Technical Report 2014-6

ADULT PACIFIC LAMPREY MIGRATION IN THE COLUMBIA AND SNAKE RIVERS: 2013 HALF-DUPLEX PIT TAG STUDIES

A Report for Study Code ADS-P-00-8

by

M. L. Keefer, C. C. Caudill, E. L. Johnson,
T. S. Clabough, M. A. Jepson, C. J. Noyes, C. T. Boggs
Department of Fish and Wildlife Sciences
University of Idaho, Moscow, ID 83844-1136

and

S. C. Corbett & M. L. Moser
Northwest Fisheries Science Center, NOAA Fisheries
2725 Montlake Blvd. East, Seattle, WA 98112

For

U.S. Army Corps of Engineers
Portland District, Portland OR

2014

Technical Report 2014-6

ADULT PACIFIC LAMPREY MIGRATION IN THE COLUMBIA AND SNAKE RIVERS: 2013 HALF DUPLEX PIT-TAG STUDIES

A Report for Study Code ADS-P-00-8

by

M. L. Keefer, C. C. Caudill, E. L. Johnson, T. S. Clabough, M. A. Jepson, C. J. Noyes, C. T. Boggs
Department of Fish and Wildlife Sciences
University of Idaho, Moscow, ID 83844-1136

and

S. C. Corbett & M. L. Moser
Northwest Fisheries Science Center, NOAA Fisheries
2725 Montlake Blvd. East, Seattle, WA 98112

For

U.S. Army Corps of Engineers
Portland and Walla Walla Districts

2014

Acknowledgements

Many people assisted with the field work and data compilation for this report and its successful completion was made possible through their efforts. Matt Knoff, Steve Lee, Kaan Oral, Mike Turner, Mike Hanks and Inga Aprans helped with collecting and tagging lampreys. Travis Dick assisted with the maintenance and downloading of the monitoring equipment. Staff at other agencies also provided lamprey detection data, including Matt Fox and Cyndi Baker (Confederated Tribes of Warm Springs Reservation of Oregon), Rod O'Connor (Blueleaf Environmental for Grant County Public Utility District), Mike Clement (Grant County Public Utility District), and Jeff Osborn (Chelan County Public Utility District). We also thank the staff of Pacific States Marine Fisheries Commission's Kennewick Field Office, especially Darren Chase and Don Warf. The U.S. Army Corps of Engineers provided funding for this study; we thank Sean Tackley, Nathan Zorich, Derek Fryer, Tammy Mackey, Jon Rerecich, Andy Traylor, Ben Hausmann, Kasey Welch, Miro Zyndol, Robert Cordie, Brad Eby, and Mark Plummer. The work reported here was conducted under a Cooperative Ecosystems Study Unit (CESU) agreement CESU W912HZ-12-2-0004with the assistance of Sean Tackley, Glen Rhett, and Deberay Carmichael.

Table of Contents

Executive Summary

The 2013 adult Pacific lamprey studies used an integrated set of technologies to address multiple questions about Pacific lamprey (*Entosphenus tridentatus*) migration in the Columbia River Hydrosystem at a variety of scales. The results summarized in this report primarily address reach-scale and system-wide migration using detection data from lamprey tagged with half duplex (HD) passive integrated transponder (PIT) tags. Companion 2013 study reports provide results from lampreys tagged with acoustic transmitters (JSATS) and released upstream and downstream from Bonneville Dam (Noyes et al. 2014), behaviors of the HD-PIT tagged fish in and near Bonneville lamprey passage structures and other modifications (Corbett et al. 2014), and results from using dual frequency identification sonar (DIDSON) to monitor adult lampreys inside and near fishways at Bonneville and John Day dams (Kirk et al. 2014).

We HD-PIT tagged lamprey collected at Bonneville Dam and monitored their passage and migration behaviors at Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Lower Granite, and Priest Rapids dams. Additional detection data from upper Columbia River dams and lower Columbia tributaries were provided by cooperating agencies. Our objectives were to calculate lamprey passage times through various river reaches, to estimate escapement past the monitored sites, and to evaluate potential correlations between lamprey migration and physiological factors.

In total, we HD PIT-tagged 943 lampreys in 2013: 876 were released downstream from Bonneville Dam near Hamilton Island, 39 were released upstream from Bonneville Dam near Stevenson, WA, and 25 were released directly into the Cascades Island lamprey passage structure (LPS). An additional 400 lampreys were double-tagged with HD-PIT tags and acoustic transmitters (JSATS) and 50 were double-tagged with HD-PIT tags and radio transmitters; results from these samples are presented in separate reports.

The 2013 escapement estimate from release downstream from Bonneville Dam past the dam was 56% (recaptures treated as not passing) to 61% (recaptures treated as passing). These estimates were among the highest in the 2005-2013 HD-PIT studies (41-58%). Escapement from the top of Bonneville Dam to the top of The Dalles Dam (52%) and from the top of The Dalles Dam to the top of John Day Dam (65%) was similar to previous years. Large lampreys were substantially more likely than small lampreys to pass through most dam-to-dam reaches. As in previous years, lampreys last detected at upriver sites were statistically larger than those last recorded closer to the release site, indicating size-dependent effects on migration distance and final distribution.

Increased cross-agency monitoring efforts improved our final accounting for tagged lamprey. A total of 6.3% of the downstream-released sample was last detected at dams in the upper Columbia River (Priest Rapids, Wanapum, Rock Island, Rocky Reach). Another 1.8% was last detected at Snake River dams, and 4.5% was detected in tributaries to the Bonneville or The Dalles reservoirs (Hood River, Fifteenmile Creek, Deschutes River). We expect additional detections at many of these sites in spring 2014 as overwintering lampreys move to spawning areas.

Lamprey migration times were highly variable in 2013, as in all previous study years. The median passage time for the downstream-released fish was 6.3 days (< 1 km$\bullet$d^{-1}) from release to the top of Bonneville Dam, faster than in any other study year. Median times between top-of-ladder antennas

were 4.0 days between Bonneville and The Dalles dams, 4.3 days between The Dalles and John Day dams, and 9.2 days between John Day and McNary dams. Each of the reaches upstream from Bonneville Dam included one reservoir and one dam.

The multi-year HD-PIT dataset provides baseline data for understanding migration-scale questions about adult Pacific lamprey and for evaluating changes in lamprey passage performance in the hydrosystem. The HD-PIT monitoring complements ongoing active telemetry and experiments to test lamprey behavior at main stem dams.

Introduction

Pacific lamprey (*Entosphenus tridentatus*) is the largest lamprey species in the Columbia and Snake rivers. Pacific lampreys are anadromous, with parasitic adults spending 1-4 years in the ocean before returning to spawn in freshwater rivers (Beamish 1980; Close et al. 2002; Moser and Close 2003). Recent studies suggest that Pacific lamprey abundance has steadily declined in the Columbia River basin and in other regional rivers since the early 1960's (Kostow 2002; Clemens et al. 2010; USFWS 2010; Murauskas et al. 2013). Habitat loss, river impoundment, ocean conditions, ocean prey base (Murauskas et al. 2013), and water pollution have all likely contributed to the decline. Lampreys also have difficulty passing through Columbia and Snake River dam fishways designed for adult salmonids (see Luzier et al. 2011 and Keefer et al. 2012 for reviews).

Monitoring Columbia River basin lamprey populations has been a challenge. Lamprey counts at dam fish ladders have only been used as indicators of relative abundance and general run timing (e.g., Keefer et al. 2009a) because most historic counts were collected during the day (most lamprey pass at night), and most counting facilities are not designed to accurately enumerate lampreys (Moser et al. 2002a; Robinson and Bayer 2005; Clabough et al. 2012). Radiotelemetry was used in an intermittent series of studies from 1997-2010 to identify lamprey problem passage areas, evaluate structural and operational modifications to fishways (e.g., Clabough et al. 2011; Johnson et al. 2012; Keefer et al. 2013b), and estimate survival of adult Pacific lamprey in the basin (e.g., Moser et al. 2002b, 2005; Johnson et al. 2012; Keefer et al. 2012, 2013a). Starting in 2005, half duplex (HD) passive integrated transponder (PIT) tag monitoring sites have been deployed at dams to monitor PIT-tagged adult lamprey. Like radio transmitters, PIT tags are uniquely identifiable, allowing individual fish monitoring. PIT tags are also relatively small and inexpensive and are not limited by battery life, useful features given that some adult lamprey overwinter in the Columbia River main stem and some lamprey are too small for radio transmitters. HD-PIT tags were selected for Pacific lamprey passage evaluations to avoid potential tag collisions with the full-duplex (FDX) PIT tags used to monitor salmonids in the basin and because HD-PIT tags have longer read ranges.

The objectives of the 2013 studies described in this report were to use HD-PIT systems to: (1) calculate adult lamprey passage rates past multiple dams and reservoirs; (2) estimate lamprey escapement past multiple dams, through individual dam-to-dam reaches, and into tributaries; (3) examine potential morphological and environmental correlates with upstream passage; and (4) examine year-to-year patterns in lamprey escapement. A more detailed evaluation of HD-PIT tagged lamprey use of lamprey passage systems (LPS) and other structural modifications at Bonneville Dam is presented in a separate report (Corbett et al. 2014). Additionally, a parallel study of lamprey tagged with acoustic transmitters and monitored using the Juvenile Salmon Acoustic Telemetry System (i.e., JSATS) is described in Noyes et al. (2014).

Methods

Lamprey Collection and Tagging

Lampreys used in this study were collected at night in traps at Bonneville Dam (Columbia River kilometer [rkm] 235). Traps were located in the fishway near the Adult Fish Facility (AFF). Additional fish were captured in portable traps in auxiliary water supply (AWS) channels. In 2013,

943 lampreys were tagged with only half-duplex passive integrated transponder (HD-PIT) tags. Lampreys were unselectively PIT tagged (i.e., those that were tagged on any given day were a random sample of the fish that were collected the previous night). However, it was unknown whether lampreys collected inside Bonneville fishways were representative of the run at large. We have hypothesized that Pacific lamprey in the smallest adult size classes may be less likely to enter fishways; there is currently no way to test the degree to which the sampling inside the fishways was biased. Tagged lampreys were released downstream from Bonneville Dam near Hamilton Island at Columbia River rkm 232.5 (n = 876), into the Cascades Island LPS (n = 25), or near the Stevenson boat ramp (n = 39). The latter group was used in experimental flume studies and was therefore not comparable to lamprey released at the same location in previous years. An additional 400 fish were double-tagged with an HD-PIT tag and a JSATS acoustic transmitter (see Noyes et al. 2014) and another 50 were double-tagged with an HD-PIT tag and a radio transmitter (see Corbett et al. 2014).

Before tagging, all fish were anaesthetized using 60 ppm (3 mL×50 L^{-1}) eugenol, measured (length and girth to the nearest mm), and weighed (nearest g). HD-PIT fish were then outfitted with a uniquely-coded, glass-encapsulated HD-PIT tag (Texas Instruments, 4×32 mm, 0.8 g). HD-PIT tags were surgically implanted in the body cavity of anaesthetized fish through a small incision (< 1 cm) along the ventral midline and in line with the anterior insertion of the first dorsal fin as described in Moser et al. (2006). Collection and tagging protocols were reviewed and approved by the University of Idaho Institutional Animal Care and Use Committee.

