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Survival and transit of in-river and transported yearling Chinook salmon in the lower Columbia River and estuary

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ABSTRACT

The lower Columbia River and estuary (LRE) is a critically important environment for outmigrating salmonids, yet uncertainties remain about the survival and behavior of barged and in-river migrating fish. Although studies have used telemetry to monitor Chinook salmon movement and survival through the LRE, comparisons between outmigration years are confounded by differences in tag technologies, array locations, and experimental designs. In the present study, multiple releases of barged and in-river Snake River spring/summer Chinook salmon were implanted with acoustic tags and monitored at multiple locations between Lower Granite Dam on the Snake River (695 km from the mouth of the Columbia River) to within 3 km of the Pacific Ocean. LRE survival estimates and transit rates of barged fish significantly varied throughout the outmigration season. The transit rates of in-river fish also varied, but without a corresponding seasonal difference in LRE survival estimates. Early release groups of barged salmon were slower and had lower survival in the LRE than in-river salmon. Estuary arrival timing and the magnitude of transit rates may contribute to significant differences in LRE mortality between in-river and barged juvenile salmon. Survival in the Lower River reaches was stable and exceeded 0.90 for both barged and in-river fish, while survival decreased markedly in the Estuary. Differential distributions of arrival to the LRE, transit rates, and survival suggest that the outmigration experience is not homogenous for barged and in-river yearling Snake River Chinook salmon, and that previous outmigration experience of threatened and endangered salmon should be considered in future management decisions and recovery plans.

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1. Introduction

The declines of Columbia River salmonid populations have been well documented. Excessive catch in the twentieth century, the completion of the Federal Columbia River Power System (FCRPS) in the 1970's, and the onset of poor ocean conditions resulted in critically low numbers of Pacific salmon (Ruckelshaus et al., 2002). Presently, five evolutionary significant units of Chinook salmon (*Oncorhynchus tshawytscha*) originating from the Columbia and Snake River basins have been listed as threatened or endangered under the U.S. Endangered Species Act (ESA, 1973; Ford, 2011).

ESA-listed Snake River populations of Chinook salmon migrate past eight hydroelectric dams (Fig. 1). Significant efforts have been made to improve and monitor salmonid survival through the FCRPS. Outmigrating salmon have been routinely implanted with Passive Integrated Transponder (PIT) tags and antennas have been positioned throughout the FCRPS since 1993 in order to assess downriver juvenile survival and adult returns (Skalski et al., 1998). Presently, cumulative survival of yearling Chinook salmon from Lower Granite Dam (river km (RKM) 695, as referenced to the mouth of the Columbia River) to Bonneville Dam (RKM 236) is

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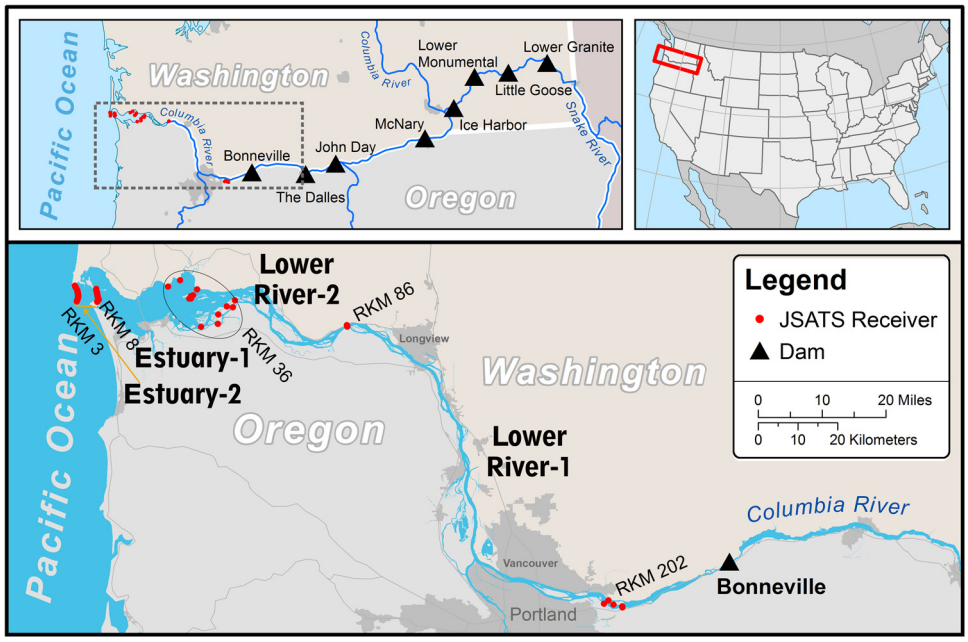

Fig. 1. Outmigration corridor of Snake River Chinook salmon with hydroelectric dams and JSATS receiver locations identified. *Image created by Andrew Holguin, UC Davis.*

roughly 50–60% (DeHart et al., 2014). Mass downstream transportation of fish by barge or truck through the FCRPS was fully implemented in 1981 to offset these losses (Raymond 1988; Ward et al., 1997), with 98% survival of barged yearling Chinook salmon to Bonneville Dam (McMichael et al., 2011a). The approximate 2:1 survival advantage of transported fish has not routinely resulted in an adult return rate twice that of salmon left to migrate in the river (in-river; DeHart et al., 2014). Consequently, barged Chinook salmon routinely have greater mortality after Bonneville Dam than in-river outmigrants (Budy et al., 2002; Schaller et al., 2014).

Variables have been identified that influence salmon survival in the various geographic regions of their life-history. The use of PIT-tagged fish has provided decades of outmigrant and adult return data that partitions mortality into FCRPS and post-FCRPS compartments. The post-FCRPS compartment is both temporally and spatially large (i.e., lower river, estuary, and ocean), because PIT-tagged fish are not detected efficiently until their return to the FCRPS as adults. Multiple studies have found significant relationships between salmon survival to adulthood and post-FCRPS experiences (Haeseker et al., 2012; Petrosky and Schaller, 2010; Schaller and Petrosky, 2007; Schaller et al., 2014; Scheuerell et al., 2009). However, modeled environmental variables and qualitative descriptions are often restricted to oceanic and plume conditions, and not lower Columbia River or estuary variables. For example, Schaller et al. (2014) conclude from multiple spatial and temporal analyses of Snake River Chinook salmon survival, that 'substantial' mortality occurs in the estuary and during early ocean residence. They report an average mortality of 61% across all studies for brood years 1954–2004 (Schaller et al., 2014), but the spatial partition between estuary and ocean is not defined. The lower Columbia River and estuary (LRE) is a critically important environment for outmigrating salmonids (Harnish et al., 2012; McMichael et al., 2010a; Ryan et al., 2003; Schreck et al., 2006), yet uncertainties remain about the survival and transit rate of barged and in-river fish in the LRE.

Monitoring the outmigration of Snake River Chinook salmon through the LRE has not been as systematic as efforts in the FCRPS. Efforts to detect PIT-tagged fish in the LRE by towing a large trawl equipped with transceivers resulted in low detection probabilities (2%; Ledgerwood et al., 2004), and signals from radio tags are attenuated as salinity increases in the LRE (Clemens et al., 2009). However, acoustic tags are unaffected by seawater and have a greater detection range (Clements et al., 2005; McMichael et al., 2010a). Chinook salmon outmigration has been monitored with acoustic tags since 2004 (Table 1), but different experimental designs have resulted from varied study objectives and the lack of obvious fixed physical structures (e.g., dams) located along the LRE in which to attach receivers. Additionally, different tagging technologies, i.e., Vemco acoustic tags (Vemco, Inc.; Nova Scotia, Canada), or JSATS acoustic tags (Juvenile Salmon Acoustic Telemetry System; non-proprietary; McMichael et al., 2010a), have had different fish size restrictions and receiver locations with various levels of LRE coverage. Studies completed with larger Vemco tags monitored outmigrants larger than 130 mm on the Pacific Ocean Shelf Tracking (POST) array, and the focus of the studies were on early ocean survival, with only 1–4 arrays located in the LRE (Table 1). By comparison, smaller Chinook salmon, more representative of the outmigrant size distribution, were implanted with JSATS tags and monitored with increased LRE coverage (6–10 receiver arrays; Table 1). However, the outmigrants were not always exclusively Snake River origin and were often collected at Columbia River dams. Fish tagged at Columbia River dams are a mix of Chinook salmon stocks, with the majority originating from the Columbia River and not the Snake River (Rechisky et al., 2014).

