0002)	0.0031 (0.0007)		
	Irrigon	Big Sheep Creek (Imnaha R)	0.0027 (0.0002)	0.0043 (8E-08)		
	Irrigon	Little Sheep Creek (Imnaha R)	0.0067 (0.0003)	0.0036 (0.0003)		
		Weighted average	0.0065 (0.0004)	0.0042 (0.0003)		

TABLE 3.3.—Fitted regression models and their associated r^2 values for each hatchery:release group. P-values are from an F-test of $H_O: y = x$ versus $H_A: y = \beta_0 + \beta_1 x$, where y is the PIT-tag SAR and x is the CWT SAR for a given run, brood year, hatchery rear site, and release location. Shaded cells note groups that have a significantly different PIT~CWT relationship compared to a 1:1 ratio. Sample size n notes the number of brood years in each hatchery:release group.

Run	Hatchery site	Release site	Regression model	P	r^2	n
Coho	Eagle Creek	Kooskia	y=-0.003+2.477x	0.440	0.757	3
	Eagle Creek	Lapwai Creek (Clearwater R)	y=0.001+0.453x	**0.002**	0.977	4
	Kooskia	Kooskia	y=-0.003+3.673x	**0.042**	0.970	3
Fall Chinook	Lyons Ferry	Captain Johns Pond	y=-0.001+1.374x	0.763	0.310	7
	Nez Perce	Nez Perce	y=-0.0001+1.129x	0.503	0.938	8
Spring Chinook	Dworshak	Dworshak	y=0.002+1.036x	**0.006**	0.553	20
	Kooskia	Clear Creek (Clearwater R)	y=0.0003+0.803x	0.904	0.295	6
	Kooskia	Kooskia	y=0.001+1.388x	**0.040**	0.554	8
	Lookingglass	Catherine Creek (Grande Ronde R)	y=-0.005+4.331x	0.124	0.944	3
	Lookingglass	Imnaha	y=0.001+1.561x	**0.067**	0.603	11
	Lookingglass	Lookingglass	y=-0.001+1.631x	**0.019**	0.971	5
	Nez Perce	Newsome Creek (SF Clearwater R)	y=0.002-10.188x	0.112	0.755	3
	Nez Perce	Meadow Creek (Selway R)	y=0.0003+12.12x	**0.018**	0.770	5
	Nez Perce	Nez Perce	y=0.004+3.159x	0.235	0.272	5
Steelhead	Dworshak	Clear Creek (Clearwater R)	y=0.004+-0.169x	0.258	0.003	6
	Dworshak	Dworshak	y=0.006+0.048x	0.319	0.000	6
	Hagerman	Sawtooth	y=0.003+3.974x	**0.094**	0.169	8
	Irrigon	Big Sheep Creek (Imnaha R)	y=0.006-1.555x	0.370	0.121	4
	Irrigon	Little Sheep Creek (Imnaha R)	y=0.001+0.173x	**<0.001**	0.101	13

Comparisons between fish of a given stock and hatchery with different release locations demonstrated inconsistencies in the relationship between CWT and PIT-tag SARs (Table 3.4). Within-hatchery comparisons for Coho and spring-run Chinook Salmon did not find congruent relationships for fish of different release locations, but did for steelhead from Dworshak National Fish Hatchery and Irrigon Hatchery (Table 3.4). These results suggest that for even the most similar fish stocks, the CWT to PIT-tag SAR relationships were not consistently similar.

TABLE 3.4.—Within-hatchery comparisons for congruency of CWT:PIT-tag SAR relationship.

Run	Hatchery site	Release site	Conclusion
Coho	Eagle Creek	Kooskia Lapwai Creek (Clearwater R)	Not congruent
Spring Chinook	Kooskia	Clear Creek (Clearwater R) Kooskia	Not congruent
	Lookingglass	Catherine Creek (Grande Ronde R) Imnaha R Lookingglass	Not congruent
	Nez Perce	Newsome Creek (SF Clearwater R) Meadow Creek (Selway R) Nez Perce	Not congruent
Steelhead	Dworshak	Clear Creek (Clearwater R) Dworshak	Congruent
	Irrigon	Big Sheep Creek (Imnaha R) Little Sheep Creek (Imnaha R)	Congruent

Relationships between CWT and PIT-tag SARs differed by run. Coho Salmon and steelhead had a positive CWT to PIT-tag SAR relationship with slopes <1.0. Spring- and fall-run Chinook Salmon also had a positive CWT to PIT-tag SAR relationship, but with slopes that are

>1.0. Coho Salmon and steelhead had significantly different CWT to PIT-tag SAR relationships compared to spring- and fall-run Chinook Salmon.

Overall, SAR estimates varied appreciably over time within a hatchery:release group. On average across all runs, measurement error made up a lower proportion of the total variability of PIT-tag SARs compared to CWT SARs (Table 3.5). Although average total variability was smaller for CWT-tag SARs, 38.9% of that variability was attributed to measurement error whereas 21.3% of total error was attributed to measurement error for PIT-tag SARs (Table 3.5).

TABLE 3.5.—Variance component analysis. Proportional contributions (%) of natural variability (σ^2) and average measurement error ($\overline{Var(\widehat{SAR}|SAR)}$) to total variance ($s^2$) for a SAR estimates calculated with CWT and PIT-tag data for a given hatchery:release group.