Monitoring Sites

Lamprey movements were monitored using an array of HD-PIT interrogation sites (Table 1). Underwater HD-PIT antennas maintained by the UI and NOAA were located inside dam fishways at the four lower Columbia River dams, at Priest Rapids Dam on the upper Columbia River, and at Ice Harbor, Lower Monumental and Lower Granite dams on the lower Snake River. Antennas were located near top-of-ladder exits at all dams. At Bonneville Dam, additional sites were located at lamprey passage structures (LPS), inside the Washington-shore and Cascades Island fishway entrances, in lamprey rest boxes, and in the flow-control section of the Cascades Island fishway. Antennas were also located near transition pools and/or the overflow weir portions of ladders at McNary and Ice Harbor dams and below the south (east) top-of-ladder site at The Dalles Dam, at a newly-installed lamprey trap in the south ladder at John Day Dam, and at the LPS in the John Day north fishway collection channel (Table 1). Additional antennas were maintained at upper Columbia River dams by the Chelan and Grant County PUDs and in several lower Columbia River tributaries by the Confederated Tribes of the Warm Springs Reservation of Oregon (CTWSRO). An instream multiplexing antenna array was also installed near the Deschutes River mouth in 2013 by CTWSRO and the Bonneville Power Administration (BPA).

Data Analyses

Reach escapement rates were calculated by dividing the number of lamprey known to pass an upstream HD site by those known to pass a site downstream or by the number released. Fish were treated as having passed a site if they were detected at the site or at a location further upstream.

Table 1. Half-duplex PIT tag interrogation sites (antennas) used by UI/NMFS to monitor lamprey passage at lower Columbia and Snake river dams in 2013. Note: additional HD monitoring sites were operated at Priest Rapids, Wanapum, Rock Island, and Rocky Reach dams (Public Utility Districts) and in Hood River, Fifteenmile Creek, Warm Springs River, and Shitike Creek (CTWSRO).

Site	Location	Number of antenna(s)
Bonneville Dam	PH 1, Bradford Island lamprey bypass	4
	PH 1, Bradford Island exit	1
	PH 2, WA-shore entrance	4
	PH 2, WA-shore ladder	4
	PH 2, WA-shore exit	1
	PH 2, WA-shore lamprey bypass	2
	PH2, WA-shore lamprey refuge boxes	2
	Cascades Island entrance	1
	Cascades Island lamprey bypass	2
	Cascades Island flow-control	1
The Dalles Dam	Below East ladder count window	4
	East ladder exit (above count window)[1]	4
	North ladder exit	3
John Day Dam	South fish ladder trap near count station	1
	South ladder exit	1
	North ladder entrance	4
	North ladder exit	2
McNary Dam	South-shore transition pool / ladder	4
	South-shore exit	3
	South-shore juvenile channel near exit	2
	North-shore transition pool / ladder	4
	North-shore exit	1
Ice Harbor Dam	South-shore entrance	2
	South-shore transition pool / ladder	4
	South-shore exit	1
	North-shore transition pool / ladder	4
	North-shore exit	4
L. Monumental Dam	North-shore ladder	4
	North-shore exit	2
	South-shore ladder	4
	South-shore exit	2
Lower Granite Dam	Ladder	4
	Ladder exit	2
Priest Rapids Dam	East ladder exit	3
	West ladder exit	3

[1] did not operate in 2013

Escapement rates were calculated across all release dates. Lamprey sizes (length, weight, and girth) were compared for groups that passed through a reach and those that did not using generalized linear models (PROC GLM, SAS) and analysis of variance. As a result of additional trapping effort, 40 lampreys were recaptured and these fish were transported to Stevenson, WA and released. Recaptured fish were excluded from escapement and passage time analyses where appropriate.

Lamprey migration times (d) and passage rates ($km \bullet d^{-1}$) were calculated from release to top-of-ladder HD-PIT antennas at dams and between monitored sites. Detection efficiencies for HD-PIT sites were estimated by dividing the number of fish detected at a site by the number that was detected upstream from that site. (Note: this method differs from some previous years, when double-tagged [radio and HD-PIT] fish were used to estimate efficiencies.) These estimates were conservative because fish could pass via unmonitored routes at many locations (e.g., navigation locks or alternate routes in and adjacent to fishways) and thus represent minimum estimates of detection efficiency in most cases.

Results

Lamprey Collection and Tagging

The approximate total adult lamprey count at Bonneville Dam through 31 October 2013 was 90,933 (N. Zorich, *personal communication*). A total of 943 lamprey were HD-PIT-tagged, or approximately 1.0% of the total estimated count of adult lampreys at Bonneville Dam (Figure 1). The tagged sample included 876 lampreys released downstream from Bonneville Dam, 25 released directly into the Cascades Island LPS (Figure 1) and 39 used for experimental flume trials. The analyses in this report are focused on the downstream release group, with brief summaries for the experimental groups. Sampling was generally proportional to daily counts except that the early season (May to first week in June) was not sampled. Handling restrictions during a warm-water period in mid-August also resulted in some under sampling.

The three lamprey size metrics were all positively inter-correlated in the combined 2013 HD-PIT sample (Figure 2). The coefficient of variation (CV) was 21% for weight, 8% for girth, and 7% for length for the total sample (Table 2). Release date was weakly, and negatively correlated with lamprey length, girth, and weight ($-0.29 < r < -0.26$, $P \leq 0.05$).

Detection Efficiency

Dam-wide detection efficiencies described in this section were based on lamprey soley tagged with HD-PIT tags (i.e., no records from double-tagged fish. See Noyes et al. (*in review*) for additional details derived from lampreys double-tagged with HD-PIT tags and acoustic transmitters).

In total, 342 lamprey from the downstream release group were detected at antennas upstream from Bonneville Dam. Of these 342, 263 (76.9%) were detected at one or more Bonneville HD antennas 204 (59.6%) were detected at top-of-ladder or top-of-LPS antennas, and 23 (6.7%) were recaptured and transported upstream. There were 115 (33.6% of 342) that passed the dam without a top-of-ladder or top-of-LPS detection record. Of the 115, 27 (23%) were last recorded at Bonneville Dam on an

antenna inside the Washington-shore fishway, 12 (10%) were in the Washington-shore LPS just downstream from the exit, 9 (8%) were at refuge boxes in the Washington-shore fishway, 3 (3%) were in the flow-control section of the Cascades Island fishway, and 64 (56%) were not detected at any site.

A total of 212 lamprey were detected at antennas upstream from The Dalles Dam. Of these, 163 (76.9%) were detected at one or more antennas at The Dalles Dam. We note that the top-of-ladder antenna at the top of the east ladder was not operated in 2013. Eighty-one lamprey were detected upstream from John Day Dam, all of which (100.0%) were detected at the top-of-ladder antennas at John Day Dam.

Seventy-one lamprey were detected at sites upstream from McNary Dam, of which 65 (91.5%) were detected at one or more McNary antennas and 41 (57.7%) were detected at McNary top-of-ladder antennas. Of the 30 that passed top-of-ladder sites undetected, 24 (80%) were last detected at antennas inside the south fishway, 1 (3%) were last detected on antennas inside the north fishway, and 6 (20%) were not detected at any McNary site.

Sample sizes at the Snake River dams were small (≤ 16) and there were limited upstream detection sites. Thirteen lamprey were detected upstream from Ice Harbor Dam, all of which (100%) were detected at an Ice Harbor antenna; 8 of the 13 (61.5%) were detected at top-of-ladder antennas. Four lamprey were detected at Lower Granite Dam, all of which were detected at Lower Monumental Dam (100%). No estimate was calculated for the Lower Granite antenna site.

A total of 37 lamprey were detected at either University of Idaho or PUD antennas at Wanapum Dam, all of which (100%) were detected at Priest Rapids antennas; 35 of the 37 (94.6%) were detected at the uppermost sites at Priest Rapids Dam. We did not estimate efficiency for the Wanapum, Rock Island, or Rocky Reach antenna arrays.

Downstream Release Group

Upstream Progression – Of the 876 lampreys released downstream from Bonneville Dam, 607 (69.3%) were subsequently recorded at one or more Bonneville Dam HD antennas inside fishways, at LPS systems, or at dams further upstream (Table 3). A total of 491 fish passed Bonneville Dam based on top-of-fishway or upstream detections (56.1% of the 876 released, and 80.9% of the 535 detected at one or more sites after release). Importantly, another 40 (4.6%) were recaptured in traps at Bonneville Dam and were released upstream.

The median tag date for HD-PIT tagged lampreys released downstream was 11 July (*mean* = 13 July). Median recorded passage dates at top-of-ladder sites were 26 July at Bonneville Dam (n = 3367), 31 July at The Dalles Dam (n = 117), 30 July at John Day Dam (n = 180), 4 August at McNary Dam (n = 49), 17 August at Priest Rapids Dam (n = 42), 27 August at Wanapum Dam (n = 31), and 20 August at Rocky Reach Dam (n = 3). In the Snake River, median passage dates were 11 August at Ice Harbor Dam (n = 10), 26 August at Lower Monumental Dam (n = 10), and 10 August at Lower Granite Dam (n = 3). Additional fish passed each dam without detection at top-of-ladder (or LPS) antennas (i.e., passage date was uncertain). Top-of-ladder dates of detection for the HD-PIT tagged fish indicated underrepresentation early in the run at Bonneville Dam (Figure 3a) compared to the run

at large and this partially carried over into the distributions at dams further upstream (Figures 3b and 3c). We note that tagged-fish sample sizes at all dams upstream from John Day Dam were small.

Dam-to-Dam Escapement – Of 876 fish released, 60.6% (n = 531) were known to have passed Bonneville Dam (including the 40 that were recaptured and released upstream), 31.5% (n = 276) passed The Dalles Dam, 20.5% (n = 180) passed John Day Dam, 9.0% (n = 79) passed McNary Dam, 5.0% (n = 44) passed Priest Rapids Dam, 3.5% (n = 31) passed Wanapum Dam, 0.8% passed Rock Island Dam (n = 7), and 0.6% (n = 5) passed Rocky Reach Dam (Tables 3 and 4). A total of 1.6% (n = 14) passed Ice Harbor Dam, 1.3% (n = 11) passed Lower Monumental Dam, and 0.3% (n = 3) passed Lower Granite Dam. Escapement from the top of Bonneville Dam was 52.0% to the top of The Dalles Dam, 3.9% to the top of John Day Dam, and 14.9% to the top of McNary Dam. Escapements were 65.2% between ladder tops at The Dalles and John Day dams and 43.9% between ladder tops at John Day and McNary dams. Of 79 lampreys that passed McNary Dam, 14 (17.7%) passed Ice Harbor Dam and 44 (55.7%) passed Priest Rapids Dam (Tables 3 and 4).

Lamprey that passed upstream sites were larger ($P < 0.05$) than those that did not pass and the patterns was generally consistent across river reaches (Table 5). This relationship between size metrics and reach escapement was the same whether recaptured fish were included or excluded. Escapement through a reach was not associated with the date that lampreys were released downstream from Bonneville Dam, except that those that passed John Day Dam were tagged 5 d earlier (on average) than those that did not).

Passage Times and Rates – Median HD-PIT tagged lamprey passage times were 6.3 d from the release site to the top of Bonneville Dam, 4.0 d between Bonneville and The Dalles dams, 4.3 d between The Dalles and John Day dams, and 9.2 d between John Day and McNary dams (top-of-ladder sites at all dams, Table 7). Median passage rates in these reaches were < 1 km●d^{-1} (release-Bonneville top), 18.3 km●d^{-1} (Bonneville-The Dalles), 9.0 km●d^{-1} (The Dalles-John Day), and 13.4 km●d^{-1} (John Day-McNary). Above McNary Dam, median passage times were 14.8 d (11.4 km●d^{-1}) between McNary and Priest Rapids dams, 4.6 d (14.8 km●d^{-1}) between McNary and Ice Harbor dams, and 6.9 d (4.4 km●d^{-1}) between Priest Rapids and Wanapum dams. Median times between Ice Harbor and Lower Monumental dams were 6.8 d (7.5 km●d^{-1}) (Table 7). Small sample sizes at Rock Island and Lower Granite dams precluded meaningful summaries for reaches that included those sites.