The proportion of Snake River populations transported through the FCRPS was the most critical outmigration variable in regression models of post-FCRPS life-cycle survival rates (1954–2004; Schaller et al., 2014). However, few studies have used active telemetry to estimate survival of transported Chinook salmon through the LRE and only a single study has reported transit times of barged salmon in the LRE (Table 1; Schreck et al., 2005). In addition, comparisons between outmigration years are confounded by differences in array locations and experimental designs, including unrealistic outmigration experiences for transported fish, i.e., multiple days to weeks of holdback at the hatchery, followed by transportation by truck to the barge rather than active swimming (Rechisky et al., 2012). The overall estimated survival of transported salmon from Lower Granite Dam to a final estuary array (RKM 46, 22, 8, or 7 depending on the study) ranged from 0.62 to 0.98 (Table 1).

Table 1
Recent acoustic tagging studies with outmigrating juvenile Snake River (stream-type) Chinook salmon in the Columbia and Snake rivers.

Year	Fish origin	Path	Tag Type	Number of releases	Fish per rel. (total)	Mean fork length (mm)	Collection site[a] (*Rel. site, if different*)	LRE arrays	Transit time, days	Survival estimate	References
2004	Snake River	Barged	Vemco	6 (3–29 May)	102–164 (763)	146.5–162.0	Lower Granite Dam (*Barge*[b])	46; 22[c]	RKM 224-46: 2–31; RKM 224-22: 3.42; RKM 22-Ocean: 1.03–1.58	Rel. to RKM 46: 0.66-0.92; RKM 46-22: 0.68–0.98; RKM 232-22: 0.62	Schreck et al. (2005), Welch et al. (2008), Clemens et al. (2009)
2005	Mixed[d]	In-River	JSATS	4 (4 May–1 Jun)	160–245 (870)	153.8	Bonneville Dam	9; 2.8	RKM 234-9: 3.6 (range 2.9–5.8)	RKM 231-9: 0.75	McComas et al. (2007)
2006	Snake River[e]	In-River	Vemco	2 (1 & 8 May)	190	146.9 & 145.6	Dworshak NFH[f] (*Kooskia NFH*)	224[c]	N.R.[g]	RKM 224+ Ocean: 0.78	Rechisky et al. (2009, 2012, 2013)
2006	Snake River[e]	Barged	Vemco	2 (6 & 14 Jun)	102 & 101	154.5 & 154.6	Dworshak NFH (*Trucked to barge*)	224[c]	N.R.	RKM 224+ Ocean: 0.54	Rechisky et al. (2012)
2006	Mixed	In-River	JSATS	4 (2–27 May)	239–245 (972)	149.7	Bonneville Dam	209; 204; 194; 8.3; 2.8	RKM 231-8.3: 4.1 (range 2.1–17.2)	RKM 231-8.3: 0.66	McComas et al. (2008)
2006	Snake River	In-River	JSATS	2 (6 & 13 May)	238 & 758 (996)	137.2	Lower Granite Dam	209; 204; 194; 8.3; 2.8	RKM 208.8-8.3: 2.4 (range 2.0–3.4)	Rel.-8.3: 0.38	McComas et al. (2008)
2008	Snake River[e]	In-River	Vemco	2 (25 Apr–2 May)	197 & 198	146.2 & 146.3	Dworshak NFH (*Kooskia NFH*)	224; 22[c]	RKM 22-Ocean: 8.21	RKM 224-22: 1.0 RKM 22+ Ocean: 0.40	Rechisky et al. (2012, 2013), Brosnan et al. (2014)
2008	Snake River[e]	Barged	Vemco	2 (17 & 23 May)	100 & 99	149.4 & 148.3	Dworshak NFH (*Trucked to barge*)	224; 22[c]	RKM 22-Ocean: 8.03	RKM 224-22: 0.77 RKM 22+ Ocean: 0.51	Rechisky et al. (2012), Brosnan et al. (2014)
2008	Snake River	In-River	JSATS	10 (23 Apr–17 May)	394–434 (4140)	133.9	Lower Granite Dam	237; 202; 193; 113; 8; 3	RKM 695-3:15–16 RKM 202-3: 2	Rel.-202: 0.48 Rel.-8.3: 0.41	McMichael et al. (2010a)
2009	Snake River[e]	In-River	Vemco	2 (4 & 11 May)	195 & 194	142.3 & 142.4	Dworshak NFH (*Kooskia NFH*)	224; 22[c]	RKM 22-Ocean: 5.96	RKM 224-22: 0.82 RKM 22+ Ocean: 0.48	Rechisky et al. (2012, 2013)
2009	Snake River[e]	Barged	Vemco	3 (17 Apr–3 Jun)	191–201 (588)	142.5–142.7	Dworshak NFH (*Trucked to barge*)	224; 22[c]	RKM 22-Ocean: 6.66–14.08	RKM 224-22: 0.69 RKM 22+ Ocean: 0.87	Rechisky et al. (2012), Brosnan et al. (2014)
2009	Mixed	In-River	JSATS	30 (27 Apr–26 May)	114–120 (3470)	139.5–161.0	John Day Dam (41 km *upstream at RKM 387*)	236; 192; 113; 86.2; 49.6; 37.3; 22; 8.3; 2.8	RKM 236-8.3: 3.4	RKM 236-8.3: 0.78	McMichael et al. (2010b)
2010	Snake River	In-River	Vemco	8 (17–24 May)	37–52 (383)	141.6	Lower Granite Dam	224; 86; 22; 7[c]	RKM 22-Ocean: 6.50	RKM 224-86: 0.96; RKM 86-22: 0.97; RKM 22-7: 0.88	Brosnan et al. (2014), Rechisky et al. (2014)
2010	Snake River	Barged	Vemco	9 (19–27 May)	22–51 (406)	141.8	Lower Granite Dam (*Barge*)	224; 86; 22; 7[c]	RKM 22-Ocean: 3.52	RKM 224-86: 0.85; RKM 86-22: 0.88; RKM 22-7: 1.0	Brosnan et al. (2014), Rechisky et al. (2014)
2010	Snake River	Barged	JSATS	6 (29 Apr–13 May)	180–307 (1392)	132–139	Lower Granite Dam (*Barge*)	153; 113; 86.2; 49.6; 37.3; 22; 8.3; 2.8	N.R.	Rel.–153: 0.98 Rel.–8.3: 0.77–0.98	McMichael et al. (2011a,b, 2013)
2010	Mixed	In-River	JSATS	34 (28 Apr – 1 Jun)	25–194 (3880)	143.3–173.8	John Day Dam (*RKM 393; RKM 307; or RKM 275*)	153; 113;86.2; 49.6; 37.3; 34; 29.3; 22; 8.3; 2.8[c]	RKM 153-8.3: 2.42	RKM 153-8.3: 0.84	McMichael et al. (2011c, 2013), Harnish et al. (2012)
2010	Mixed	In-River	Vemco	15 (28 Apr–13 May)	48–52, 98 (790)	161.3	John Day Dam (42 km *upstream at RKM 388*)	224; 86; 22; 7[c]	RKM 22-Ocean: 9.99	RKM 224-86: 1.0; RKM 86-22: 0.90; RKM 22-7: 0.89	Brosnan et al. (2014), Rechisky et al. (2014)
2011	Snake River	In-River	Vemco	9 (23 Apr–28 May)	N.R. (80)	147.6	Bonneville Dam	22; 7[c]	RKM 22-Ocean: 9.36	Rel.-RKM 22: 0.83; RKM 22-7: 1.0	Brosnan et al. (2014), Rechisky et al. (2014)
2011	Snake River	Barged	Vemco	4 (3–22 May)	~50 (200)	142.3	Lower Granite Dam (*Barge*)	22; 7[c]	RKM 22-Ocean: 3.84	Rel.-RKM 22: 0.83; RKM 22-7: 0.92	Brosnan et al. (2014), Rechisky et al. (2014)

[a] Common Snake and Columbia River sites: Lower Granite Dam (RKM 695); John Day Dam (RKM 347); The Dalles Dam (RKM 307); Bonneville Dam (forebay to juvenile bypass facility RKM 236-231); McGowan's Channel & Skamania (RKM 224); and Astoria Bridge (RKM 22).