			SAR_{CWT}			SAR_{PIT}		
Run	Mark	Release	s^2	σ^2	$\overline{Var(\widehat{SAR}\|SAR)}$	s^2	σ^2	$\overline{Var(\widehat{SAR}\|SAR)}$
Coho	Eagle Creek	Kooskia	1.68E-05	74.9	25.1	0.000136	98.1	1.9
	Eagle Creek	Lapwai Creek	7.25E-05	97.0	3.0	1.52E-05	93.4	6.6
	Kooskia	Kooskia	1.73E-05	98.1	1.9	0.000241	98.2	1.8
Fall Chinook	Lyons Ferry	Captain Johns Pond	3.76E-06	0.0	100.0	2.29E-05	97.7	2.3
	Nez Perce	Nez Perce	7.27E-06	41.8	58.2	9.89E-06	93.4	6.6
Spr. Chinook	Dworshak	Dworshak	4.18E-06	97.6	2.4	8.12E-06	98.3	1.7
	Kooskia	Clear Creek	1.91E-05	98.0	2.0	4.17E-05	88.8	11.2
	Kooskia	Kooskia	1.49E-06	97.1	2.9	5.17E-06	94.5	5.5
	Lookingglass	Catherine Creek	1.03E-07	0.0	100.0	2.05E-06	94.9	5.1
	Lookingglass	Imnaha	1.47E-05	96.9	3.1	5.96E-05	99.3	0.7
	Lookingglass	Lookingglass	1.47E-05	98.3	1.7	4.04E-05	89.8	10.2
	Nez Perce	Newsome Creek	3.33E-09	0.0	100.0	4.58E-07	41.5	58.5
	Nez Perce	Meadow Creek	3.00E-09	0.0	100.0	5.72E-07	73.4	26.6
	Nez Perce	Nez Perce	1.20E-06	94.7	5.3	4.41E-05	62.5	37.5
Steelhead	Dworshak	Clear Creek	9.90E-07	0.0	100.0	8.81E-06	67.5	32.5
	Dworshak	Dworshak	1.13E-06	84.7	15.3	1.96E-05	98.4	1.6
	Hagerman	Sawtooth	3.97E-07	92.8	7.2	3.71E-05	63.0	37.0
	Irrigon	Big Sheep Creek	2.30E-07	0.0	100.0	4.60E-06	0.4	99.6
	Irrigon	Little Sheep Creek	8.89E-06	88.7	11.3	2.64E-06	42.7	57.3
		Average	9.72E-06	61.1	38.9	3.68E-05	78.7	21.3

Discussion

This study did not find a consistent relationship between SARs calculated with CWT recovery or PIT-tag detection data for 19 hatchery groups across four upper Snake River salmonid stocks (i.e. Coho Salmon, steelhead, and spring- and fall-run Chinook Salmon). Consequently, my results suggested that these two approaches cannot be readily used as surrogates for one another given that the CWT to PIT-tag SAR relationship may be unique to each hatchery:release group. Although this analysis was based on a limited number of years of SAR values, more years of data are unlikely to reverse this observation.

With no clear relationship between CWT and PIT-tag SARs, we must consider which approach may be most appropriate. A variance component analysis determined that average measurement error was smaller for SAR estimates calculated with PIT-tag detection data than with CWT recoveries. Thus, PIT-tag SARs are more likely to capture natural variability and less likely to be affected by sampling error. This may be because PIT-tag SARs are a simple binomial proportion based on tag detection at LGR, whereas CWT SAR estimates must be adjusted for the various sampling rates, sample sizes, and sample locations used to collect fish snouts that are then sub-sampled for dissection and tag code identification (Skalski and Townsend 2005; Nandor et al. 2010). Furthermore, because there is no clear relationship between CWT and PIT-tag SARs, we cannot compare the two SAR estimates across tag techniques as comparisons are confounded between methods. Therefore, investigators shout not compare SARs across hatcheries or years that use different tag techniques, further emphasizing the need to standardize SAR estimation methodology in the basin.

This study challenges the current approach to evaluating smolt-to-adult returns and exhorts managers to reevaluate their mitigation evaluation practices as better technologies emerge. Despite the tens of millions of fish marked annually with CWTs and costly sampling design for subsequent recovery (Nandor et al. 2010), the simple binomial proportion approach using PIT-tag releases and automated detections appears to be the most precise method for calculating smolt-to-adult return of upper Snake River salmonids. Additionally, PIT-tags are the most appropriate tag technique for comparing wild versus hatchery SARs given that wild-origin salmonids are primarily PIT-tagged. PIT-tags are also the only technique for calculating SARs for Sockeye and summer-run Chinook Salmon as they are currently almost exclusively PIT-tagged. Further analysis should be conducted for mid- and upper-Columbia River populations for verification and comparison of the CWT to PIT-tag SAR relationship.

However, PIT-tag detection may become the only reliable measure for enumerating adult returns given the possible threat to reduce or eliminate coded wire tagging of some salmonid stocks. Recent scrutiny of the Hatchery Scientific Review Group by the Northwest Indian Fisheries Commission (2018) has led to the suspension of three Washington Fish and Wildlife Commission policy guidelines (2018). If more policy guidelines are suspended, the requirement to externally mark all hatchery-origin salmonids with an adipose fin clip is at risk (Washington Fish and Wildlife Commission 2009) as would be subsequent CWT recovery. Clipped adipose fins identify fish with CWT (Nandor et al. 2010) and the elimination of this marking would hinder or eliminate CWT recovery operations. Therefore, I recommend that the Northwest Power and Conservation Council transition to using PIT-tag SARs to assess salmonid recovery efforts in the Columbia River basin.

Discussion

A major contribution of this work is the home array database for known-source salmonids in the upper Snake River basin. In this thesis, I have shown how this database can be used to evaluate research and recovery efforts for salmonids as well as where PIT-tag detection coverage in Snake River tributaries could be improved. In this discussion, I will provide a status review of PIT-tag detection coverage and identify how we can better use these arrays in a network-sense. Additionally, I will discuss other potential uses for tributary PIT-tag array data in future research.

Current status

The number of total PIT-tag arrays in the upper Snake River basin classified as instream remote detection in PTAGIS increased from 27 to 63 from 2010 to 2017 (Figure 1). In 2017, 82.5% of these arrays were capable of detecting both juvenile and adult salmonids, 15.9% detected only juveniles, and the remaining 1.6% detected only adults.

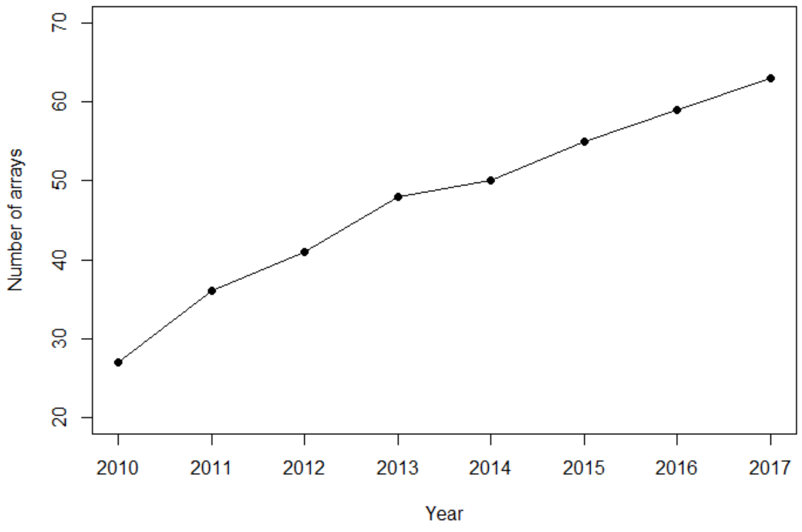

FIGURE 4.1.—From 2010–2017, the total number of PIT-tag arrays classified as instream remote detection (i.e. in tributaries) above LGR.