Last Detection Summary – A total of 244 (27.9%) of the 876 lampreys released near Hamilton Island were not subsequently detected (Table 8). Another 92 (10.5%) were last recorded at HD antennas inside Bonneville Dam fishways, 158 (18.0%) were at top-of-ladder exit sites or LPS sites, and 18 (2.1%) were recaptured at the AFF (including one mortality). Seven fish (1.1%) were last recorded in Fifteenmile Creek or its tributaries and 10 (1.1%) were recorded in the Hood River system. A total of 114 (13.0%) were last detected at The Dalles Dam, and 22 (2.5%) were recorded in the Deschutes River. Above the Deschutes River, 127 (14.5%) were at John Day Dam, 14 (1.6%) were at McNary Dam, 16 (1.8%) were at Snake River dams, and 55 (6.3%) were at dams in the upper Columbia River (Priest Rapids through Rocky Reach dams) (Table 8).

When lampreys were grouped based on final recorded location, median release dates varied only slightly among groups with adequate sample size (Figure 6). Fish last recorded in Bonneville tributaries (Hood River and Fifteenmile Creek) and in the Snake River were tagged slightly earlier, on median, than the other groups. In contrast, there were clear among-group differences in lamprey size

(Figure 7). On median, lampreys were largest in the Snake River (531 g) and upper Columbia River (492 g) groups. Lampreys were smallest in the groups last recorded in Bonneville tributaries (*median* = 330 g) and at the release site (*median* = 412 g).

Stevenson Release Group (used in flume study)

The 39 HD-PIT tagged lampreys released near Stevenson, WA were not tagged in proportion to the run (Figure 1). This subsample was collected on seven dates from 15 June to 25 July (*mean* = 7 July). Mean size metrics for the upstream release group were slightly higher than those for the downstream release group at the time of release (Table 2). We did not estimate passage times or escapement rates for this experimental group. Final detection locations suggest that the extra handling in the experiment did not have a large negative effect on upstream distribution. Twenty-seven (69%) were last recorded at or upstream from The Dalles Dam, including 8 (21%) at the top of John Day Dam and 6 (15%) at dams in the upper Columbia River (Table 8).

Cascades Island LPS Release Group

Twenty-five HD PIT-tagged lampreys were experimentally released into the lower Cascades Island LPS in 2013. Releases occurred on 5 dates from 10 July to 11 September (Figure 1). On average, these lampreys were slightly smaller than those in the downstream release group and those from the flume study that were released near Stevenson (Table 2).

Final detections for the 25 fish were: 14 (56%) in the Cascades Island LPS, 1 (4%) inside the Cascades Island fishway, 7 (28%) inside or at the top of The Dalles fishways, 3 (12%) at Wanapum Dam, and 1 (7%) at Rocky Reach Dam (Table 8). Relatively late collection dates, small sample size, and the release site precluded direct comparisons with the downstream release group.

Detection of Lamprey Tagged in 2012

A total of 33 (2.8%) of the 1,198 lampreys tagged in 2012 were detected on HD antennas in 2013. These included 27 (3.3%) of the 819 HD-only fish released downstream from Bonneville Dam, 1 (4.0%) of the 25 HD-only fish released near Stevenson, WA, 4 (8.0%) of 25 released into the Cascades Island LPS, and 6 (2.0%) of 299 double-tagged (JSATS + HD PIT) fish released. The median 2012 release date for the 33 overwintering fish was 22 July (*range* = 6 June to 7 September). Final recorded locations included: 9 (51%) (27%) at Bonneville Dam, 1 (3%) at The Dalles Dam, 9 (27%) at John Day Dam, 1 (3%) each at McNary and Lower Monumental dams, 3 (9%) each at Priest Rapids and Wanapum dams, and 6 (18%) at Rocky Reach Dam. The last 2013 records were in April (12%), May (18%), June (27%), July (18%), August (3%), and September (21%). Most of the late 2013 detections were at Rocky Reach Dam.

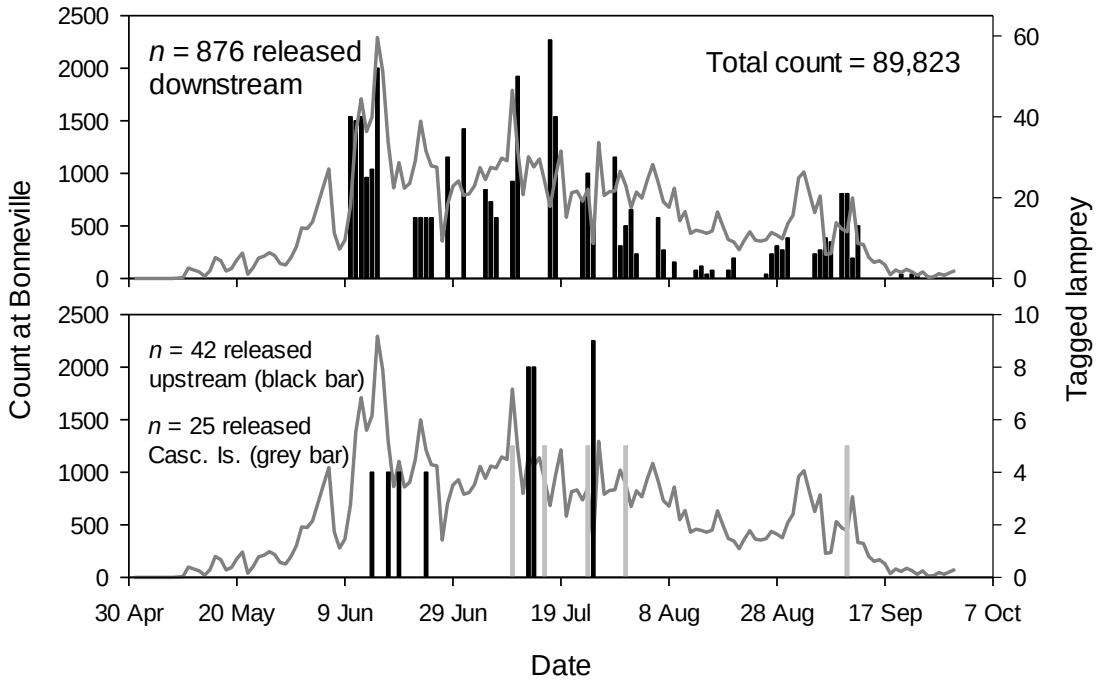

Figure 1. Number of adult Pacific lamprey counted passing Bonneville Dam during the day and night (solid line) and the numbers that were collected and HD-PIT tagged (bars) in 2013. Top panel shows fish released downstream from Bonneville Dam near Hamilton Island and bottom panel shows fish released upstream from the dam near Stevenson, WA or directly into the Cascades Island LPS.

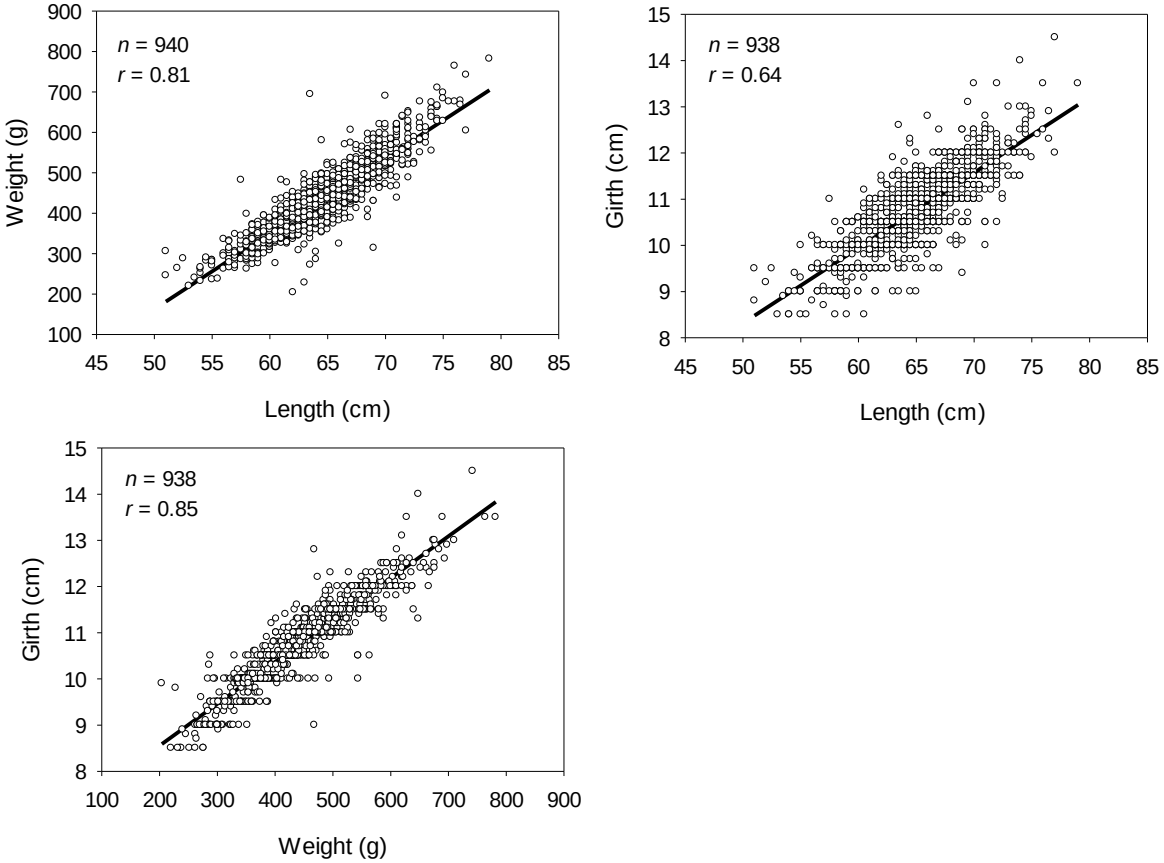

Figure 2. Linear relationships between length, weight, and girth metrics for adult lampreys HD-PIT tagged in 2013. Note: all release groups combined. All $P < 0.005$.