[b] Release to "Barge" indicates barge transport from Lower Granite Dam to the barge release point, RKM 227-220.

[c] Receivers also located beyond the Columbia River mouth in the Pacific Ocean.

[d] Mixed—Fish collected at locations downstream of the Columbia and Snake river confluence can be a mix of both origins, with the majority experiencing previous Columbia River outmigration and not Snake River outmigration (Rechisky et al., 2014).

[e] Chinook salmon were exclusively of hatchery origin with no previous outmigration history.

[f] NFH—National Fish Hatchery; Dworshak NFH and Kooskia NFH are located 810 and 870 river kilometers from the Pacific Ocean, respectively (Rechisky et al., 2012).

[g] N.R.—Not Reported.

Intra-seasonal comparisons of Snake River Chinook salmon transiting the LRE with barged or in-river outmigration histories are not intuitive given the variation in previous study objectives and tagging technologies. Consequently, researchers assume, explicitly or implicitly, that there are no differences between barged and in-river outmigrants (Clemens et al., 2009; Muir et al., 2006). The aim of the present study was to determine if hatchery-reared Snake River spring/summer Chinook salmon with different outmigration histories in the FCRPS also have different outmigration experiences in the LRE. The specific objectives of the study are to determine if barged and in-river outmigrants have:

1. Equivalent survival in the LRE;
2. Equivalent transit times and rates in the LRE; and
3. Seasonal differences in LRE migration and ocean entry.

The outcomes from this study will indicate to managers and researchers if, and when, outmigration history, outmigration timing, or specific LRE reaches should be considered separately in future study and conservation efforts that address the Columbia River and estuary migration.

2. Materials and methods

2.1. Study sites

The study area includes the migration corridor of spring/summer Chinook salmon originating from the Snake River basin (Fig. 1). Specifically, the yearling Snake River spring/summer Chinook salmon (hereafter referred to as Chinook salmon) were collected and tagged at the Lower Granite Dam tailrace (RKM 695) on the Snake River. The survival and transit time of an individual fish's outmigration was then monitored from Lower Granite Dam to within three kilometers of entering the Pacific Ocean using autonomous acoustic receivers located in the LRE. The acoustic receivers (model N201, Sonic Concepts, Inc., Bothell, WA) were arranged into transects (arrays) across the river or side channels located approximately at RKM 202, 86, 36, 8, and 3 (Fig. 1). The first reach, i.e. the Dams reach, began at their release at Lower Granite Dam (either to the river or barge; RKM 695) and continued to below Bonneville Dam and Skamania Landing to RKM 202. The Lower River reaches included a reach from RKM 202–86 (hereafter referred to as Lower River-1), as well as the reach from RKM 86–36 (hereafter referred to as Lower River-2). The Estuary reaches, spanned from RKM 36–8, and RKM 8–3 (hereafter referred to as Estuary-1 and Estuary-2). The array identified as RKM 36 spanned individual receivers located on either side of the main channel from RKM 46.6–29.3, and is referred to as RKM 36 due to the majority of detections at that location. Additional detailed descriptions of the arrays, equipment, and deployment strategy can be found in McMichael et al. (2010a) and Titzler et al. (2010).

2.2. Study fish

Chinook salmon ($n = 2530$) that actively migrated to Lower Granite Dam were collected from the juvenile bypass system from 22 April to 19 May, 2008. The Chinook salmon were randomly assigned to a treatment group (in-river or barged) according to their collection date, in order to obtain roughly equal numbers of fish per treatment that were representative of hatchery-reared yearling Chinook salmon passing Lower Granite Dam throughout the outmigration season. Within each of the treatment groups, there were five nested release groups of tagged fish temporally spread across the outmigration period, with roughly 100–400 fish per release group (Table 2).

2.2.1. Tagging

Chinook salmon were collected and transferred to indoor tanks (505 L) supplied with flow-through river water and were held for 24–48 h prior to tagging. The fish were then implanted with a uniquely-coded PIT tag and a JSATS acoustic transmitter. Tags and surgical methods are described in detail in McMichael et al. (2010a). Fish measurements, i.e. fish fork lengths and weights, were obtained from anesthetized fish immediately prior to surgery (Table 2). Only Chinook salmon with missing adipose fins that had not been previously implanted with PIT tags and had fork lengths ≥95 mm were tagged. The barged and in-river treatment groups were handled equally during pre-surgery holding and tagging. Directly after surgery, the tagged salmon were held in separate treatment group recovery tanks (505 L) with flow-through river water for 36–48 h prior to their release to the river or barge. Water temperatures in the holding tanks ranged from 10.3 to 10.9 °C throughout the holding and tagging periods. Post-surgery mortality within the recovery tanks was approximately 1%.

2.2.2. Releases

Following post-surgery holding, salmon in the in-river treatment group ($n = 1249$) were transferred from the post-surgery holding tank to an 18,500-L tank supplied with flow-through river water. The fish were then released into the Lower Granite Dam tailrace via a hose connected to the juvenile bypass outflow. Salmon in the barged treatment group ($n = 1281$) were released to a barge approximately 1 h prior to departure from Lower Granite Dam. Fish traveled in the holds of U.S. Army Corps of Engineers 8000-series barges for 32–44 h until the holds were emptied downstream of Bonneville Dam near Skamania Landing (RKM 227). The tagged fish were transported with the general population of outmigrants (e.g., steelhead, fall and spring Chinook) that were also collected at Lower Granite Dam bypass facility.

2.3. Survival analyses

Smolt survival was estimated in each reach using the Cormack-Jolly-Seber release-recapture model (Cormack, 1964; Jolly, 1965; Seber, 1965) for fish from each treatment group and further parsed by the five release groups of each treatment group using the program ATLAS v1.5.3 (Lady et al., 2012). Estimated survival was corrected within ATLAS based on a probability distribution of tag failure at each receiver array. The probability distribution was fit to a tag life assessment conducted with 133 tags monitored for failure over 60 days. Standard errors were also computed within ATLAS using the bootstrap method of Townsend et al. (2006) and 1000 bootstrap iterations. The penultimate array at RKM 8 was the last point in the outmigration where the probability of detection and survival could be estimated. The result was an estimated conditional probability of survival through the Dams, Lower River-1, Lower River-2, and Estuary-1 reaches for each release group. In addition, cumulative survival through multiple reaches was estimated as the product of the survival probabilities from the individual reaches, with standard errors estimated using the Delta method (Seber, 2002, pp. 7–9). Differences in survival were compared with an Analysis of Variance (ANOVA), and a post-hoc Tukey multiple comparison test was used to identify differences between release groups (Zar, 1999). When there were no significant differences in reach survival among the release groups of a given treatment, the release groups were pooled into a single treatment group for that reach. Differences were considered significant at $\alpha \leq 0.05$.