The number of PIT-tag arrays varies by subbasin. By the end of 2017, there were 16 arrays in the Clearwater River subbasin, 8 arrays in the Grand Ronde/Asotin River subbasin, 9 arrays in the Imnaha River subbasin, and 30 arrays in the Salmon River subbasin (Figure 2). Adult migrants are also reported as recaptured at other sites in the basin, including at hatcheries, weirs, traps, acclimation facilities, and via in-stream surveys (not shown). Recapture efforts at these sites vary annually and depend on sampling goals. The number of individual adult recapture sites have ranged from 26 to 39 from 2012–2016.

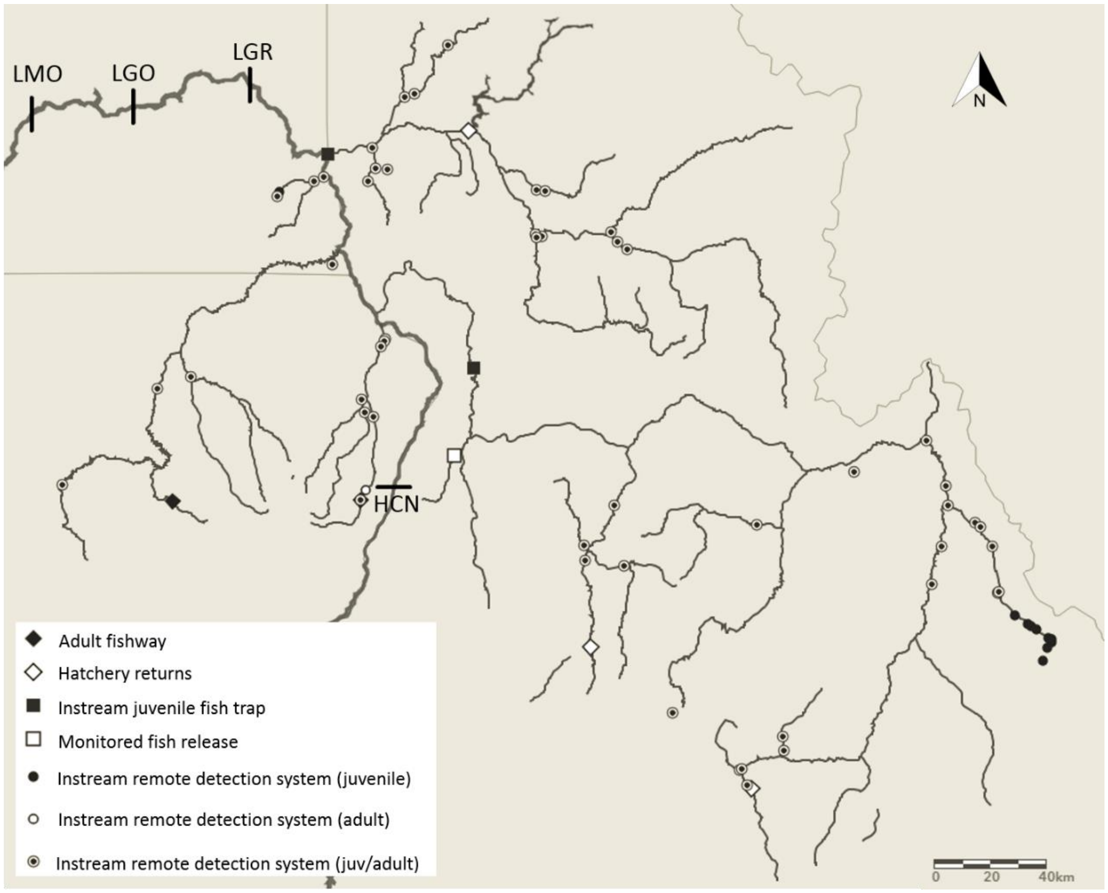

FIGURE 4.2—A map of the upper Snake River basin and the location of PIT-tag arrays at adult fishways, hatcheries, juvenile fish traps, juvenile release site, and instream remote detection sites

in 2017. Instream remote detection sites were further classified by life stage detected. LMO = Lower Monumental Dam, LGO = Little Goose Dam, LGR = Lower Granite Dam, and HCN = Hells Canyon Dam.

Summarization of stock detection potential for returning adult migrants, 2012–2016

Stock detection potential varies by stock and is complicated by rear-type. Wild-origin salmonids tagged as juveniles have the same mark- and release-site, usually a smolt trap or in-stream location. Thus, if the mark/release-site has a proximal detection mechanism, the stock has complete detection potential. In contrast, hatchery-origin salmonids often have separate mark- and release-sites. Hatchery fish are usually marked at their hatchery of origin and released at an acclimation pond or in-stream location elsewhere in the basin, sometimes up to hundreds of rkm away. As such, some fish can have partial detection potential (i.e. detection to either their mark- or release-site). Fish reared at hatcheries outside of upper Snake River tributaries further complicate the discussion of complete and partial detection potential as the release-site is the only accessible option once a fish has ascended Lower Granite Dam. Thus, if there is a detection mechanism proximal to the release-site, fish from these facilities have complete detection potential. It should also be noted that the term *potential* is intentional. Although a fish may have a detection mechanism proximal to a natal site, detection is not guaranteed as detection probabilities vary with flow conditions, maintenance needs, and other factors. For this thesis, I assumed detection efficiency was constant across the treatments (i.e. passage route and juvenile transportation history).