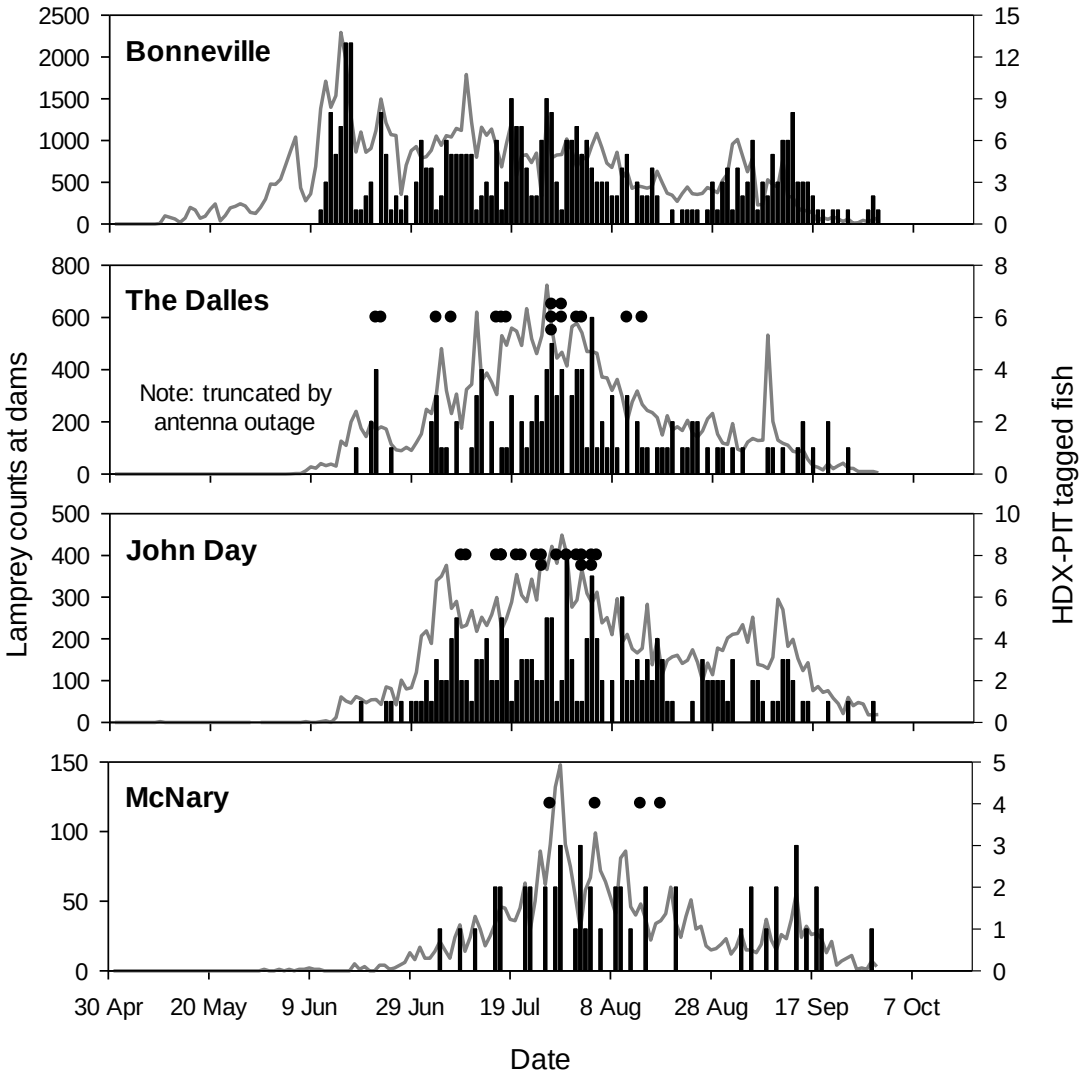

Figure 3a. Daily numbers of adult Pacific lamprey counted passing lower Columbia River dams via fish ladders (gray lines) and the numbers of HD-PIT tagged fish that were detected at top-of-ladder antennas (black bars = detections from fish released downstream from Bonneville; ● = detections from fish released upstream from Bonneville Dam or into the Cascades Island LPS) in 2013. Notes: many tagged lampreys passed dams undetected, particularly at The Dalles and McNary dams; counts include all available counts (day, night, LPS, capture). Note scale differences.

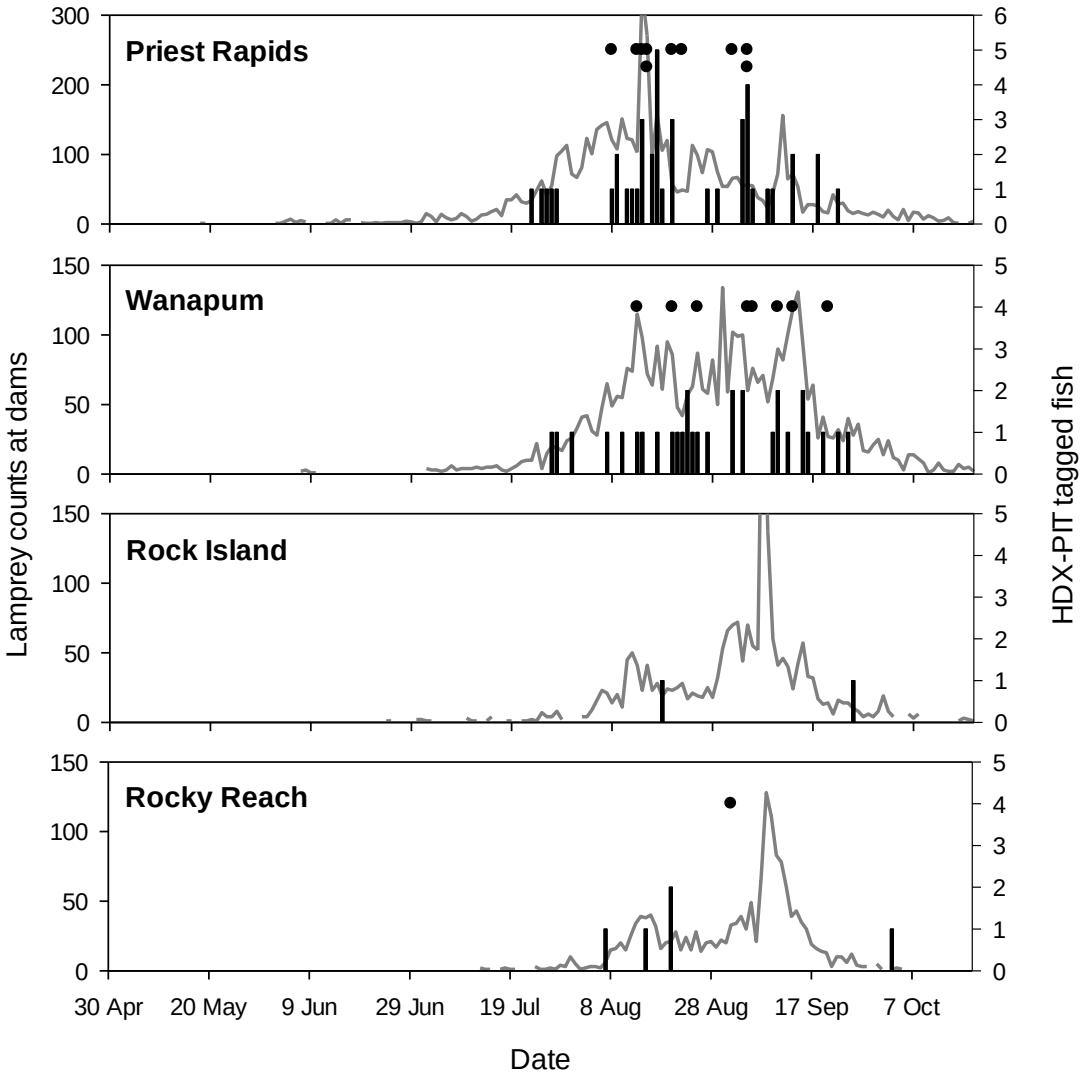

Figure 3b. Daily numbers of adult Pacific lamprey counted passing upper Columbia River dams via fish ladders (gray lines) and the numbers of HD-PIT tagged fish that were detected at top-of-ladder antennas (black bars = detections from fish released downstream from Bonneville; ● = detections from fish released upstream from Bonneville Dam or into the Cascades Island LPS) in 2013. Notes: detection data at Wanapum, Rock Island, and Rocky Reach dams provided by Chelan and Grant County PUDs; count data are daytime count station only. Note scale differences.

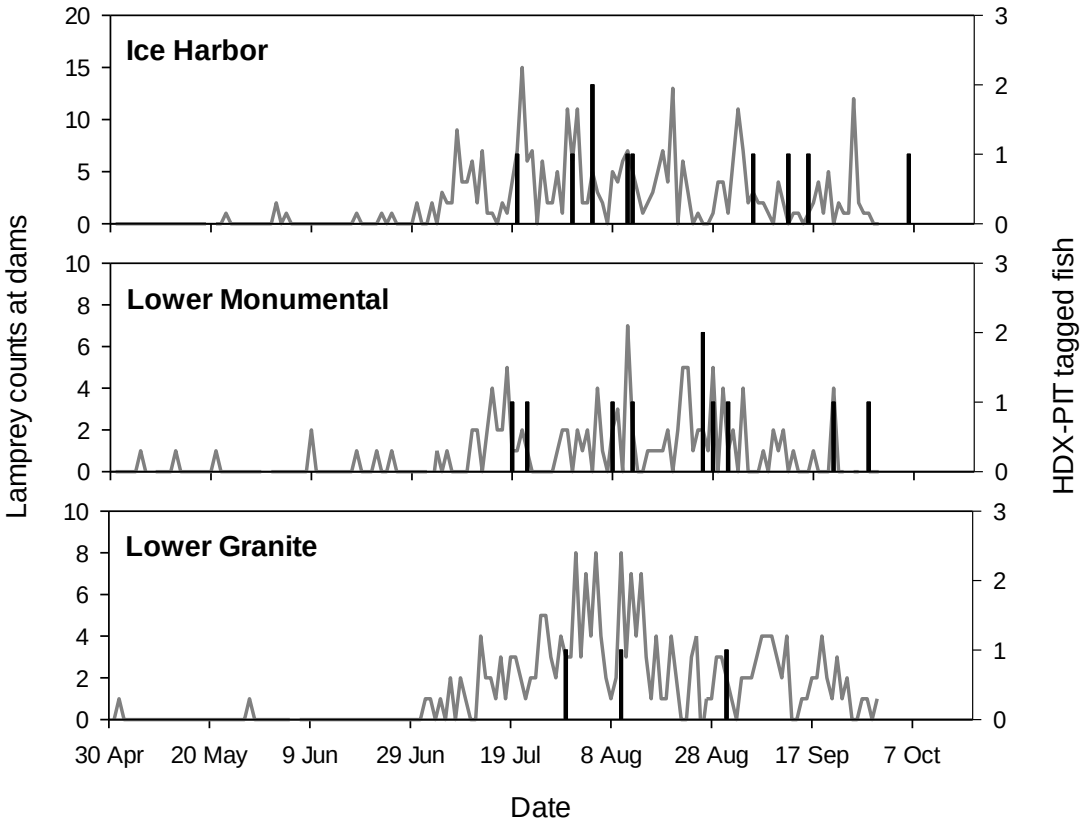

Figure 3c. Daily numbers of adult Pacific lamprey counted passing Snake River dams via fish ladders (gray lines) and the numbers of HD-PIT tagged fish that were detected at top-of-ladder antennas (black bars = detections from fish released downstream from Bonneville) in 2013. Notes: small numbers of fish passed undetected; count data are daytime count station only. Note scale differences.

Table 2. Length, girth, and weight of adult Pacific lampreys collected and tagged with HD-PIT tags and released downstream from Bonneville Dam near Hamilton Island (HAM), upstream from the dam near Stevenson, WA (STE), or in the Cascades Island LPS (CI) in 2013.

	Length (cm)			Girth (cm)			Weight (g)		
Type	*n*	Mean	*sd*	*n*	Mean	*sd*	*n*	Mean	*sd*
PIT-HAM	871	65.0	4.4	872	10.8	0.9	872	443.7	91.9
PIT-STE[1]	42	66.1	4.5	42	11.2	1.0	42	468.7	91.1
PIT-CI	25	63.8	4.9	25	10.5	0.8	25	418.8	95.4
All fish	941	65.0	4.4	939	10.8	0.9	942	443.0	92.0

[1] the Stevenson release group was used in flume studies and is not comparable to past years; *n* = 39 released

Table 3. Minimum numbers of adult lamprey that passed each site estimated as the number of adult HD-PIT tagged lamprey detected at dam antennas or inferred to pass sites based on upstream detections in 2013. Lamprey were released **d**ownstream from Bonneville Dam near Hamilton Island, upstream from the dam near Stevenson, WA, or into the Cascades Island LPS. See Table 1 for antenna locations.