Table 2
Outmigration and tagging characteristics of the spring/summer Chinook salmon treatment groups.

Treatment	Release	Collection date	Tagging Date	Release date	Mean fork length (SD), mm	Mean weight (SD), g	Total released
In-river	1	22 April	24 April	25 April	125.9 (13.6)	19.7 (6.8)	252
	2	30 April	1 May	2 May	137.7 (16.5)	26.7 (10.6)	248
	3	12–13 May	14 May	15 May	142.9 (9.4)	28.9 (6.1)	245
	4	14–15 May	16 May	17 May	142.4 (9.1)	28.2 (5.6)	243
	5	18 May	20 May	21 May	143.6 (9.1)	29.0 (6.0)	261
	Total				138.5 (13.6)	26.5 (8.0)	1249
Barged	1	22 April	23 April	24 April	124.6 (11.8)	19.4 (6.0)	257
	2	29 April	30 April	1 May	140.7 (16.7)	28.5 (11.7)	220
	3	5–6 May	6–7 May	8 May	142.1 (12.2)	29.9 (8.0)	329
	4	16–17 May	18 May	19 May	143.1 (9.5)	28.1 (6.0)	380
	5	18–19 May	20 May	21 May	141.7 (9.9)	28.1 (6.2)	95
	Total				138.6 (14.0)	26.9 (8.6)	1281

2.4. Transit analyses

Times and rates of transit were determined for all tagged fish detected at two successive acoustic receiver arrays. Transit time (days) between arrays was calculated as the time and date the fish was first detected at the downstream array minus the time and date of first detection at the upstream array or the time of release to the river at Lower Granite Dam. Transit rates (km/d) between arrays were based on the transit time and distance, in river kilometers, between successive receivers. For barged fish, transit times and rates through the Dams reach included time spent in the barge to RKM 227, as well as time outmigrating in the river to the acoustic array at RKM 202 following release from the barge.

Transit rate data tended to be non-normal and right-skewed. Consequently, median and quartile values (25 and 75%) are reported. An ANOVA was used to compare mean transit rates whenever treatment or release groups had normally-distributed rates. Whenever a treatment or release group had transit rates with a non-normal distribution, a nonparametric Kruskal-Wallis one-way analysis of variance comparison was performed with Conover-Inman pair-wise comparison tests. Significant differences were identified at $\alpha \leq 0.05$.

3. Results

3.1. Array arrival and detection

Chinook salmon in the in-river and barged release groups had an overlapping presence in the LRE from 26 April to 24 June 2008, but had different arrival times at the acoustic receiver arrays (Fig. 2). The five distinct releases of fish at Lower Granite Dam in the in-river treatment had partially merged by their arrival at the LRE. The arrival times of salmon in the first and second in-river treatment release groups were not significantly different at each of the LRE receiver arrays (Fig. 2). Similarly, the arrival times of salmon from the third and fourth in-river release groups were also not significantly different at Lower River arrays. The five distinct releases of fish in the barged treatment had limited mixing upon their arrival at the LRE. Specifically, the arrivals of the first and second release groups at the Estuary-1 and Estuary-2 arrays were the only array arrivals from barged releases that were not significantly different in the LRE.

Barged and in-river release groups had different distributions of LRE arrival and exit (Fig. 3). In-river release groups For example, 95% of the fish in the in-river release groups arrived at the LRE over a 13-day period, and 95% left the LRE over a similar time range (Fig. 3a–e). By contrast, barged release groups arrived at the LRE in pulses (Fig. 3f–j), due to the common release point approximately 35 RKM upriver. Both barged and in-river release groups had their widest range in LRE arrival and exit times early in the outmigration. Over the outmigration season, the greatest change occurred among the barged release groups. The 95%-arrival period of barged fish at the first LRE array was 6 days for the first release group, and decreased to 0.23 days for the last release group. The contrast was even greater at the last LRE array, where the 95%-arrival period of barged fish was 24 days for the first release group, and decreased to 1.3 days for the last release group (Fig. 3f, j).

The acoustic arrays located in the LRE had significantly different detection probabilities for fish in the in-river and barged treatments (data not shown). The probability of detecting fish from the barged treatment was greater than from the in-river treatment at the Lower River arrays ($p \leq 0.001$), but there were no differences at the Estuary arrays ($p \geq 0.400$). Fish from both treatment groups had the greatest detection probabilities at the first arrays of the Lower River-1 and Estuary-2 reaches (0.788–0.890), and were least likely to be detected at the arrays bounding the Lower River-2 reach (0.352–0.716). The detection probabilities of in-river fish originating from the five release groups were not significantly different at each array location ($p \geq 0.100$).

3.2. Survival

3.2.1. Survival of in-river fish

The cumulative (total) survival of all fish in the in-river treatment group from Lower Granite Dam to the Estuary-2 reach was 0.461 (Table 3). The lowest survival probability occurred in the Dams reach (0.537); followed by high and relatively stable survival in the Lower River reaches (0.975–0.986), which decreased to 0.895 in the Estuary-1 reach (Table 3). The five in-river release groups had no significant differences in survival through the LRE reaches (Table 3). Only survival in the Dams reach was significantly different among in-river release groups ($p \leq 0.010$). However, greater Dams reach survival for a release group did not indicate greater estuary survival for that group. For example, the third release group had the greatest total (0.545) and Dams reach survival probabilities (0.634), but one of the lowest Estuary-1 reach survival probability (0.840). The probability of survival of the in-river treatment fish in the Dams reach (0.48–0.63) was similar to other studies that monitored Snake River basin hatchery spring Chinook salmon with acoustic tags (0.48) or PIT-tags (0.50–0.70) from Lower Granite Dam to Bonneville Dam in 2008 (DeHart et al., 2014; McMichael et al., 2010a).

3.2.2. Survival of barged fish

The cumulative estimated survival of all fish in the barged treatment group from Lower Granite Dam to the Estuary-2 reach was 0.688 (Table 3). Estimated survival for the pooled barged treatment was greatest in the Dams and Lower River reaches

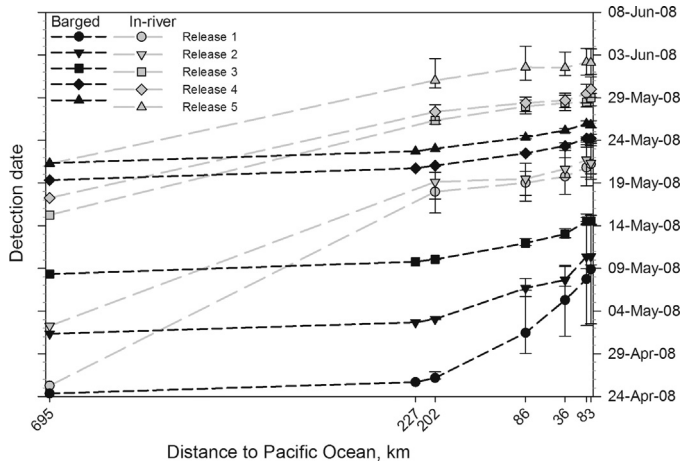

Fig. 2. Median arrival times of individual release groups of salmon within the in-river and barged treatment groups at each acoustic array. Error bars represent the 25 and 75% quartiles.

Table 3
Estimated survival probability[a] (standard error) of tagged spring/summer Chinook salmon by treatment group, release group, and study reach.