Overall, the proportion of wild-origin runs without detection potential at their natal sites upstream of LGR decreased between 2012 and 2016. For wild-origin adult salmonids returning to the upper Snake River basin in 2016, 100% of summer-run Chinook Salmon runs had complete detection potential upstream, while 78.3% of returning spring-run Chinook Salmon runs and 85.3% of returning steelhead runs had complete detection potential proximal to home. From 2012–2016, returning summer-run Chinook Salmon originated from approximately 10 locations in the Salmon River subbasin and these locations had detection coverage in all study years. However, wild-origin spring-run Chinook Salmon and steelhead originate from multiple subbasins and detection coverage varies between them. In 2016, steelhead and spring-run Chinook Salmon tagged at the Grande Ronde River Trap (GRNTRP), Crooked River Trap (CFCTRP), and East Fork Potlatch River (POTREF) did not have detection potential proximal to home. In the Salmon River subbasin, steelhead tagged at the Rapid River Smolt Trap (RPDTRP) and spring-run Chinook Salmon tagged at the Marsh Creek (MARTRP) and Lower Marsh Creek traps (MARTRP2) also lacked detection potential and were undetectable to home. Steelhead tagged at the Snake Trap (SNKTRP) also lacked an adult return detection mechanism. These undetectable runs made up 6.3% to 13.0% of the overall returning wild-origin steelhead and 17.6% to 39.1% of the overall returning spring-run Chinook Salmon from 2012–2016. Improving detection coverage at these sites would have allowed >80% of wild-origin steelhead and spring-run Chinook Salmon complete detection potential, highlighting the need to pair smolt traps with an adult detection or recovery mechanism.

Improvements in detection potential for hatchery-origin salmonids across the years 2012–2016 also varies by stock. In all study years, hatchery-origin Sockeye Salmon runs had complete detection potential upstream of Lower Granite Dam, while summer-run Chinook and Coho Salmon had complete detection potential by 2013 and 2015, respectively. The opportunity for complete detection potential was likely facilitated for these stocks because they are limited in geographic range and have had far fewer mark- and release-site combinations compared to steelhead, spring- and fall-run Chinook Salmon. For example, across the study years, Sockeye, Coho, and summer-run Chinook Salmon stocks had ≤5 unique mark- and release-site combinations, while steelhead, spring- and fall-run Chinook Salmon had between 13 to 31.

Improvements have been made, however, in expanding detection potential for hatchery-origin spring-run Chinook Salmon. The proportion of spring-run Chinook Salmon runs without detection potential at either their mark- or release-sites decreased after 2014 due to the expansion of recovery potential at Clearwater Hatchery (CLWH) and detection potential at the Dworshak National Fish Hatchery adult trap (DWL). However, in 2016 three hatchery-origin spring-run Chinook Salmon mark:release groups wholly lacked detection potential and were undetectable to home: (1) those tagged and released at the Grande Ronde River Trap (GRNTRP), (2) those tagged and released at the Nez Perce Tribal Hatchery (NPTH), and (3) those tagged at NPTH and released at Meadow Creek, on the Selway River (MEADOC). Other natal sites lacking detection coverage in 2016 included Powell Rearing Pond (POWP) and the Selway River near the mouth to Moose Creek (SELWY1). Installation of two PIT-tag arrays, SW1 and SW2, expanded detection coverage into the Selway River in November 2016. Thus, fish released at Meadow Creek and other sites in the Selway River now have detection potential proximal to home. Installation of an array in the Lower Lochsa River (LRL) in October 2016 also expanded detection coverage in the region and fish returning to POWP now have detection potential for returning adult migrants as well. Further improvements should be made to allow for detection or recovery at the Grande Ronde River Trap and Nez Perce Tribal Hatchery. Fish with natal sites at these locations made up an average of 4% of total returning hatchery-origin spring-run Chinook Salmon detected at Lower Granite Dam. However, in addition to installing SW1, SW2, and LRL, improving detection coverage at GRNTRP, and NPTH across the years 2012–2016 would have allowed between 92.6% to 100% of individual adult hatchery-origin spring-run Chinook Salmon detection potential.

Detection potential for hatchery-origin steelhead remained relatively constant from 2012–2015, with 68.8% to 74.2% of returning adult steelhead mark:release groups with at least partial detection potential. However, this decreased to 59.3% in 2016. This decrease was due to the adult trap at Dworshak National Fish Hatchery (DWL) shutting down on August 13, prior to the arrival of most fall migrants. Future operation of the adult trap during the fall season will increase the proportion of hatchery-origin steelhead capable of being detected to home. In 2016, fish without any detection or recovery potential after ascending Lower Granite Dam were generally raised outside of the basin and released at Cottonwood Acclimation Pond (COTP), in the Little Salmon River (LSALR), in the Salmon River between the Middle Fork and Pahsimeroi River (SALR3), and in the mainstem of the Snake River (SNAKE4). Hatchery-origin steelhead marked and released at smolt traps like the Grande Ronde River Trap, Salmon Trap, and Snake Trap also lacked detection potential to home. Fish from these locations made up 19.7% to 33.8% of the returning hatchery-origin adult steelhead from 2012–2016. By improving detection or recovery potential at DWL, COTP, LSALR, and the smolt traps, 86.0% to 94.3% of returning hatchery-origin steelhead could have at least had partial detection potential during the study years 2012–2016.

Detection potential upstream of Lower Granite Dam continues to be low for hatchery-origin fall-run Chinook Salmon. In fact, from 2012 to 2016, only those with a natal site at Luke’s Gulch Acclimation Facility had a proximal detection mechanism. Prior to 2016, those marked at Dworshak National Fish Hatchery also had detection potential via the adult trap. On average, 73.3% of hatchery-origin fall-run Chinook salmon mark:release groups wholly lacked detection potential upstream of Lower Granite Dam during the study years 2012–2016. These fish had natal sites at acclimation ponds such as Cedar Flats (CEFLAF), Big Canyon Creek (BCCAP), Captain John Rapids (CJRAP), Pittsburg Landing (PLAP), and the North Lapwai Valley (NLVP). Given that fall-run Chinook Salmon are mainstem spawners, many are also released at in-river sites like the Grande Ronde River near the mouth of the Wallowa River (GRAND1), the Snake River between the Clearwater and Salmon Rivers (SNAKE3), and the Snake River between the Salmon River and Hells Canyon Dam (SNAKE4). Those marked and released at the Nez Perce Tribal Hatchery (NPTH) also lacked detection or recovery potential. Although some sites, like those in mainstem rivers, are not conducive to adult recovery or PIT-tag array installation, detection coverage could be improved at acclimation facilities and associated hatcheries. Fish with natal sites at acclimation facilities and Nez Perce Tribal Hatchery made up 56.2% to 74.4% of returning adult fall-run Chinook in 2012–2016. Improving detection coverage at these sites would have allowed 80.8% to 88.6% of returning fall-run Chinook Salmon partial detection potentisal in a given study year.