	Release group		
Site	Hamilton Island Minimum past (*n*)	Stevenson Minimum past (*n*)	Cascades Island Minimum past (*n*)
Release	876	39	25
Bonneville[1]	607	-	-
Bonneville top[2]	491-531[4]	-	11
The Dalles[1]	348	27	11
The Dalles top[2]	276	21	7
John Day[1]	212	14	4
John Day top[2]	180	14	4
McNary[1]	85	6	4
McNary top[2]	79	6	4
Ice Harbor[1]	16	-	-
Ice Harbor top[2]	14	-	-
L. Monumental[1]	13	-	-
L. Monument top[2,3]	11	-	-
L. Granite[1]	4	-	-
L. Granite top[2,3]	3	-	-
Priest Rapids[5]	55	6	4
Priest Rapids top[5]	44	6	4
Wanapum[5]	39	5	4
Wanapum top[5]	31	4	4
Rock Island[5]	18	2	1
Rock Island top[5]	7	2	1
Rocky Reach[5]	7	2	1
Rocky Reach top[5]	5	1	0

[1] all fishway antennas, including LPS at Bonneville
[2] top-of-ladder antennas, including LPS at Bonneville
[3] no or limited upstream sites to assess missed detections
[4] higher numbers include fish recaptured in Bonneville traps and released upstream
[5] combined detections at UI and PUD antennas

Table 4. Adult HD-PIT tagged lamprey escapement estimates for fish released downstream from Bonneville Dam near Hamilton Island, upstream from the dam near Stevenson, WA, or into the Cascades Island LPS in 2013. Estimates exclude double-tagged fish. See Table 3 for sample sizes.

Reach	Hamilton Island Escapement	Stevenson Escapement	Cascades Island Escapement
Release-Bonneville	69.3%	-	-
Release-Bonneville top[1]	56.1-60.6%	-	-
Release-The Dalles	39.7%	69.2%	44.0%
Release-The Dalles top	31.5%	53.8%	28.0%
Release-John Day	24.2%	35.9%	16.0%
Release-John Day top	20.5%	35.9%	16.0%
Release-McNary	9.7%	15.4%	16.0%
Release-McNary top	9.0%	15.4%	16.0%
Release-Ice Harbor top	1.6%	-	-
Release-Lower Monumental top	1.2%	-	-
Release-Lower Granite top	0.3%	-	-
Release-Priest Rapids top	6.3%	14.3%	16.0%
Release-Wanapum top	3.5%	9.5%	16.0%
Release-Rock Island top	0.8%	4.8%	4.0%
Release-Rocky Reach top	0.6%	2.4%	-
Bonneville-Bonneville top[1]	80.9-87.5%	-	-
Bonneville top-The Dalles top	52.0%	-	63.6%
Bonneville top-John Day top	33.9%	-	36.4%
Bonneville top-McNary top	14.9%	-	36.4%
Bonneville top-Ice Harbor top	2.6%	-	-
Bonneville top-L. Monum. top	2.1%	-	-
Bonneville top-L. Granite top	0.6%	-	-
Bonneville top-Pr. Rapids top	8.3%	-	36.4%
Bonneville top-Wanapum top	5.8%	-	36.4%
Bonneville top-Rock Island top	1.3%	-	9.1%
Bonneville top-Rocky Reach top	0.9%	-	-
The Dalles top-John Day top	65.2%	66.7%	57.1%
The Dalles top-McNary top	28.6%	28.6%	57.1%
The Dalles top-Ice Harbor top	5.1%	-	-
The Dalles top-L. Monum. top	4.0%	-	-
The Dalles top-L. Granite top	1.1%	-	-
The Dalles top-Pr. Rapids top	15.9%	28.6%	57.1%
The Dalles top-Wanapum top	11.2%	19.0%	57.1%
The Dalles top-Rock Island top	2.5%	9.5%	14.3%
The Dalles top-Rocky Reach top	1.8%	4.8%	-

[1] lower estimate treats recaptured fish as not passing; higher estimate treats them as passed

Table 4 (cont).

Reach	Hamilton Island Escapement	Stevenson Escapement	Cascades Island Escapement
John Day top-McNary top	43.9%	42.9%	100.0%
John Day top-Ice Harbor top	7.8%	-	-
John Day top-L. Monum. top	6.1%	-	-
John Day top-L. Granite top	1.7%	-	-
John Day top-Priest Rapids top	24.4%	42.9%	100.0%
John Day top-Wanapum top	17.2%	28.6%	100.0%
John Day top-Rock Island top	3.9%	14.3%	25.0%
John Day top-Rocky Reach top	2.8%	7.1%	-
McNary top-Ice Harbor top	17.7%	-	-
McNary top-L. Monum. top	13.9%	-	-
McNary top-L. Granite top	3.8%	-	-
McNary top-Priest Rapids top	55.7%	100.0%	100.0%
McNary top-Wanapum top	39.2%	66.7%	100.0%
McNary top-Rock Island top	8.9%	33.3%	25.0%
McNary top-Rocky Reach top	6.3%	16.7%	-
Priest Rapids top-Wanapum top	70.5%	66.7%	100.0%
Priest Rapids top-Rock Island top	15.9%	33.3%	25.0%
Priest Rapids top-Rocky Reach top	11.4%	16.7%	-
Wanapum top-Rock Island top	22.6%	50.0%	25.0%
Wanapum top-Rocky Reach top	16.1%	25.0%	-
Rock Island top-Rocky Reach top	71.4%	50.0%	-
Ice Harbor top-L. Monum. Top	78.6%	-	-
Ice Harbor top-L. Granite top	21.4%	-	-
L. Monum. top-L. Granite top	27.3%	-	-

[1] lower estimate treats recaptured fish as not passing; higher estimate treats them as passed

Table 5. Mean HD-PIT tagged lamprey tag dates and size metrics in relation to their escapement through the monitored reaches, for 876 fish released downstream from Bonneville Dam in 2013. Top-of-ladder sites were used for the upper end of each reach[1]. *P* values are from analysis of variance tests (ANOVA).

	Reach		Pass		No pass		
Variable	Start	End	*n*	*mean*	*n*	*mean*	*P*
Tagdate	Release	Bonneville top	531	14 Jul	345	13 Jul	0.468
	Release	The Dalles top	276	12 Jul	600	15 Jul	0.257
	Release	John Day top	180	10 Jul	696	15 Jul	**0.031**
	Release	McNary top	79	9 Jul	797	14 Jul	0.065
	Release	Ice Harbor top	14	7 Jul	862	14 Jul	0.370
	Release	Priest Rapids top	44	6 Jul	832	14 Jul	0.065
Length (cm)	Release	Bonneville top	531	65.2	345	64.4	**0.027**
	Release	The Dalles top	276	66.3	600	64.2	**< 0.001**
	Release	John Day top	180	66.7	696	64.4	**< 0.001**
	Release	McNary top	79	67.4	979	64.6	**< 0.001**
	Release	Ice Harbor top	14	69.3	862	64.8	**0.002**
	Release	Priest Rapids top	44	66.8	832	64.8	**0.018**
Weight (g)	Release	Bonneville top	531	452.0	345	429.7	**< 0.001**
	Release	The Dalles top	276	472.6	600	429.7	**< 0.001**
	Release	John Day top	180	479.4	696	433.9	**< 0.001**
	Release	McNary top	79	496.2	797	438.0	**< 0.001**
	Release	Ice Harbor top	14	538.6	862	441.7	**< 0.001**
	Release	Priest Rapids top	44	487.0	832	440.9	**0.001**
Girth (cm)	Release	Bonneville top	531	10.8	345	10.6	**0.017**
	Release	The Dalles top	276	11.0	600	10.6	**< 0.001**
	Release	John Day top	180	11.1	696	10.6	**< 0.001**
	Release	McNary top	79	11.3	797	10.6	**< 0.001**
	Release	Ice Harbor top	14	11.8	862	10.7	**< 0.001**
	Release	Priest Rapids top	44	11.2	832	10.7	**0.003**

[1] lamprey recaptured at Bonneville and released upstream were treated as passing

Table 6. Mean HD-PIT tagged lamprey weight in relation to their escapement through the monitored dam-to-dam reaches, for fish released downstream from Bonneville Dam in 2013. Top-of-ladder sites were used for the upper end of each reach[1]. *P* values are from analysis of variance tests (ANOVA).

	Reach		Pass		No pass		
Variable	Start	End	*n*	*mean*	*n*	*mean*	*P*
Weight (g)	Bonneville top	The Dalles top	276	472.6	255	429.7	< **0.001**
	The Dalles top	John Day top	160	479.4	96	460.0	0.067
	John Day top	McNary top	79	496.2	101	466.2	**0.009**
	McNary top	Ice Harbor top	14	538.6	65	487.0	**0.011**
	McNary top	Priest Rapids top	44	487.0	35	507.7	0.191
	Ice Harbor top	L. Monumental top	11	532.7	3	560.0	0.469
	L. Monumental top	L. Granite top	3	510.7	8	541.0	0.408
	Priest Rapids top	Wanapum top	31	496.9	13	463.4	0.148
	Wanapum top	Rocky Island top	7	505.4	24	494.4	0.702
	Rocky Island top	Rocky Reach top	5	497.2	2	526.0	0.586

Table 7. Summary of HD-PIT tagged adult lamprey passage times (d) through monitored reaches of the lower Columbia River, for fish released downstream from Bonneville Dam in 2013. Only includes reaches with 5 or more fish.

		Passage time (d)			
Reach	*n*	Median	Mean	Quartile 1	Quartile 3
Release to pass Bonneville Dam	365	6.29	11.68	2.23	15.28
Release to pass The Dalles Dam	117	16.04	18.92	8.24	26.40
Release to pass John Day Dam	180	18.71	22.99	12.57	29.17
Release to pass McNary Dam	49	29.24	35.44	22.16	44.23
Release to pass Priest Rapids Dam	42	43.78	45.93	35.28	55.76
Release to pass Wanapum Dam	31	50.42	53.76	41.62	61.35
Release to pass Rocky Reach Dam	5	52.12	50.10	33.33	62.29
Release to pass Ice Harbor Dam	10	40.86	40.34	28.65	46.42
Release to pass L. Monumental Dam	10	37.20	48.56	33.82	58.41
Release to pass L. Granite Dam	3	47.48	47.40	42.94	51.90
Bonneville top to pass The Dalles Dam	73	4.04	6.65	2.85	6.78
Bonneville top to pass John Day Dam	103	9.97	12.20	6.79	14.12
Bonneville top to pass McNary Dam	23	18.91	24.00	15.73	30.58
Bonneville top to pass Priest Rapids Dam	23	33.00	34.82	25.49	33.63
Bonneville top to pass Wanapum Dam	17	43.72	47.28	39.43	51.23
Bonneville top to pass Ice Harbor Dam	6	24.75	28.07	22.56	33.63
The Dalles top to pass John Day Dam	59	4.28	7.41	3.00	9.18
The Dalles top to pass McNary Dam	16	16.57	24.34	12.79	36.92
The Dalles top to pass Priest Rapids Dam	14	27.81	29.74	22.22	36.71
The Dalles top to pass Wanapum Dam	10	38.49	38.06	29.80	46.10
The Dalles top to pass Ice Harbor Dam	7	21.20	24.84	17.67	30.63
The Dalles top to pass L. Monumental Dam	5	25.75	25.67	19.13	32.18
John Day top to pass McNary Dam	49	9.18	14.43	6.90	18.00
John Day top to pass Priest Rapids Dam	42	24.97	28.29	19.11	36.09
John Day top to pass Wanapum Dam	31	34.85	36.30	24.88	41.34
John Day top to pass Rocky Reach Dam	5	29.17	37.62	29.05	44.85
John Day top to pass Ice Harbor Dam	10	17.36	15.68	8.99	17.94
John Day top to pass L. Monumental Dam	10	21.95	20.99	17.23	22.64
McNary top to pass Priest Rapids Dam	23	14.83	17.68	9.67	23.31
McNary top to pass Wanapum Dam	15	25.93	24.07	13.66	30.68
McNary top to pass Ice Harbor Dam	8	4.58	6.19	2.71	7.21
McNary top to pass L. Monumental Dam	6	12.22	12.82	10.35	13.63
Priest Rapids top to pass Wanapum Dam	29	6.85	10.36	3.21	11.10
Wanapum top to pass Rocky Reach Dam	5	10.07	10.16	5.93	12.97
Ice Harbor top to pass L. Monumental Dam	6	6.81	8.42	4.43	12.48

Note: overwintering fish not included; recaptured fish included

Table 8. Last recorded locations for HD-PIT-only tagged adult Pacific lampreys in 2013 released downstream from Bonneville Dam near Hamilton Island, into the Cascades Island LPS, and upstream from the dam near Stevenson, WA. WA = Washington shore fishway; LPS = lamprey passage structure. Note: Hood River, Fifteenmile Creek, and Warm Springs River sites were maintained by the CTWRSO; some Wanapum sites and all Rock Island, Rocky Reach sites were maintained by Chelan and Grant county PUDs.