Treatment	Release	Outmigration reach					
		Dams	Lower River-1	Lower River-2	Estuary-1	Lower River + Estuary (LRE)	Total (Release to RKM 8)
In-river	1	0.479[3] (0.033)	0.968 (0.039)	0.965 (0.059)	0.903 (0.072)	0.864 (0.065)	0.404 (0.039)
	2	0.520 (0.034)	0.955 (0.043)	0.953 (0.060)	0.882 (0.057)	0.820 (0.051)	0.418 (0.034)
	3	0.634[1,5] (0.032)	1.019 (0.038)	0.978 (0.052)	0.864 (0.049)	0.840 (0.039)	0.545 (0.035)
	4	0.549 (0.033)	0.998 (0.033)	0.973 (0.052)	0.989 (0.074)	0.966 (0.071)	0.527 (0.046)
	5	0.505[3] (0.032)	0.976 (0.034)	1.001 (0.057)	0.873 (0.062)	0.880 (0.055)	0.430 (0.035)
	Pooled	0.537 (0.015)	0.986 (0.017)	0.975 (0.025)	0.895 (0.027)	0.869 (0.024)	0.462 (0.017)
Barged	1	0.977[4] (0.010)	0.955 (0.018)	0.904 (0.041)	0.785 (0.056)	0.681[4] (0.046)	0.662 (0.043)
	2	0.962[4] (0.013)	0.982 (0.025)	0.932 (0.059)	0.664[4] (0.063)	0.599[4,5] (0.049)	0.585[5] (0.047)
	3	0.987[4] (0.008)	0.954 (0.019)	0.925 (0.035)	0.793 (0.041)	0.712 (0.034)	0.690 (0.032)
	4	0.856[1,2,3,5] (0.019)	0.985 (0.019)	0.994 (0.037)	0.854[2] (0.039)	0.832[1,2] (0.030)	0.716 (0.028)
	5	0.966[4] (0.021)	0.999 (0.042)	0.944 (0.060)	0.923 (0.060)	0.860[2] (0.051)	0.841[2] (0.050)
	Pooled	0.941 (0.007)	0.977 (0.010)	0.950 (0.020)	0.788 (0.023)	0.725 (0.018)	0.688 (0.017)

[a] Significant differences ($p \leq 0.05$) between release groups within a treatment and reach (column) are indicated by numbers: [1] Significantly different from Release 1; [2] Significantly different from Release 2; [3] Significantly different from Release 3; [4] Significantly different from Release 4; [5] Significantly different from Release 5.

(0.941–0.977), and was the lowest in the Estuary-1 reach (0.788). The pooled survival estimate determined for the Dams reach (0.94) was slightly lower than the historically assumed, and recently supported, estimate of 0.98 (McMichael et al., 2011a). The lower estimate was mostly due to the low survival (0.856) of a single release group, which may indicate some barge-specific variability about the assumed survival estimate. The five barged release groups had significantly different survival in the combined LRE reaches. However, there were no significant differences in survival between release groups in the Lower River-1 and Lower River-2 reaches when the LRE survival was analyzed by reach ($p \geq 0.562$). The last two release groups had the greatest cumulative survival in the combined LRE reaches (and total outmigration), with the three earlier release groups having the lowest survival estimates in the combined LRE reaches (Fig. 4a).

Salmon in the barged treatment group had greater cumulative survival from Lower Granite Dam to the Estuary-2 reach than salmon in the in-river treatment ($p < 0.001$; Table 3). The difference in survival between the two treatments was greatest in the Dams reach (0.537–0.941, respectively). However, this trend reversed in the combined LRE reaches, with the in-river treatment group having significantly greater survival than the barged treatment ($p < 0.001$). Specifically, fish in the in-river treatment had significantly greater survival in the Estuary-1 reach than barged fish ($p \leq 0.002$), but there were no significant differences in survival in the Lower River reaches between the pooled treatments ($p \geq 0.427$), or between the individual release groups across the barged and in-river treatments ($p \geq 0.886$; Fig. 4a). As mentioned previously, the estimated survival of the five in-river release groups was not significantly different through the LRE reaches. The resulting pooled

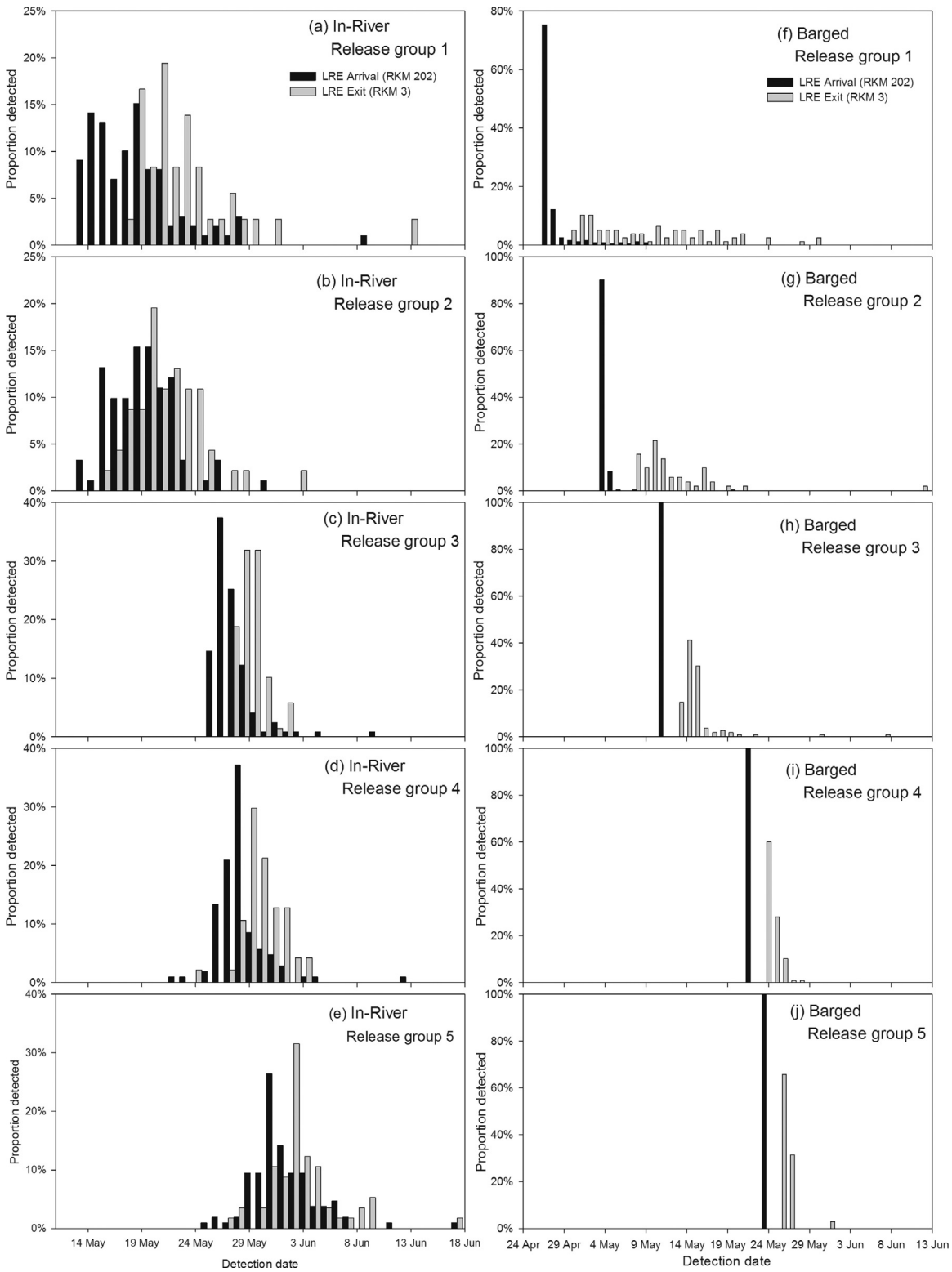

Fig. 3. The distributions of LRE arrival and exit for individual release groups of Chinook in the in-river (a–e) and barged (f–j) treatment groups. *Bin widths are approximately 1 day*.

in-river treatment group had significantly greater cumulative LRE survival than the first three barged release groups, and no significant differences in survival with the last two barged release groups.