Hatchery recoveries

There are 10 hatcheries in the upper Snake River basin that are accessible for adult return: Clearwater Hatchery, Dworshak National Fish Hatchery, Lookingglass Hatchery, Kooskia National Fish Hatchery, Nez Perce Tribal Hatchery, Oxbow Hatchery, Pahsimeroi Hatchery, Rapid River Hatchery, Sawtooth Hatchery, and Wallowa Hatchery. McCall Hatchery is not accessible, but operates an adult trap at a satellite facility to recapture migrants for broodstock collection and reports fish as recaptured at MCCA. Therefore, I considered McCall Hatchery an accessible location for homing. Although the Nez Perce Tribal Hatchery has an adult return site, I did not consider it an accessible homing location. Given that only 19 salmonids were reported as recaptured at Nez Perce Tribal Hatchery from 2012–2016, and all of these recaptures occurred in 2016 and were of non-known source adults, it is unclear if NPTH can be considered consistently capable of detection and recovery. Therefore, I did not consider NPTH a reliable homing site and classified fish tagged and released at NPTH undetectable to home.

Other recommendations

In addition to improving adult detection coverage at smolt traps, hatchery acclimation ponds, and at Nez Perce Tribal Hatchery, we can increase the utility of PIT-tag data by being cognizant of where we release fish in relation to PIT-tag arrays. This particular issue is currently unique to fish released at Lolo Creek in the Clearwater River subbasin, but risks repetition elsewhere in the Columbia River basin. From 2012–2016, there were 1,700–8,000 steelhead and 7,000–11,000 spring-run Chinook Salmon released at 3–7 sites within Lolo Creek in a given year. However, since their installation in 2011, there are only two PIT-tag arrays in Lolo Creek and they are located 21 and 25 rkm upstream from the mouth (LC1 and LC2). Therefore, fish released downstream of LC1 do not have a home detection mechanism. Of course, some of the fish released below LC1 migrate farther upstream during their spawning migration, are detected, and their survival and homing success can be accounted for. However, we cannot account for the survival and homing success of fish that return to their release-site downstream of LC1 and do not migrate farther upstream. As a result, 54.3% to 96.8% of steelhead released in Lolo Creek from 2012–2016 lacked detection potential. This was also an issue for a smaller proportion of spring-run Chinook Salmon released in Lolo Creek prior to 2014, but the practice of releasing juvenile Chinook Salmon downstream of detection sites has since ceased. Various factors may have informed the decision of where to install LC1 and LC2 and where to release juvenile salmonids in the system. For example, it is possible that the reach between the mouth of Lolo Creek and LC1 is not conducive to PIT-tag array installation and/or the locations achieve specific research objectives. It is also possible that the lower reaches of Lolo Creek are more favorable for juvenile steelhead rearing. Whatever the case may be, we should consider changing our release practices or installing an additional PIT-tag array to capture the survival and homing data of these salmonids.

Future research

This thesis investigated how data from PIT-tag arrays in the Snake River basin may be used to evaluate adult homing success in relation to research and recovery efforts. However, given that 98.4% of PIT-tag arrays in Snake River tributaries are capable of detecting tagged juvenile salmonids, this PIT-tag detection network may also be useful in assessing juvenile survival and out-migration success. For example, we may be able to use data from PIT-tag arrays to estimate juvenile mortality en route to LGR and identify reaches particularly detrimental to out-migration survival. These data may also be useful in studying juvenile out-migration timing and transit time to LGR and how it varies by stock and location, as well as with environmental conditions like water temperature and flow. Data from these arrays may also help evaluate if habitat restoration efforts in tributaries have improved juvenile out-migration abundance. Moving forward, we should continue thinking beyond the hydrosystem and consider salmonid life cycles in their entirety. We can achieve this by considering the holistic utility of a PIT-tag and approaching the PIT-tag arrays in the upper Snake River basin as a network, rather than a patchwork of individual arrays.

References

Anchor QEA LLC, LGL Alaska Research Associate Inc., and Columbia Basin Research. 2017. Final adult passage and post-passage behavior report. Walla Walla, WA. Project No. 161163-02.01.

Bjornn, T. C., and C. A. Peery. 1992. A review of literature related to movements of adult salmon and steelhead past dams and through reservoirs in the lower Snake River. U.S. Fish and Wildlife Service and Idaho Cooperative Fish and Wildlife Research Unit for U.S. Army Corps of Engineers, Walla Walla, Washington.

Boggs, C. T., M. L. Keefer, C. A. Peery, T. C. Bjornn, and L. C. Stuehrenberg. 2004. Fallback, reascension, and adjusted fishway escapement estimates for adult Chinook Salmon and steelhead at Columbia and Snake River dams. Transactions of the American Fisheries Society 133(4):932–949.

Bond, M. H., P. A. H. Westley, A. H. Dittman, D. Holecek, T. Marsh, and T. P. Quinn. 2017. Combined effects of barge transportation, river environment, and rearing location on straying and migration of adult Snake River fall-run Chinook Salmon. Transactions of the American Fisheries Society 146(1):60–73.

Bonneville Power Administration. 2001. The Columbia River System: Inside Story. Portland, Oregon.

Bonneville Power Administration. 2016. Fact Sheet: BPA invests in fish and wildlife. Bonneville Power Administration, Portland, Oregon.

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(1):31–42.

Brent, R. 1973. Algorithms for minimization without derivatives. Prentice-Hall, Englewood Cliffs, New Jersey.

Bromaghin, J. F., T. J. Underwood, and R. F. Hander. 2007. Residual effects from fish wheel capture and handling of Yukon River Fall Chum Salmon. North American Journal of Fisheries Management 27(3):860–872.

Brown, R. S., D. R. Geist, and M. G. Mesa. 2006. Use of electromyogram telemetry to assess swimming activity of adult spring Chinook salmon migrating past a Columbia River dam. Transactions of the American Fisheries Society 135(2):281–287.