	Hamilton Island (*n* =876)		Stevenson (*n* = 39)		Cascades Island (*n* = 25)	
Last recorded location	*n*	%	*n*	%	*n*	%
Release site	244	27.9%	12	30.8%	2	8.0%
Bonneville Dam – Casc. Is. flow cont.	23	2.6%				
Bonneville Dam – lamprey rest boxes	16	1.8%				
Bonneville Dam – Casc. Is. LPS[1]	2	0.2%			12	48.0%
Bonneville Dam – WA ladder	52	5.9%				
Bonneville Dam – recapture[2]	18	2.1%				
Bonneville Dam – WA LPS[4]	34	3.9%				
Bonneville Dam – WA ladder exit	93	10.6%				
Bonneville Dam – Bradford LPS[3]	11	1.3%				
Bonneville Dam – Bradford exit	18	2.1%				
Hood River	10	1.1%				
Fifteenmile Creek	7	0.8%				
At The Dalles Dam	72	8.2%	6	15.3%	4	16.0%
The Dalles ladder exits	42	4.8%	6	15.3%	3	12.0%
Deschutes River mouth	14	1.6%	1	2.6%		
Shitike Creek (Deschutes)	2	0.2%				
Sherars Falls (Deschutes)	2	0.2%				
Warm Springs River (Deschutes)	4	0.5%				
At John Day Dam	[5]32	3.7%				
John Day ladder exits	95	10.8%	8	20.5%		
At McNary Dam	6	0.7%				
McNary Dam ladder exits	8	0.9%				
Ice Harbor Dam	3	0.3%				
Lower Monumental Dam	9	1.0%				
Lower Granite Dam	4	0.5%				
Priest Rapids Dam	16	1.8%	1	2.6%		
Wanapum Dam	21	2.4%	3	7.7%	3	12.0%
Rock Island Dam	11	1.3%				
Rocky Reach Dam	7	0.8%	2	5.1%	1	4.0%

[1] recaptured fish; [2] includes 17 recaptured fish and 1 mortality (CRITFC)
[3] includes 1 not recorded at uppermost LPS site; [4] includes 4 not recorded at uppermost LPS site
[5] includes 9 captured at the JD trap by Tribal groups

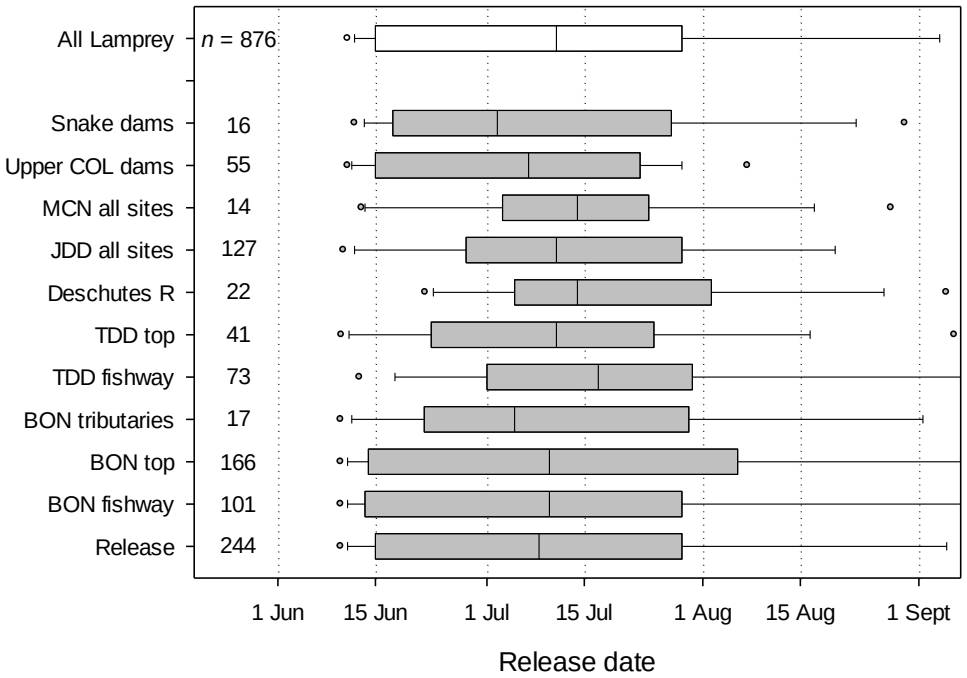

Figure 6. Distributions of lamprey release dates downstream from Bonneville Dam by the final recorded locations for each fish. Fishway locations include fish last recorded inside fishways without evidence of passing. Box plots show 5th, 25th, 50th, 75th and 95th percentiles.

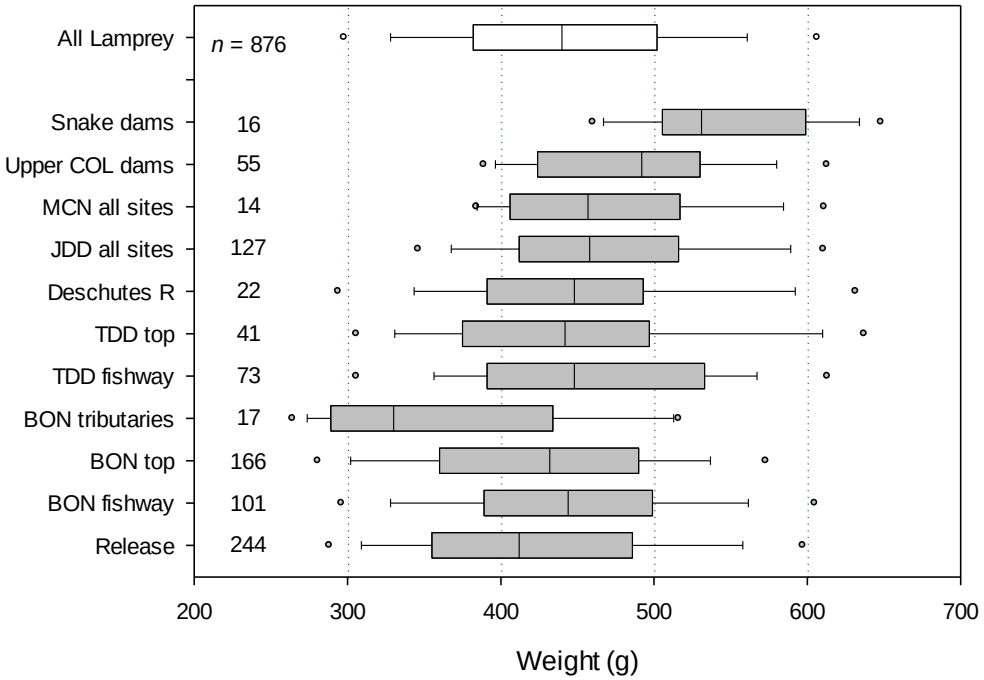

Figure 7. Distributions of lamprey weights (g) by the final recorded locations for each fish (grey boxes). Data shown are for lamprey released downstream from Bonneville Dam**.** Fishway locations include fish last recorded inside fishways without known passage. Box plots show 5th, 25th, 50th, 75th and 95th percentiles.

Discussion

2013 HD-PIT Sample

Institutional constraints at Bonneville Dam resulted in a delayed start to the Pacific lamprey tagging effort in 2013 (Figure 1). The tagged sample therefore did not include migrants in May and early June and made it somewhat more difficult to make direct comparisons between the 2013 results and results from previous years. However, the 2013 sample was reasonably representative of the lamprey passing the Bonneville fishways for the majority of the migration season (see Figure 3). Future multi-year escapement and distribution analyses can statistically control for the delayed start in 2013 (e.g., Keefer et al. 2013c).

Escapement

The migration-scale escapement summaries generated by the 2005-2013 HD-PIT studies provide the most consistently collected baseline monitoring data for adult Pacific lamprey in the Columbia River Basin. In 2013, lamprey escapement for the downstream release group from release past Bonneville Dam (56%) was at the upper end of the distribution of estimates in HD-PIT samples from 2005-2012 (41-56%, Table 9). The past-Bonneville estimate of 56% was likely an underestimate because additional fish were recaptured inside the fishways and were transported upstream in 2013; had these recaptured fish passed the dam volitionally, the escapement estimate would have been 61%. Furthermore, the low top-of-fishway detection efficiency at the Bonneville HD antenna array suggests that additional fish passed the dam undetected. The estimate is therefore conservative, as in past years.

The percentage of lampreys that passed John Day Dam (21%) and McNary Dam (9%) in 2013 compared favorably with previous estimates of 14-24% past John Day Dam and 2-8% past McNary Dam. Dam-to-dam estimates in 2013 were higher than in previous years for the John Day-McNary (44%) and McNary-Priest Rapids (56%) reaches; they were in the range of previous estimates for The Dalles-John Day and McNary- Ice Harbor reaches (Table 9). Detection efficiency of ~100% at the top-of-ladder John Day Dam sites make this the best location for year-to-year comparisons.

As mentioned above, full-migration comparisons of the 2013 escapement estimates to estimates from other years should be made cautiously. We would expect that the bias in the 2013 sample for later migrants would result in lower escapement past upriver dams because we have seen a reduction in upstream passage in late summer when water temperatures reach annual highs (e.g., Keefer et al. 2012, 2013a). However, in a multi-year analyses using radio-tagged lamprey, we also found that low discharge and warm temperatures were associated with high passage efficiency at Bonneville Dam (Keefer et al. 2012b). The slightly below-average discharge and warm-temperature conditions in 2013 (Appendix A) may have resulted in relatively more fish past Bonneville, but relatively higher attrition in upstream reaches. These environmental and tagging effects may be partially countervailing.

Our multi-year analyses of HD-PIT tagged lamprey escapement past Bonneville and John Day dams have indicated that there have been modest improvements in adult passage at the lower river dams through time (Keefer et al. 2013c), and the 2013 results support this conclusion. Importantly, our modeling effort using the 2005-2012 data statistically controlled for lamprey size, release date, and environmental factors (note: continued synthesis is planned). Positive operations-related effects on

Table 9. Summary of release to top-of ladder and dam-to-dam reach escapement estimates for HD-PIT tagged (only) lampreys released downstream from Bonneville Dam from 2005-2013 and recorded at or known to pass top-of-ladder sites at monitored dams. Numbers in parentheses are the number past the upstream dam for the reaches starting at release and the number at the downstream dam for the dam-to-dam estimates.