3.3. Transit

3.3.1. In-river treatment

The cumulative median transit time of all fish in the in-river treatment group from release at Lower Granite Dam through the Estuary-2 reach was 14.2 days, with minimum and maximum val-

Table 4
Median transit rate[a] and interquartile range (25–75%), km/d, of tagged spring/summer Chinook salmon by treatment group, release group, and study reach.

Treatment release	Outmigration reach						
	Dams[b]	Lower River-1	Lower River-2	Estuary-1	Estuary-2	Lower River + Estuary (LRE)	Total (Release to RKM 8)
In-river							
1	21.7[2,3,4,5] (20–24)	96.5[3,4,5] (91–107)	78.7[3,4,5] (69–88)	42.1[2,3,4,5] (33–48)	137.2 (81–195)	77.5[2,3,4,5] (70–86)	26.7[2,3,4,5] (24–29)
2	29.2[1,3,4,5] (26–33)	102.3[5] (94–110)	80.7[3,5] (72–91)	50.7[1] (39–60)	163.1 (120–198)	82.9[1,3] (80–90)	36.3[1,3,4,5] (33–39)
3	44.5[1,2,4,5] (41–46)	104.5[1,5] (98–111)	89.8[1,2] (84–102)	54.2[1] (45–63)	147.5 (90–192)	88.4[1,2] (85–94)	50.3[1,2,4,5] (49–54)
4	48.8[1,2,3] (45–54)	104.7[1] (102–109)	89.6[1] (76–95)	54.9[1] (45–66)	152.4 (82–196)	88.1[1,2] (82–92)	54.3[1,2,3] (49–59)
5	50.4[1,2,3] (40–55)	109.4[1,2,3] (102–117)	93.5[1,2] (83–105)	48.4[1] (41–63)	170.6 (81–208)	87.5[1,2] (79–93)	58.4[1,2,3] (51–66)
Pooled	40.8 (27–49)	103.7 (96–111)	86.9 (77–97)	49.8 (41–60)	158.4 (88–198)	86.9 (80–92)	48.8 (37–56)
Barged							
1	270.4[2,3,4,5] (193–289)	26.5[2,3,4,5] (14–43)	36.2[3,4,5] (26–42)	13.1[3,4,5] (4–25)	112.4[4,5] (47–157)	17.3[3,4,5] (12–31)	50.3[3,4,5] (33–84)
2	285.8[1,3,4,5] (275–294)	36.3[1,3,4,5] (26–45)	38.5[3,4,5] (28–45)	14.6[3,4,5] (9–20)	94.1[4,5] (18–172)	27.2[3,4,5] (20–34)	76.4[3,4,5] (55–87)
3	283.7[1,2,4,5] (277–289)	61.1[1,2,4,5] (49–73)	52.3[1,2,4,5] (43–60)	20.2[1,2,4,5] (15–27)	146.4[4,5] (65–178)	44.9[1,2,4,5] (39–50)	111.4[1,2,4,5] (101–121)
4	290.2[1,2,3,5] (282–296)	81.0[1,2,3] (75–89)	67.2[1,2,3] (60–78)	38.9[1,2,3] (27–50)	161.7[1,2,3] (115–201)	62.9[1,2,3,5] (54–71)	141.5[1,2,3,5] (128–153)
5	292.4[1,2,3,4] (286–301)	87.1[1,2,3] (73–97)	67.9[1,2,3] (56–77)	37.2[1,2,3] (29–46)	172.0[1,2,3] (103–219)	69.9[1,2,3,4] (62–80)	153.8[1,2,3,4] (139–166)
Pooled	285.2 (273–292)	52.1 (32–74)	45.6 (34–60)	23.0 (14–36)	140.4 (74–185)	45.4 (27–60)	113.4 (80–140)

[a] Significant differences ($p \leq 0.05$) between release groups within a treatment and reach (column) are indicated by numbers: [1] Significantly different from Release 1; [2] Significantly different from Release 2; [3] Significantly different from Release 3; [4] Significantly different from Release 4; [5] Significantly different from Release 5.
[b] Transit rate through the Dams reach for fish in the Barged treatment group includes transit within a barge hold.

ues of 5 and 48 days, respectively. The majority of the transit time (12.1 days) and the lowest median transit rate (40.8 km/d) occurred in the Dams reach. The median transit rates through the Lower River reaches (103.7 and 86.9 km/d) were more than twice the rate through the Dams reach (Table 4). Upon entering the Estuary-1 reach, the transit rate decreased to 49.8 km/d, before a three-fold increase in transit rate occurred over the last 5 km (158 km/d) in the Estuary-2 reach. The spatial trend of decreasing transit rates in the Lower River followed by a rapid increase in the Estuary-2 reach was consistent across each release of the in-river fish.

The individual in-river release groups displayed significant temporal trends within specific reaches and combined reaches. The transit rates of fish significantly increased from first to the fourth in-river release group over the total outmigration distance and the Dams reach ($p \leq 0.001$; Table 4), and then stabilized for the last two in-river release groups ($p = 0.104$). As the in-river release groups outmigrated to the ocean, the differences in their transit rates in the LRE reaches became less apparent (Table 4). Ultimately, the Estuary-2 reach had the highest transit rates with no significant differences between the release groups ($p = 0.701$).

3.3.2. Barged treatment

The total median transit time of all fish in the barged treatment group was 6.1 days. The median transit time through the combined LRE reaches was 4.39 days, with a wide range of times (2.2–52 days). After barging through the Dams reach, the median transit rates through the Lower River-1 and −2 reaches were 46 and 52 km/d, respectively (Table 4). The transit rate significantly decreased further to 23 km/d ($p \leq 0.001$) upon entering the Estuary-1 reach, before a greater than five-fold increase in the Estuary-2 reach (140 km/d; $p \leq 0.001$). This spatial trend, i.e., decreasing transit rates in the Estuary-1 reach followed by a rapid increase in the final Estuary-2 reach, was consistent across each release group of the barged treatment (Table 4).

The individual barged release groups displayed significant temporal trends in transit time within specific reaches and combined reaches (Fig. 4b). The transit rates were initially stable for barged release groups 1 and 2, and then significantly increased for each subsequent release group through the combined LRE reaches. Within the individual reaches of the LRE, the later release groups (i.e. 4 and 5) had significantly faster transit rates than the earlier release groups (i.e. 1, 2, and 3; Table 4).

3.3.3. Comparisons of in-river and barged fish

Salmon in the barged treatment group had a significantly greater transit rate over the total outmigration distance than salmon in the in-river treatment group. However, fish in the barged treatment only had greater transit rates when they were transported for 95% of the Dams reach (68% of the total distance) at an average rate of 338 km/d. The in-river treatment group's transit rates were significantly greater than the barged treatment's rates through the combined LRE reaches, as well as through each individual reach of the LRE ($p \leq 0.019$; Table 4).