Burnett, N. J., S. G. Hinch, M. R. Donaldson, N. B. Furey, D. A. Patterson, D. W. Roscoe, and S. J. Cooke. 2014. Alterations to dam-spill discharge influence sex-specific activity, behaviour and passage success of migrating adult sockeye salmon. Ecohydrology 7:1094–1104.

Castro-Santos, T., A. Cotel, and P. Webb. 2009. Fishway evaluations for better bioengineering: an integrative approach. American Fisheries Society Symposium 69:557–575.

Caudill, C. C., W. R. Daigle, M. L. Keefer, C. T. Boggs, M. A. Jepson, B. J. Burke, R. W. Zabel,

T. C. Bjornn, and C. A. Peery. 2007. Slow dam passage in adult Columbia River salmonids associated with unsuccessful migration: delayed negative effects of passage obstacles or condition-dependent mortality? Canadian Journal of Fisheries and Aquatic Sciences 64(7):979–995.

Caudill, C. C., M. L. Keefer, T. S. Clabough, G. P. Naughton, B. J. Burke, and C. A. Peery. 2013. Indirect effects of impoundment on migrating fish: temperature gradients in fish ladders slow dam passage by adult Chinook salmon and steelhead. PLoS ONE 8(12).

Clabough, T. S., M. A. Jepson, S. R. Lee, M. L. Keefer, C. C. Caudill, L. Martinez-Rocha, J. Renner, C. Erdman, L. Sullivan, and K. Hatch. 2014. Radio-tagged Chinook salmon and steelhead passage behavior at Lower Monumental, Little Goose and Lower Granite Dams - 2013. University of Idaho and Blue Leaf Environmental for U.S. Army Corps of Engineers, Walla Walla, Washington.

Clay, C. H. 1995. Design of fishways and other fish facilities, 2nd edition. Lewis Publishers, CRC Press, Boca Raton, Florida.

Clements, S. P., B. J. Hicks, J. F. Carragher, and M. Dedual. 2002. The effect of a trapping procedure on the stress response of wild Rainbow Trout. North American Journal of Fisheries Management 22(3):907–916.

Cook-Tabor, C. 2017. PSC - Selective Fishery Evaluation Committee. 2017 Update to Mark Committee. http://www.rmpc.org/files/mark-mtg-2017-docs/SFEC_Presentation_to_2017_Mark_Meeting(Carrie_Cook_Tabor).pdf.

Cooke, S. J., S. G. Hinch, G. T. Crossin, D. A. Patterson, K. K. English, M. C. Healey, J. M. Shrimpton, G. Van Der Kraak, and A. P. Farrell. 2006. Mechanistic basis of individual mortality in Pacific salmon during spawning migrations. Ecology 87(6):1575–1586.

Crossin, G., S. Hinch, S. Cooke, D. Welch, D. Patterson, S. Jones, A. Lotto, R. Leggatt, M. Mathes, J. Shrimpton, G. Van Der Kraak, and A. Farrell. 2008. Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. Canadian Journal of Zoology 86:127–140.

Dickerson, B. R., T. P. Quinn, and M. F. Willson. 2002. Body size, arrival date, and reproductive success of pink salmon, *Oncorhynchus gorbuscha*. Ethology Ecology & Evolution 14(1):29–44.

Ebel, W. J. 1980. Transportation of Chinook salmon, *Oncorhynchus tshawytscha*, and steelhead, *Salmo gairdneri*, smolts in the Columbia River and effects on adult returns. Fishery Bulletin 78(2).

Ebel, W. J., D. L. Park, and R. Johnseni. 1973. Effects of transportation on survival and homing of Snake River Chinook Salmon and steelhead trout. Fishery Bulletin 71(2).

Fenkes, M., H. A. Shiels, J. L. Fitzpatrick, and R. L. Nudds. 2016. The potential impacts of migratory difficulty, including warmer waters and altered flow conditions, on the reproductive success of salmonid fishes. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 193:11–21.

Fish Passage Center. 2016. 2016 Annual Report. Prepared for Northwest Power and Conservation Council and the Bonneville Power Administration, Portland, Oregon. Project No. 1994-033-00.

Geist, D. R., C. S. Abernethy, S. L. Blanton, and V. I. Cullinan. 2000. The use of electromyogram telemetry to estimate energy expenditure of adult fall Chinook salmon. Transactions of the American Fisheries Society 129(1):126–135.

Gilhousen, P. 1990. Prespawning mortalities of sockeye salmon in the Fraser River system and possible causal factors. International Pacific Salmon Fisheries Commission, Bulletin 26.

Goniea, T. M., M. L. Keefer, T. C. Bjornn, C. A. Peery, D. H. Bennett, and L. C. Stuehrenberg. 2006. Behavioral thermoregulation and slowed migration by adult fall Chinook Salmon in response to high Columbia River water temperatures. Transactions of the American Fisheries Society 135(2):408–419.

Grant County Public Utility District. 2018. Calendar year 2017: Activities under Priest Rapids hydroelectric project license (FERC No. 2114). Prepared for the Federal Energy Regulatory Commission, Washington, D.C.

Grill, G. 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters 10.

Harmon, J. R. 2003. A trap for handling adult anadromous salmonids at Lower Granite Dam on the Snake River, Washington. North American Journal of Fisheries Management 23(3):989–992.

Hinch, S. G., S. J. Cooke, A. P. Farrell, K. M. Miller, M. Lapointe, and D. A. Patterson. 2012. Dead fish swimming: a review of research on the early migration and high premature mortality in adult Fraser River Sockeye Salmon *Oncorhynchus nerka*. Journal of Fish Biology 81(2):576–599.

Hruska, K. A., S. G. Hinch, D. A. Patterson, and M. C. Healey. 2011. Egg retention in relation to arrival timing and reproductive longevity in female Sockeye Salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 68(2):250–259.

Independent Scientific Advisory Board. 1998. Response to the questions of the implementation team regarding juvenile salmon transportation in the 1998 season. Report 98-2. Northwest Power Planning Council, Portland, Oregon.

Independent Scientific Group. 1996. Return to the river: restoration of salmonid fishes in the Columbia River ecosystem. Northwest Planning Council. Portland, Oregon.

Jefferts, K. B., P. K. Bergman, and H. F. Fiscus. 1963. A coded-wire identification system for macro-organisms. Nature 198:460–462.