		Release to ladder exit			
Year	Rel	BO	TD	JD	MN
2005	841	0.53 (446)	-	-	0.05 (40)
2006	2000	0.41 (822)	0.28 (558)	0.19 (382)	0.04 (80)
2007	757	0.52 (393)	0.33 (246)	0.17 (129)	0.05 (35)
2008	608	0.52 (318)	0.27 (166)	0.18 (109)	0.05 (28)
2009	368	0.47 (172)	0.25 (90)	0.14 (50)	0.02 (8)
2010	13	[1]0.58 (7)	0.23 (3)	0.15 (2)	-
2011	800	[2]0.56 (451)	0.30 (238)	0.24 (190)	0.08 (65)
2012	823	[3]0.50 (414)	0.26 (212)	0.22 (177)	0.08 (69)
2013	876	[4]0.56 (491)	0.32 (276)	0.21 (180)	0.09 (79)

	Ladder exit to ladder exit				
	BO - TD	TD - JD	JD - MN	MN - IH	MN - PR
2005	n/a	n/a	n/a	0.05 (40)	n/a
2006	0.67 (840)	0.69 (565)	0.21 (387)	0.06 (82)	n/a
2007	0.63 (393)	0.52 (247)	0.27 (129)	0.14 (35)	n/a
2008	0.52 (318)	0.66 (166)	0.26 (109)	0.18 (28)	0.11 (28)
2009	0.52 (172)	0.56 (90)	0.16 (50)	0.0 (8)	0.50 (8)
2010	0.38 (8)	0.67 (3)	-	-	-
2011	0.52 (462)	0.80 (238)	0.34 (190)	0.23 (65)	0.54 (65)
2012	0.47 (447)	0.83 (212)	0.39 (177)	0.16 (69)	0.49 (69)
2013	0.52 (531)	0.65 (276)	0.44 (180)	0.18 (79)	0.56 (79)

[1] 0.62 (n = 8); [2] 0.58 (n = 460); [3] 0.54 (n = 447); [4] 0.61 (n = 531) when recaptures were treated as passing the dam

Table 10. Numbers of HD-PIT tagged lampreys (only) released downstream from Bonneville Dam from 2005-2013, mean lamprey length, weight, and girth and the median passage time (days) to pass selected reaches in the lower Columbia River. Note: weight was not collected for all fish in all years.

					Median passage times (d)			
Year	Released	Mean Length	Mean Weight	Mean Girth	Release - Top BO	Top BO - Top TD	Top TD - Top JD	Top JD - Top MN
2005[1]	841	67.9	500	11.5	n/a	n/a	n/a	n/a
2006	2000	67.0	482	11.2	9.6 d	5.1 d	4.1 d	12.8 d
2007	757	64.8	445	10.9	6.5 d	4.0 d	4.3 d	8.8 d
2008	608	64.7	434	10.6	7.7 d	4.9 d	3.7 d	5.4 d
2009	368	65.3	443	10.8	11.5 d	6.7 d	4.1 d	9.8 d
2010	13	63.0	-	-	-	-	-	-
2011	800	64.8	437	10.8	10.2 d	4.3 d	3.4 d	9.1 d
2012	823	65.3	449	10.9	11.3 d	4.7 d	3.3 d	7.5 d
2013	876	65.0	444	10.8	6.3 d	4.0 d	4.3 d	9.2 d

[1] released into the Bradford Island fishway

lamprey passage include increased fishway entrance efficiency at Bonneville Dam as a result of night-time fishway velocity reductions at Powerhouse 2 (Johnson et al. 2012a). Other structural improvements inside Bonneville fishways, along with the installation of LPSs have increased overall dam passage efficiency at Bonneville Dam (Moser et al. 2011; Corbett et al. 2013). Upstream from Bonneville Dam, the USACE has implemented operational and structural changes to fishways to benefit lampreys (e.g., orifice rounding, addition of diffuser plating, weir modifications, addition of ramps to raised orifices, raising picket leads, blocking access to routes without exits, etc.) at lower Columbia and lower Snake River dams. The cumulative effects of these changes may or may not have contributed to higher escapement, particularly past the upriver sites (i.e., John Day and McNary dams).

The 2013 escapement data for the downstream release group consistently indicated higher passage efficiency for larger fish at a variety of spatial scales, consistent with many previous studies (e.g., Keefer et al. 2009b, 2013a, 2013b). We have hypothesized that this pattern is related to swimming ability, energetic reserves, and/or to more negative handling effects for smaller fish (e.g., Moser et al. 2007). However, handling effects almost certainly cannot fully account for the size effects reported across recent studies because the size effect has been evident regardless of tag type and size (i.e., HD vs. radiotelemetry) and handling time (i.e., longer for radiotelemetry) and there has been no evidence of an interaction between size and tag effects. There is also some recent evidence that the relationship between migration distance and lamprey body size may have a genetic basis. Hess et al. (*in press*) found some markers that link Pacific lamprey phenotype (e.g., body size) with migration distance in the Columbia River basin.

Passage times

Lamprey migration times through dam-to-dam study reaches generally fell within the ranges reported in previous HD-PIT study years (Table 10). An exception was that lamprey passed from release past Bonneville Dam slightly faster than in any other year, perhaps as a result of the relatively late sampling in 2013 (i.e., warmer temperatures, lower flow). Because HD-PIT monitoring was limited to fishways, it was not possible to separate the time lampreys spent passing dams versus migrating through reservoirs. Median migration rates from ladder top to ladder top (i.e., past one reservoir + one dam) were mostly 9-18 $km \bullet d^{-1}$. These rates were similar to the median (11 $km \bullet d^{-1}$) and maximum (21 $km \bullet d^{-1}$) passage rates recorded for radio-tagged lampreys in the unimpounded John Day, Snake, and Clearwater rivers (Robinson and Bayer 2005; McIlraith et al. *in review*) and were faster than rates recorded for radio-tagged lampreys in the Willamette River (Clemens et al. 2012). Noyes et al. (*in review*) study of JSATS-tagged adult lamprey separate migration rates for reservoirs.

Final distribution

More locations were monitored with HD-PIT antennas in 2013 than in any previous year. The most important addition was the FD-HD site at the mouth of the Deschutes River, where the HD option was enabled in August. This site complements the recent increased coverage at the upper Columbia River dams, and in the Hood River, Umatilla River, and Fifteenmile Creek drainages. These sites help with a final accounting for fish that would not have been possible previously. We note that the addition of new monitoring sites complicates direct inter-annual comparisons of reach escapement, proportions unaccounted for between dams, and final distribution estimates. Despite improvements,

monitoring tributary entry remains a critical challenge for adult lamprey HD PIT tagging studies. The existing FD-PIT site on the John Day River would need to be retrofitted to include HD capability and evaluating the detection efficiency of antennas in large rivers will be challenging. Gaps also persist at many other tributaries potentially used by adult lamprey (e.g., sites below Bonneville Dam, Wind, Klickitat, White Salmon, Willow Creek, Walla Walla, etc.).

About 28% of HD-PIT tagged adults were not detected after release in 2013. This was the lowest percentage in the multi-year study, but continues to be cause for concern. The underlying reasons for failed passage and the ultimate fate of these adults remain unknown. These fish may have been lost to the reproductive population (true migration and reproductive failure), moved upstream without detection, and/or they may have moved into downstream tributaries or used the Bonneville Dam tailrace for spawning. Identifying the fate of non-passing fish remains an important question and has begun to be addressed by the JSATS-tagged fish (see Noyes et al. *in review*).

HD Antenna detection efficiency

There was no radiotelemetry component to the 2013 adult lamprey studies, and therefore no opportunity to directly estimate HD-PIT antenna detection efficiency at individual locations using double-tagged fish. Instead, efficiencies were estimated using a combination of fish detections at individual dams (or combined top-of-ladder sites) in combination with detections at upstream antenna sites. This is an imperfect method for several reasons. First, there is a risk of underestimating detection efficiency when fish pass a dam via unmonitored routes (e.g., navigation locks or off-fishway routes that do not pass through antennas) but are subsequently detected upstream. Second, sample sizes for individual sites are limited to the number of fish detected upstream from that site. For example, 81 lamprey were detected upstream from John Day Dam and were used to estimate detection efficiency, but at least 180 passed John Day Dam (i.e., 106 fish detected at John Day antennas were excluded from efficiency estimates at the dam because they were not detected upstream).

As in past years, the highest detection efficiencies at HD-PIT antennas were at the top-of-ladder sites at John Day Dam. The fishways at these sites have relatively small cross-sections and there are no alternative routes past the antennas. Efficiencies were also high at the combined antenna sites at Ice Harbor, Lower Monumental, and Priest Rapids dams. Efficiency continues to be well below preferred levels at Bonneville, The Dalles and McNary dams. In part this is due to aging antenna infrastructure, as many individual antennas have been in place since 2005 and opportunities to repair or replace these sites are intermittent. Additionally, these sites consist of single antennas at each location rather than a series of antennas (as are used at the Bonneville Dam FD PIT antennas at the Bradford Island and Washington Shore fishway exits). Improving efficiency for the HD-PIT system can be achieved by building antenna redundancy into the most important monitoring sites (e.g., Bonneville Dam exits), as has been done for the highly efficient full duplex (FD) arrays. In the meantime, detection efficiencies for HD-PIT antenna sites will remain lower than preferred; these issues continue to add uncertainty into escapement estimates.

Conclusions

The multi-year HD-PIT studies have provided a wealth of information about lamprey behavior at reach and full migration scales. The resulting multi-year dataset is by far the best baseline data for evaluating changes in lamprey passage performance in the FCRPS hydrosystem at the migration scale as improvements are implemented. The HD-PIT monitoring complements active telemetry and experimental testing, and we think this type of integrated, multi-scale approach will continue to advance our understanding of lamprey passage at dams and their distribution in the basin.

A pressing gap in our understanding of adult lamprey migration in the Columbia system is the lack of information about lamprey distribution and fate. Nearly half of the tagged fish in radiotelemetry and HD-PIT studies failed to pass Bonneville Dam in most years, and almost nothing is known about where these fish go or whether they spawn. There is little evidence to assess whether large numbers return to tributaries downstream from the dam because monitoring at these sites has been limited with the exception of the Willamette River. Some fish may spawn in the main stem Columbia River, in tailrace or off-channel habitats, or hold in the main channel prior to tributary entry in the spring. The JSATS acoustic telemetry research from 2010-2013 (Naughton et al. 2011; Noyes et al. 2012, *in review*) is also helping resolve some questions related to lamprey movement and distribution to spawning areas. Fine scale mobile tracking or the use of 3-D acoustic receiver arrays in the Bonneville Dam tailrace could help resolve the fate of lampreys which do not pass and simultaneously provide useful information on distribution and passage behavior during the approach to the dam face and fishway entrances.

The current HD PIT monitoring array is not designed to monitor lamprey behavior at the spatial scales needed to diagnose passage problems inside fishways. Unless additional antennas are installed at known or suspected problems areas, continued active (e.g., radio or acoustic telemetry) or passive (e.g., video or DIDSON) monitoring will likely be needed to provide information about the selection and design of fishway modifications. Our current understanding of where passage problems occur inside fishways and how remediation efforts could be prioritized was recently summarized in several complimentary publications (Johnson et al. 2012; Keefer et al. 2012, 2013a, 2013b, 2014).

References

Beamish, R. J. 1980. Adult biology of the river lamprey (*Lampetra ayresi*) and the Pacific lamprey (*Lampetra tridentate*) from the Pacific coast of Canada. Canadian Journal of Fisheries and Aquatic Sciences 37:1906-1923.

Clabough, T. S., E. L. Johnson, M. L. Keefer, C. C. Caudill, and M. L. Moser. 2011. Evaluation of adult Pacific lamprey passage at the Cascades Island fishway after entrance modifications, 2010. Technical Report 2011-3 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers, Portland District.

Clabough, T. S., M. L. Keefer, C. C. Caudill, E. L. Johnson, and C. A. Peery. 2012. Use of night video to enumerate adult Pacific lamprey passage at hydroelectric dams: challenges and opportunities for improved escapement estimates. North American Journal of Fisheries Management 32:687-695.

Clemens, B. J., T. R. Binder, M. F. Docker, M. L. Moser, and S. A. Sower. 2010. Similarities, differences, and unknowns in biology and management of three parasitic lampreys of North America. Fisheries 35(12):580-594.