The individual release groups of in-river fish had generally greater transit rates in the LRE than the individual barged fish release groups, but differences decreased as fish from both treatments approached the Pacific Ocean. In the first LRE reach (Lower River-1), the first three barged release groups had significantly slower transit rates than each of the in-river release groups ($p \leq 0.030$); and the last two barged release groups were significantly slower than the in-river release groups 1, 2, and 4 ($p \leq 0.003$). By the last LRE reach (Estuary-2), only the two slowest barged release groups (release groups 1 and 2) had significantly lower tran-

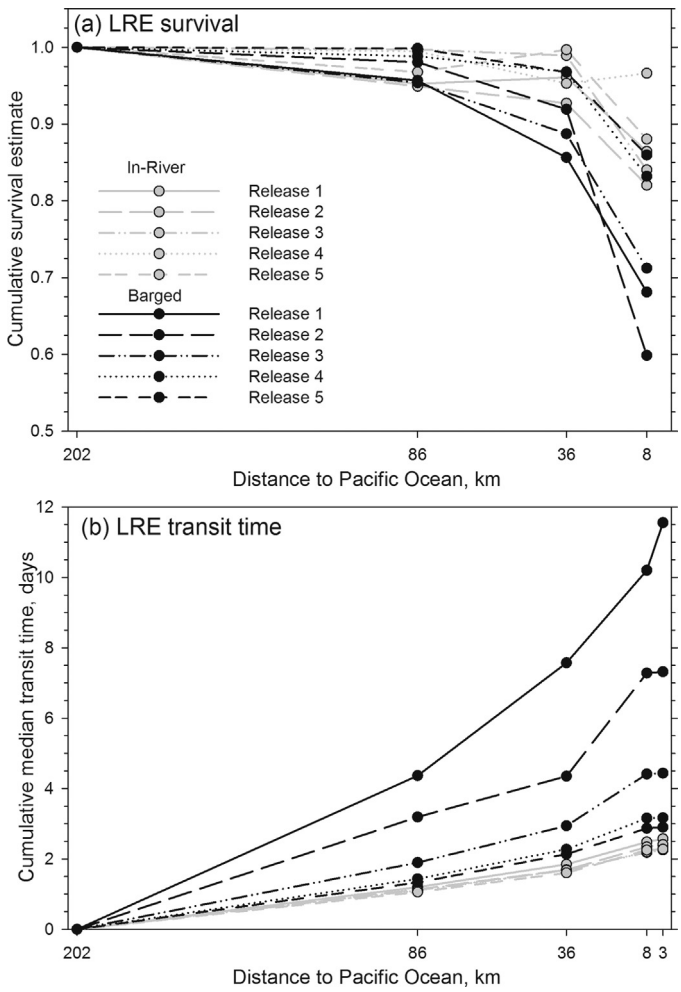

Fig. 4. Cumulative reach survival (a) and median transit time (b) estimated for each release group of tagged salmon in the in-river and barged treatment groups.

sit rates than the two fastest in-river release groups (release groups 2 and 5; $p \leq 0.028$).

4. Discussion

Chinook salmon in the in-river and barged treatment groups both actively migrated through the LRE, but their overall and LRE experiences were affected by their different outmigration histories through the FCRPS. Salmon in the barged treatment had greater overall rates of transit and survival from Lower Granite Dam to the Pacific Ocean than in-river salmon. Treatment group differences were at their greatest (i.e., 0.40 difference survival estimates and 240 km/d difference in transit rates) after the Dams reach. The gaps between treatments then narrowed to 0.23 for survival and 65 km/d for transit rate, as trends reversed and fish in the in-river treatment group had greater estimated survival and transit rates in the LRE than fish in the barged treatment. The present study was not designed to assess differences in adult survival between the treatment groups. However, a much larger PIT-tagging effort monitored the 2008 juvenile outmigration of Chinook salmon from Snake River basin hatcheries, as well as their adult returns. The difference in survival of Chinook salmon with barged or in-river outmigration histories was at its least (<0.02) when adults returned to Lower Granite Dam (DeHart et al., 2014). One could assume that the adipose fin-clipped salmon tagged over the length of the outmigration period at Lower Granite Dam in the present study were representative of the larger 2008 outmigration. Combining the lifetime survival estimates of the 2008 Chinook salmon outmigrants, the greatest benefit from transportation, i.e., survival advantage over in-river outmigrants, was present immediately after barge release (0.40). This advantage then continually diminished—with just under half of the barged treatment's survival advantage lost in the LRE (0.18) and half lost in the ocean (0.20).

4.1. In-river outmigration

The in-river treatment's outmigration had a seasonally homogenous character through the LRE. There were no seasonal differences in the reach-specific survival estimates of the five in-river release groups in the LRE, which indicates the in-river treatment could be considered as a whole. Transit rates within LRE reaches were also similar across most in-river release groups despite releases that occurred over a 4-week period at Lower Granite Dam. Only a slight seasonal effect was determined for in-river fish, with a slower swimming first release group. The temporal and spatial trends in survival and transit rate in the LRE were similar to those determined in previous studies using acoustic-tagged Chinook salmon, despite differences in tagging technologies, fish origin, and outmigration year. Specifically, high survival (0.94–1.0) in the Lower River reaches, i.e., Bonneville Dam tailrace to RKM 36 (Harnish et al., 2012; McMichael et al., 2010a,b; Rechisky et al., 2014).

The survival estimates and transit rates of fish in the in-river treatment decreased as they approached the mouth of the Columbia River (i.e. 0.895 and 50 km/d, respectively, Estuary-1 reach). This longitudinal variation has also been consistent across acoustic tagging studies and outmigration years. However, transit rate data is limited, and the present study is the only study to report transit rates in the LRE exclusively for yearling Snake River Chinook salmon.

4.2. Barged outmigration

Chinook salmon that are barged through the FCRPS have seasonal variations in survival and transit rates in the LRE that should be considered when assessing the benefits and management of fish transportation. Although there were consistently high survival estimates in Lower River reaches for all five of the barged release groups, the survival estimates in the estuary were initially low and then steadily increased throughout the outmigration season. The barged transit rates were also initially low and then steadily increased throughout the outmigration season, and this trend was consistent in each of the LRE reaches. The seasonal and spatial trends in the survival estimates and transit rates of the barged release groups were consistent with trends observed for barged fish tagged during the 2004 outmigration (Schreck et al., 2005). Lower survival was also estimated in the Estuary relative to the Lower River during the 2010 barged fish outmigration, but the total LRE survival was much higher (0.93; McMichael et al., 2011b) than in 2004 (0.64; Clemens et al., 2009; Schreck et al., 2005) and 2008 (0.72; present study). The distinctions between studies included: differing brood and outmigration years; numbers of tagged fish; size of tagged fish; tag size and burden; and tagging period and duration.

4.3. Mechanisms affecting in-river and barged outmigration

Potential mechanisms underlying Chinook salmon survival and transit rate patterns in the LRE can be gleaned from comparisons between fish with different FCRPS experiences. For example, our findings suggest that the magnitude of transit rates and estuary arrival timing may contribute to significant differences in LRE mortality. Barged salmon tended to be slower, with greater mortality, in the LRE than in-river salmon. Slower transit rates have been asso-

ciated with increased mortality due to additional time for exposure to predation in the LRE (Schreck et al., 2006). The transit rates in the LRE were significantly different among release groups of barged fish in the present study, ranging from 17.3 to 69.9 km/d, and there were significant differences in mortality. By contrast, the transit rates in the LRE were also significantly different among the in-river release groups, ranging from 77.5 to 88.4 km/d, but there were no significant differences in mortality. A similar outcome was found among in-river outmigrants in 2010, suggesting additional factors may affect mortality (Harnish et al., 2012). One factor may be the magnitude transit rate, indicated by the first three barged release groups having significantly lower transit rates and survival in the LRE than the last two barged release groups and the pooled in-river treatment.

A related factor affecting differences in mortality may be estuary arrival time. For example, the first three barged release groups arrived and exited the LRE before any in-river release groups arrived; while the last two barged release groups arrived and exited the LRE concurrently with the in-river release groups (Fig. 2). Differential survival between returning in-river and barged adults has been attributed to ocean arrival timing, and our results suggest that temporal differences may begin before ocean entry. Smolt to Adult Returns (SARs) of Chinook salmon barged earlier in the season have been less than those of salmon transported later (Muir et al., 2006; Wagner et al., 2004). Differential ocean arrival could result in early barged outmigrants entering the ocean under different upwelling conditions, prevailing currents and temperatures, which could initially impact the direction of migration (McMichael et al., 2013); plume residency time (Brosnan et al., 2014; McMichael et al., 2013); plume productivity (Litz et al., 2014); ocean predation (Emmett et al., 2006); and ultimately survival (Haeseker et al., 2012; Petrosky and Schaller, 2010; Schaller and Petrosky, 2007; Schaller et al., 2014; Scheuerell et al., 2009).