Johnson, J. K. 2004. Regional overview of coded wire tagging of anadromous salmon and steelhead in northwest America. Regional Mark Processing Center, Pacific States Marine Fisheries Commission, Portland, Oregon.

Kareiva, P., M. Marvier, and M. McClure. 2000. Recovery and management options for spring/summer chinook salmon in the Columbia River basin. Science (New York, N.Y.) 290(5493):977–979. American Association for the Advancement of Science.

Keefer, M. L., C. C. Caudill, C. A. Peery, and S. R. Lee. 2008. Transporting juvenile salmonids around dams impairs adult migration. Ecological Applications 18(8):1888–1900.

Keefer, M. L., M. A. Jepson, T. S. Clabough, C. C. Caudill, T. C. Bjornn, B. J. Burke, K. Frick, A. L. Matter, M. L. Moser, C. A. Peery, and L. C. Stuehrenberg. 2017. Migration of adult salmonids in the Federal Columbia River Hydrosystem: a summary of radiotelemetry studies, 1994-2014. Department of Fish and Wildlife Sciences & Idaho Cooperative Fish and Wildlife Research Unit and Northwest Fisheries Science Center prepared for U.S. Army Corps of Engineers, Portland District.

Keefer, M. L., C. A. Peery, T. C. Bjornn, M. A. Jepson, and L. C. Stuehrenberg. 2004. Hydrosystem, dam, and reservoir passage rates of adult Chinook Salmon and steelhead in the Columbia and Snake Rivers. Transactions of the American Fisheries Society 133(6):1413–1439.

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(3):361–372.

Kendall, N. W., G. W. Marston, and M. M. Klungle. 2017. Declining patterns of Pacific Northwest steelhead trout (*Oncorhynchus mykiss*) adult abundance and smolt survival in the ocean. Canadian Journal of Fisheries and Aquatic Sciences 74:1275–1290.

Larinier, M. 2001. Environmental issues, dams and fish migration. FAO Fisheries Technical Paper, 419: 45-90.

Leonard, N. J., M. A. Fritsch, J. D. Ruff, J. F. Fazio, J. Harrison, and T. Grover. 2015. The challenge of managing the Columbia River Basin for energy and fish. Fisheries Management and Ecology 22:88–98.

Mantua, N., I. Tohver, A. Hamlet, N. Mantua, I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102:187–223.

Marsh, D. M., W. P. Connor, and W. Connor. 2005. A study to compare smolt-to-adult return rates (SARs) of Snake River fall Chinook salmon under alternative transportation and dam operational strategies. Prepared for U.S. Army Corps of Engineers, Walla Walla, WA.

McCann, J., B. Chockley, E. Cooper, B. Hsu, H. Schaller, and S. Haeseker. 2017. Comparative Survival Study of PIT-tagged spring/summer/fall Chinook, summer steelhead, and Sockeye 2017 Annual Report. Project No. 1996-020-00.

McCullagh, P., and J. A. Nelder. 1989. Generalized linear models, 2nd edition. Chapman & Hall/CRC Press, London, United Kingdon.

McCutcheon, C. S., E. F. Prentice, and D. L. Park. 1994. Passive monitoring of migrating adult steelhead with PIT tags. North American Journal of Fisheries Management 14(1):220–223.

Mills, D. 1991. Ecology and management of Atlantic salmon. Chapman & Hall, London.

Mills, D. 1994. Evidence of straying from wild Atlantic salmon, *Salmo salar L.*, smolt transportation experiments in northern Scotland. Aquaculture Research 25(S2):3–8. Wiley/Blackwell (10.1111).

Morris, M. S., E. F. Holcombe, A. J. Borsky, P. J. Bentley, and B. P. Sandford. 2018. Detection of PIT-tagged juvenile salmonids migrating in the Columbia River Estuary, 2017. Portland, Oregon. Project No. 1993-029-00.

Mote, P. W., E. A. Parson, A. F. Hamlet, W. S. Keeton, D. Lettenmaier, N. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter, and A. K. Snover. 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climatic Change 61:45–88.

Muir, W. D., D. M. Marsh, B. P. Sandford, S. G. Smith, and J. G. Williams. 2006. Post-hydropower system delayed mortality of transported Snake River stream-type Chinook Salmon: unraveling the mystery. Transactions of the American Fisheries Society 135(6):1523–1534.

Murauskas, J. G., J. K. Fryer, B. Nordlund, and J. L. Miller. 2014. Trapping effects and fisheries Research: A case study of Sockeye Salmon in the Wenatchee River, USA. Fisheries 39(9):408–414.

Nandor, G. F., J. R. Longwill, and D. L. Webb. 2010. Overview of the coded wire tag program in the Greater Pacific Region of North America. Page PNAMP Special Publication: Tagging, Telemetry and Marking Measures for Monitoring Fish Populations—A compendium of new and recent science for use in informing technique and decision modalities. Pacific Northwest Aquatic Monitoring Partnership Special Publication 2010-002.

National Marine Fisheries Service. 2008. Endangered Species Act Section 7(a)(2) Consultation Biological Opinion And Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. National Academies Press.

National Wildlife Federation v. National Marine Fisheries Service. 2017. Case No. 3:01-cv-0640-SI, Opinion and Order, District of Oregon, March 27, 2017.

Naughton, G. P., C. C. Caudill, M. L. Keefer, T. C. Bjornn, C. A. Peery, and L. C. Stuehrenberg. 2006. Fallback by adult Sockeye Salmon at Columbia River dams. North American Journal of Fisheries Management 26(2):380–390.

Naughton, G. P., C. C. Caudill, C. A. Peery, T. S. Clabough, M. A. Jepson, T. C. Bjornn, and L. C. Stuehrenberg. 2007. Experimental evaluation of fishway modifications on the passage behaviour of adult Chinook Salmon and steelhead at Lower Granite Dam, Snake River, USA. River Research and Applications 23(1):99–111.

Newman, K. 1997. The design and analysis of salmonid tagging studies in the Columbia Basin. Volume II. Estimating salmonid survival with combined PIT-CWT tagging. Prepared for the Bonneville Power Administration, Project Number 91-051-00, Portland, Oregon.

NMFS. 2016. Status of ESA listings and critical habitat designations for West coast salmon and steelhead. National Marine Fisheries Service, West Coast Region, Portland, Oregon.