Clemens, B. J., M. G. Mesa, R. J. Magie, D. A. Young, and C. B. Schreck. 2012. Pre-spawning migration of adult Pacific lamprey, *Entosphenus tridentatus*, in the Willamette River, Oregon, U.S.A. Environmental Biology of Fishes 93:245-254.

Close, D., M. Fitzpatrick, and H. W. Li. 2002. The ecological and cultural importance of a species at risk of extinction, Pacific lamprey. Fisheries 27(7):19-24.

Corbett, S., M. L. Moser, K. Firck, W. Wassard, M. L. Keefer, and C. C. Caudill. 2014. Development of passage structures for adult Pacific lamprey at Bonneville Dam, 2013. Report to Portland District of the U.S. Army Corps of Engineers, Portland, OR.

Corbett, S., M. L. Moser, W. Wassard, M. L. Keefer, and C. C. Caudill. 2013. Development of passage structures for adult Pacific lamprey at Bonneville Dam, 2011-2012. Report to Portland District of the U.S. Army Corps of Engineers, Portland, OR.

Hess, J. E., C. C. Caudill, M. L. Keefer, B. J. McIlraith, M. L. Moser, and S. R. Narum. *In press*. Genes that predict long distance migration and large body size in a migratory fish. Evolutionary Applications.

Johnson, E. L., C. C. Caudill, M. L. Keefer, T. S. Clabough, C. A. Peery, M. A. Jepson, and M. L. Moser. 2012a. Movement of radio-tagged adult Pacific lampreys during a large-scale fishway velocity experiment. Transactions of the American Fisheries Society 141:571-579.

Keefer, M. L., M. L. Moser, C. T. Boggs, W. R. Daigle, and C. A. Peery. 2009a. Variability in migration timing of adult Pacific lamprey (*Lampetra tridentata*) in the Columbia River, U.S.A. Environmental Biology of Fishes 85:253-264.

Keefer, M. L., M. L. Moser, C. T. Boggs, W. R. Daigle, and C. A. Peery. 2009b. Effects of body size and river environment on the upstream migration of adult Pacific lampreys (*Lampetra tridentata*). North American Journal of Fisheries Management 29:1214-1224.

Keefer, M. L., T. C. Clabough, M. A. Jepson, E. L. Johnson, C. T. Boggs, and C. C. Caudill. 2012. Adult Pacific lamprey passage: data synthesis and fishway improvement prioritization tools. Technical Report 2012-8 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers, Portland District.

Keefer, M. L., C. T. Boggs, C. A. Peery, and C. C. Caudill. 2013a. Factors affecting dam passage and upstream distribution of adult Pacific lamprey in the interior Columbia River basin. Ecology of Freshwater Fish 22:1-10.

Keefer, M. L., C. C. Caudill, T. S. Clabough, M. A. Jepson, E. L. Johnson, C. A. Peery, M. D. Higgs, and M. L. Moser. 2013b. Fishway passage bottleneck identification and prioritization: a case study of Pacific lamprey at Bonneville Dam. Canadian Journal of Fisheries and Aquatic Sciences 70:1551-1565.

Keefer, M. L., C. C. Caudill, E. L. Johnson, T. S. Clabough, M. A. Jepson, C. T. Boggs, S. C. Corbett, and M. L. Moser. 2013c. Adult Pacific lamprey migration in the lower Columbia River: 2012 half-duplex tagging studies.

Keefer, M. L., C. C. Caudill, and M. L. Moser. 2014. Fishway bottleneck relief models: a case study using radio-tagged Pacific lamprey. Transactions of the American Fisheries Society 143:1049-1060.

Kirk, M. A., M. L. Keefer, C. C. Caudill. 2014. Evaluating Pacific lamprey behavior in fishways at Bonneville and John Day dams using dual-frequency identification sonar (DIDSON), 2013. Technical Report 2014-8 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers, Portland District.

Kostow, K. 2002. Oregon lampreys: natural history, status, and analysis of management issues. Oregon Department of Fish and Wildlife, Information report 2002-01, Portland, OR.

Luzier, C.W., H. A.Schaller, J. K. Brostrom, C. Cook-Tabor, D. H. Goodman, K. Nelle, and B. Strief. 2011. Pacific lamprey (*Entosphenus tridentatus*) assessment and template for conservation measures. U.S. Fish and Wildlife Service, Portland, Oregon.

McIlraith, B. J., C. C. Caudill, B. P. Kennedy, C. A. Peery, and M. L. Keefer. *In review*. Seasonal migration behaviors and distribution of adult Pacific lamprey (*Entosphenus tridentatus*) in unimpounded reaches of the Snake River basin. North American Journal of Fisheries Management.

Moser, M., A. Matter, L. Stuehrenberg, and T. Bjornn. 2002a. Use of an extensive radio receiver network to document Pacific lamprey (*Lampetra tridentata*) entrance efficiency at fishways in the Lower Columbia River, USA. Hydrobiologia 483:45-53.

Moser, M., P. Ocker, L. Stuehrenberg, and T. Bjornn. 2002b. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA. Transactions of the American Fisheries Society 131:956-965.

Moser, M. L, and D. A. Close. 2003. Assessing Pacific lamprey status in the Columbia River basin. Northwest Science 77:116-125.

Moser, M., D. Ogden, and C. Peery. 2005. Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2002. Seattle, Northwest Fisheries Science Center, National Marine Fisheries Service: 59.

Moser, M., D. Ogden, D. Cummings, and C. Peery. 2006. Development and evaluation of a lamprey passage structure in the Bradford Island auxiliary water supply channel, Bonneville Dam, 2004. Seattle, Northwest Fisheries Science Center, National Marine Fisheries Service.

Moser, M. L., D. A. Ogden, and B. P. Sandford. 2007. Effects of surgically implanted transmitters on anguilliform fishes: lessons from lamprey. Journal of Fish Biology 71:1847-1852.

Moser, M. L., M. L. Keefer, H. T. Pennington, D. A. Ogden, and J. E. Simonson. 2011. Development of Pacific lamprey fishways at a hydropower dam. Fisheries Management and Ecology 18:190-200.

Murauskas, J. G., A. M. Orlov, and K. A. Siwicke. 2013. Relationships between the abundance of Pacific lamprey in the Columbia River and their common hosts in the marine environment. Transactions of the American Fisheries Society 142:143-155.

Naughton, G. P. D. C Joosten, T. S. Clabough, M. A. Jepson, E. L. Johnson, and C. C. Caudill. 2011. Evaluation of adult Pacific lamprey behavior in Bonneville Reservoir using the Juvenile Salmon Acoustic Telemetry system, 2010. Technical Report 2011-6 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers, Portland District.

Noyes, C. J., C. C. Caudill, T. S. Clabough, D. C. Joosten, E. L. Johnson, M. L. Keefer, and G. P. Naughton. 2012. Adult Pacific lamprey migration behavior and escapement in the Bonneville reservoir and lower Columbia River monitored using the Juvenile Salmonid Acoustic Telemetry System (JSATS), 2011. Technical Report 2012-4 of Idaho Cooperative Fish and Wildlife Research Unit to U.S. Army Corps of Engineers, Portland District.

Noyes, C. J., C. C. Caudill, T. S. Clabough, D. C. Joosten, and M. L. Keefer. 2014. Adult Pacific lamprey migration behavior and escapement in the Bonneville reservoir and lower Columbia River monitored using the Juvenile Salmonid Acoustic Telemetry System (JSATS), 2013. Technical Report 2014-7 of the Department of Fish and Wildlife Sciences to U.S. Army Corps of Engineers, Portland District.

Robinson, T. C., and J. M. Bayer. 2005. Upstream migration of Pacific lampreys in the John Day River, Oregon: behavior, timing, and habitat use. Northwest Science 79:106-119.

US FWS. 2010. Pacific lamprey (*Lampetra tridentata*) draft assessment and template for conservation measures. U.S. Fish and Wildlife Service, Portland, OR.

Appendix A. 2012 Columbia River discharge and temperature profiles.

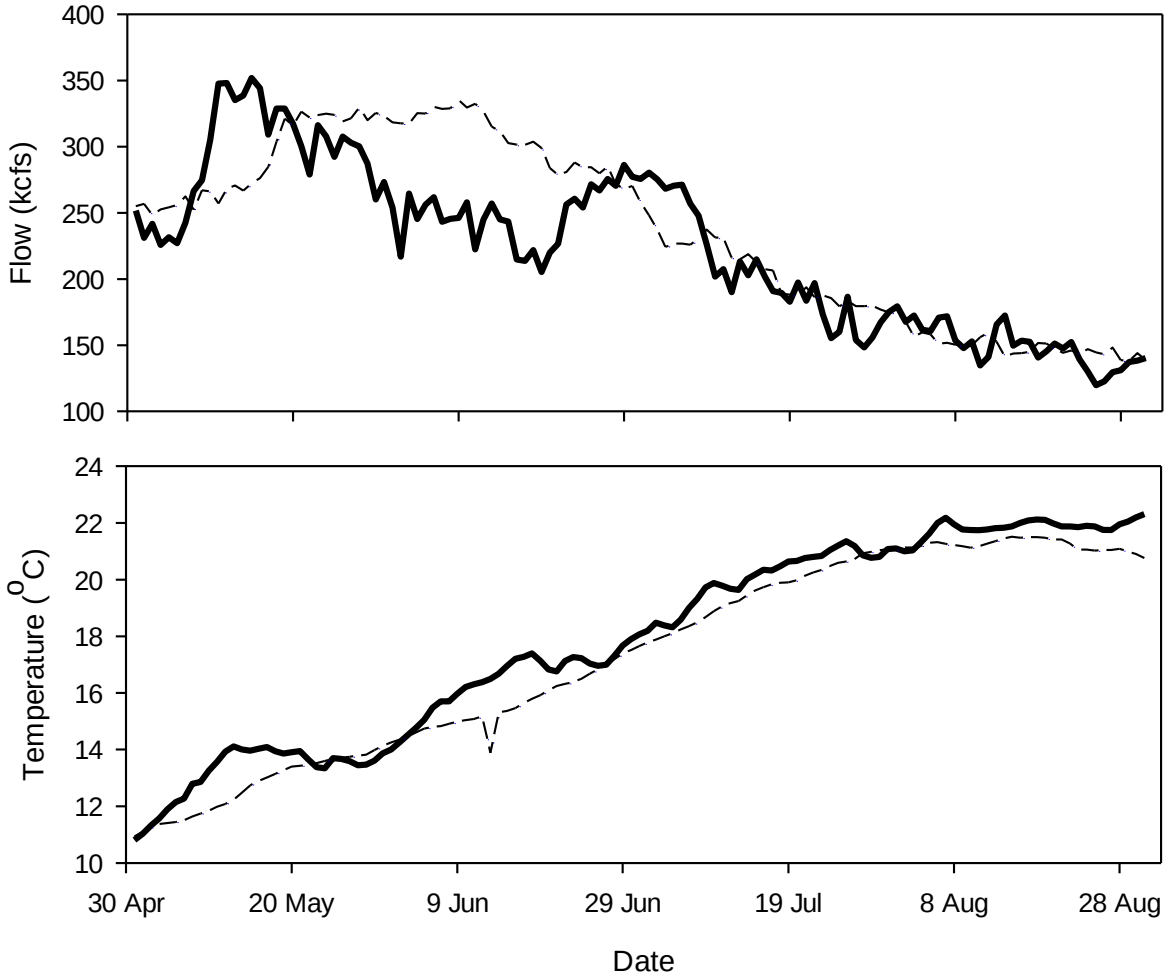

Figure A1. Mean daily Columbia River flow (kcfs) and temperature (°C) at Bonneville Dam in 2013 (solid line) and the 2003-2012 average (dashed line).