The direction of Columbia River flow does not change between early and late outmigration periods like currents in the Pacific Ocean, but the magnitude of river discharge and the predation pressure can change in the LRE. The predation rates of Caspian tern and double-crested cormorants from East Sand Island colonies (RKM 8) on outmigrating hatchery Chinook salmon were greatest in April 2008 and decreased in May as more outmigrating salmon were present in the Estuary (Collis et al., 2009). Mean lower Columbia River discharge rates also increased from April (6610 m^3/s) to May (11,050 m^3/s) in 2008, with daily increases occurring after 5 May (Beaver Army Terminal-14246900; http://waterdata.usgs.gov/or/nwis). Water transit time is the volume of the reservoir divided by the flow rate through the reservoir (Petrosky and Schaller, 2010), and has been shown to be highly correlated with salmon outmigration rates and survival between hydroelectric dams (Haeseker et al., 2012). Increased transit rates in the Lower River would then be expected as Columbia River discharges rates increase. However as Chinook salmon approach the mouth of the Columbia River, tidal oscillations have a greater influence on outmigration progress (Harnish et al., 2012; Schreck et al., 2005).

In addition to temporal changes to LRE environmental conditions, health and physiological differences among the outmigrant populations may have also affected survival. The presence of disease and pathogens can be significantly different between barged and in-river outmigrants (Van Gaest et al., 2011), and has been associated with increased outmigrant mortality (Hostetter et al., 2011; Schreck et al., 2006). However, prevalence of pathogens in barged and in-river Chinook salmon was comparatively low during the 2008 outmigration (Eder et al., 2009).

Salmon growth and development during the outmigration season could contribute to increased survival and swim speeds. Muir et al. (2006) argue that transit time differences in the FCRPS between barged and in-river outmigrants results in a lost growth opportunity and contributes to greater predation of barged fish transported earlier in the season and lower adult returns. This should result in greater mortality of early barged release groups just below Bonneville Dam, where high predation rates and abundance of piscine predators were reported by Ward et al. (1995). In contrast to this hypothesis, the highest LRE survival occurred in the Lower River reaches below Bonneville Dam (0.90–1.00), with no significant differences between treatments or release groups. Survival probabilities in the Lower River reaches routinely exceeds 0.90 for acoustic tagged barged and in-river Chinook salmon outmigrants (Harnish et al., 2012; McMichael et al., 2010a,b, 2011b; Rechisky et al., 2014).

Barged fish transported early in the season may be less physiologically prepared to enter seawater (Congleton et al., 2000). For example, Snake River yearling Chinook salmon that were barged from Lower Granite Dam early in the 2008 outmigration season had reduced smoltification status compared to Chinook salmon from the same hatchery transported later in the season or that outmigrated in-river to Bonneville Dam (Eder et al., 2009). Decreased smoltification status may have manifested in the greater dispersion of arrival times and slower transit rates in early barged release groups of acoustic-tagged salmon, which decreased with later release groups (Fig. 3). Decreased smoltification status has been associated with increased avian predation of outmigrants in the Estuary near Caspian tern and double-crested colonies located at Rice (RKM 35) and East Sand islands (RKM 8; Schreck et al., 2006). By contrast, advanced smoltification can result in an increase of directed downstream swimming speed in juvenile salmonids (Giorgi et al., 1991; Lundqvist, 1985).

4.4. Conclusions and implications for management and recovery

Assuming equivalent transit rates in the LRE for Chinook salmon with barged or in-river outmigration histories would result in flawed estimates of ocean arrival timing. We found that barged salmon had longer transit times in the LRE than in-river salmon, with the earliest barge release groups having the lowest transit rates. However, the lower transit rate of fish in the barged treatment group through the LRE did not offset the differential travel time between barged and in-river salmon through the FCRPS (i.e., 36 h versus 10–23 days, respectively). As a result, fish barged from Lower Granite Dam entered the ocean at different times than fish migrating the entire 695 km in-river. Transporting Chinook salmon through the FCRPS was initiated to offset direct mortality associated with the passage of hydroelectric dams (Ward et al., 1997). Since 2006, the annual start of transport operations has been delayed to time ocean entry and improve returns (DeHart et al., 2014). In the present study, only barged fish that were transported 18 days after the start of general barging (1 May, 2008; (DeHart et al., 2014)) entered the ocean at the same time as tagged in-river fish. If aligning ocean entry of transported and in-river fish is a priority, then outmigration histories and intra-annual transit rates must be considered.

Differential distributions of arrival to the LRE, transit rates, and survival suggest that the outmigration experience is not homogenous for barged and in-river yearling Snake River Chinook salmon. Seasonal and treatment differences in transit rate exist that affect ocean arrival timing for both barged and in-river fish. Similarly, transportation and LRE outmigration may affect the post-FCRPS survival of wild Chinook salmon differently than the hatchery-reared Chinook salmon used in the present study, suggesting that management decisions require information from Chinook salmon with different origins and outmigration histories (Holsman et al., 2012). Information on the survival and transit of hatchery-reared Chinook salmon has been collected from a patchwork of receiver locations, tagged populations, and tag technologies. Similar out-

comes between different acoustic telemetry studies and differences in the LRE experiences of barged and in-river Chinook salmon outmigrants can be used to focus future research, monitoring, and recovery management plans. For example, survival in the Lower River reaches is stable and routinely exceeds 0.90, while mortality increases markedly in the Estuary for acoustic tagged barged and in-river Chinook salmon outmigrants (Harnish et al., 2012; McMichael et al., 2010a,b, 2011b; Rechisky et al., 2014). Consequently, an increased emphasis on acoustic receivers in the last 48 RKM may be warranted. The common temporal and spatial location of mortality among barged outmigrants in 2004 (Schreck et al., 2005) and 2008 suggests that the greater Estuary mortality may be attributed to avian predation. Repeated annual tracking of outmigrants through this reach should reveal if predation management efforts (BRNW (Bird Research Northwest), 2013; Evans et al., 2012) are resulting in increased survival.

Modeling efforts indicate correlation between freshwater environmental variables during hydropower outmigration and Chinook salmon ocean survival (Haeseker et al., 2012). This interaction may indicate that FCRPS operations can increase freshwater and early ocean survival by manipulating plume conditions (Brosnan et al., 2014). However, Litz et al. (2014) found that pelagic community structure in the plume was not related to Columbia River flow or basin-scale oceanographic indices (e.g.; Pacific Decadal Oscillation or PDO), suggesting that more information is needed on the potential interactions of the Columbia River and plume dynamics before management plans are enacted. In addition, the significant ocean survival term of Haeseker et al. (2012) is actually a composite of ocean and LRE survival.

River systems have become more modified as human interactions and uses increase. Consequently, monitoring efforts must also increase to evaluate the effects of these modifications on outmigrating and resident fish. More directed management plans could focus on how hydropower operations and conservation plans can affect the river and estuary experience of salmon with modified outmigration histories. The Northwest Power and Conservation Council (NPCC) has included restoring the ecosystem function of the LRE as a strategic priority, with long-term monitoring and evaluation of salmon survival and migration (NPCC, 2014). This would require enacting systematic data collection within the LRE to test the effectiveness of current and proposed management plans associated with hydropower facility spill, barge timing, avian management, and habitat improvements (NPCC, 2014). Acoustic telemetry technology can be used to characterize salmon survival and transit within the LRE for in-river and barged outmigrants, but data collection and experimental methods have not been standardized. Once a system is in place, annual data can be reviewed to test assumptions for hatchery Chinook salmon, as well as for other outmigrating populations, specifically ESA-listed stocks.

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