NOAA Fisheries. 2011. Snake River spring summer Chinook adult upstream survival: Bonneville to Lower Granite Dam.

Northwest Fisheries Science Center. 2015. Status review update for Pacific salmon and steelhead listed under the Endangered Species Act: Pacific Northwest.

Northwest Indian Fisheries Commission. 2018. Role of the Hatchery Scientific Review Group, June 14 2018. Letter to Governor Inslee of Washington State. Olympia, Washington.

Northwest Power and Conservation Council. 2014. Columbia River Basin Fish and Wildlife Program 2014.

Ogden, D. A. 2016. Operation of the adult trap at Lower Granite Dam, 2015. National Marine Fisheries Service for Bonneville Power Administration, U.S. Department of Energy, Portland, Oregon. Project No. 2005-002-00.

Pacific Marine Fisheries Commission. 2009. 2009 PIT Tag Specification Document. Prepared for the PIT Tag Steering Committee. Gladstone, Oregon.

Pankhurst, N. W., and M. Dedualj. 1994. Effects of capture and recovery on plasma levels of cortisol, lactate and gonadal steroids in a natural population of Rainbow Trout. Journal of Fish Biology 45(6):1013–1025.

Park, D. L. 1985. A review of smolt transportation to bypass dams on the Snake and Columbia rivers. Report to U.S. Army Corps of Engineers, Contract DACW68-84-H-0034, Seattle, Washington.

Peterson, W. T., J. L. Fisher, C. A. Morgan, J. O. Peterson, B. J. Burke, and K. Fresh. 2015. Ocean ecosystem indicators of salmon marine survival in the Northern California Current. Prepared by National Marine Fisheries Service and Oregon State University.

Prentice, E. F., T. A. Flagg, and C. S. Mccutcheon. 1990. Feasibility of using implantable Passive Integrated Transponder (PIT) tags in salmonids. American Fisheries Society Symposium 7:317–322.

Quinn, T. P. 2005. The behavior and ecology of Pacific salmon and trout. University of Washington Press, Seattle, Washington.

Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile Chinook Salmon and steelhead from the Snake River, 1966 to 1975. Transactions of the American Fisheries Society 108(6):505–529.

Reischel, T. S., and T. C. Bjornn. 2003. Influence of fishway placement on fallback of adult salmon at the Bonneville Dam on the Columbia River. North American Journal of Fisheries Management 23(4):1215–1224.

Roscoe, D. W., and S. G. Hinch. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries 11(1):12–33.

Schilt, C. R. 2007. Developing fish passage and protection at hydropower dams. Applied Animal Behavior Science 104:295–325.

Seamons, T. R., P. Bentzen, and T. P. Quinn. 2004. The effects of adult length and arrival date on individual reproductive success in wild steelhead trout (*Oncorhynchus mykiss*). Canadian Journal of Fisheries and Aquatic Sciences 61(2):193–204.

Skalski, J. R., and R. L. Townsend. 2005. Pacific Northwest hatcheries smolt-to-adult ratio (SAR) estimation using coded wire tags (CWT) data.

Slatick, E., D. L. Park, and W. J. Ebel. 1975. Further studies regarding effects of transportation on survival and homing of Snake River chinook salmon and steelhead trout. Fishery Bulletin 73(4):925–931.

Smith, S. G., T. M. Marsh, and W. P. Connor. 2017. Responses of Snake River Fall Chinook Salmon to dam passage strategies and experiences. Prepared for U.S. Army Corps of Engineers, Walla Walla, WA MIPR No. W68SBV20386114.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136–1155.

Strange, J. S. 2012. Migration strategies of adult Chinook Salmon runs in response to diverse environmental conditions in the Klamath River Basin. Transactions of the American Fisheries Society 141(6):1622–1636.

U.S. Army Corps of Engineers. 2017. 2017 Fish Passage Plan. U.S. Army Corps of Engineers, Northwestern Division, CENWD-PDW-R.

U.S. Army Corps of Engineers Northwestern Division, Bureau of Reclamation Pacific Northwest, and Bonneville Power Administration. 2017. Endangered Species Act. Federal Columbia River Power System, 2016 Comprehensive Evaluation.

Underwood, T. J., J. F. Bromaghin, and S. P. Klosiewski. 2004. Evidence of handling mortality of adult Chum Salmon caused by fish wheel capture in the Yukon River, Alaska. North American Journal of Fisheries Management 24(1):237–243.

Vijayan, M. M., and T. W. Moon. 1992. Acute handling stress alters hepatic glycogen metabolism in food-deprived Rainbow Trout (*Oncorhynchus mykiss*). Canadian Journal of Fisheries and Aquatic Sciences 49.

Wagner, P., and T. Hillson. 1993. 1991 Evaluation of adult fallback through the McNary Dam juvenile bypass system. Washington Department of Fisheries for U.S. Army Corps of Engineers, Contract DACW68-82-C-0077 Task Order No. 10.

Ward, D. L., R. R. Boyce, F. R. Young, and F. E. Olney. 1997. A review and assessment of transportation studies for juvenile Chinook salmon in the Snake River. North American Journal of Fisheries Management 17(3):652–662.

Washington Fish and Wildlife Commission. 2009. Washington Department of Fish and Wildlife hatchery and fishery reform: Policy No. C-3619.

Washington Fish and Wildlife Commission. 2018. Meeting Minutes: June 14-16, 2018. Olympia, Washington.

Widener, D. L., J. R. Faulkner, S. G. Smith, T. M. Marsh, and R. W. Zabel. 2018. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and Reservoirs, 2017. Report of research by the National Marine Fisheries Service for the Bonneville Power Administration, Contract 40735, Project 199302900, Portland, Oregon.

Williams, J. G., G. Armstrong, C. Katopodis, M. Larinier, and F. Travade. 2012. Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. River Research and Applications 28(4):407–417.

Williams, J. G., S. G. Smith, R. W. Zabel, W. D. Muir, M. D. Scheuerell, B. P. Sandford, D. M. Marsh, R. A. McNatt, and S. Achord. 2005. Effects of the Federal Columbia River Power System on salmonid populations. NOAA Technical Memorandum NMFS-NWFSC-63, Seattle.

Zar, J. H. 2010. Biostatistical analysis, 5th edition. Prentice-Hall/Pearson, Upper Saddle River, NJ.