Detection of Passive Integrated Transponder (PIT) Tags on Piscivorous Avian Colonies in the Columbia River Basin, 2010

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EXECUTIVE SUMMARY

In 2010, the National Marine Fisheries Service, in collaboration with Oregon State University and Real Time Research, Inc., continued a multi-year project to recover passive integrated transponder (PIT) tags from piscivorous bird colonies in the Columbia River basin. Each year, juvenile Pacific salmon *Oncorhynchus* spp. are PIT-tagged for various studies throughout the basin. During 2010, we recovered 106,972 PIT-tags with no previous history of detection on an avian colony. Of this total, more than 84,000 (79%) originated from fish released for migration in 2010.

Of the 84,000 tags recovered from fish migrating in 2010, 68% were from colonies of the Caspian tern *Hydroprogne caspia* and double-crested cormorant *Phalacrocorax auritas* on East Sand Island in the Columbia River estuary. Other locations with substantial numbers of tags recovered were the tern colonies on Crescent and Goose Island and a cormorant colony on Foundation Island. Crescent and Foundation Islands are located in Lake Wallula, the reservoir upstream from McNary Dam; Goose Island is located in Potholes Reservoir, southeast of Rocky Reach Dam. Recoveries on these three islands accounted for approximately 23% of all PIT-tags recovered on avian colonies in 2010. A notable percentage of tags (4%) was also recovered from a California gull *Larus californicus* colony on Miller Rocks Island in Lake Celilo (The Dalles Dam reservoir). Sampling at other colonies in the basin generally yielded less than 2% of the tags recovered.

As in previous years, PIT-tagged steelhead *O. mykiss* were generally more vulnerable to avian predation than other salmonid species. For example, the mean weekly predation rate of PIT-tagged steelhead was 12% for fish detected at Bonneville Dam and 14% for fish released from transport barges downstream from the dam ($P = 0.11$). In comparison, predation rates on East Sand Island were less than 5% for PIT-tagged Chinook *O. tshawytscha*, coho *O. kisutch*, and sockeye salmon *O. nerka* detected at Bonneville Dam. For these species, predation rates of fish detected at Bonneville and their counterparts released from transport barges were similarly low, and were not significantly different ($P > 0.05$).

Among the most vulnerable stocks in the Columbia River basin during 2010 was lower Columbia River hatchery subyearling fall Chinook salmon. On East Sand Island, the mean predation rate by terns and cormorants on these fish was 20.6%, and was significantly different than the 5.8% mean predation rate of subyearling Chinook salmon detected passing Bonneville Dam ($P < 0.05$). For subyearling Chinook salmon, cormorants consumed a significantly larger ratio than terns of both lower Columbia River hatchery fish (76:24%) and fish originating from the interior Columbia River basin detected passing Bonneville Dam (83:17%). However, the difference in these proportional consumption rates of subyearling Chinook salmon were not significant ($P = 0.30$).

In contrast, for coho salmon, the 13.6% mean predation rate on lower Columbia River hatchery fish was not significantly different than the 8.1% mean predation rate for fish detected passing Bonneville Dam ($P = 0.15$). However, the ratio of lower Columbia River coho salmon consumed by cormorants and terns nesting on East Sand Island (77:23%) was significantly different than the ratio consumed by these bird species of coho salmon detected at Bonneville Dam (35:65%; $P < 0.05$).

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INTRODUCTION

Since 1987, juvenile Pacific salmon *Oncorhynchus* spp. have been tagged with passive integrated transponder (PIT) tags to evaluate measures implemented to improve their survival through the Federal Columbia River Power System. Detections of these tags have also aided in identifying the causes of decline for salmonid populations at different life history stages (NMFS 2000). The number of PIT-tagged juvenile salmonids released into the Columbia River basin varies annually, but has increased from less than 50,000 in 1987 to over 2 million in 2003 (PSMFC 2010). At the time of tagging, individual tag codes and information such as species and origin are recorded in a regional database, the PIT Tag Information System (PTAGIS) for the Columbia River Basin. Codes entered in PTAGIS at the time of tagging can be matched with subsequent PIT-tag detection records at dams and other interrogation sites. These data can then be used to establish the migration history and often the ultimate fate of individual fish.

Since the mid-1960s, colonies of Caspian terns *Hydroprogne caspia* have shifted northward from California, and in the 1980s these colonies began to breed in significant numbers on small islands in the Columbia River estuary (Gill and Mewladt 1983). By 2001, over 12,000 terns were reported along the north Pacific coast (USACE 2001). Colonies of double-crested cormorants *Phalacrocorax auritas* have also expanded rapidly in the Columbia River estuary, from initial sightings in the 1980s (Carter et al. 1995) to approximately 14,000 breeding pairs in 2007 (BRN 2010). Both the Caspian tern and double-crested cormorant colonies in the Columbia River estuary are considered to be the largest of their respective species in North America.

Large-scale efforts to detect PIT tags on avian predator colonies in the Columbia estuary began in 1998 (Ryan et al. 2001). One goal of these efforts was to obtain PIT-tag data with which to compare the vulnerability to predation of different salmonid species, runs or rear types, and areas of origin (Collis et al. 2001; Ryan et al. 2003). Detection data indicated high levels of predation on many species of salmonids by avian piscivores from these large breeding colonies.

These initial findings prompted management agencies to relocate the Caspian tern colony from Rice Island, located in a freshwater reach of the Columbia River estuary (river kilometer 35), to East Sand Island, which is located in a brackish-water reach (rkm 8). The relocation was intended to mitigate predation on salmonids by moving terns closer to food sources consisting of non-salmonid, marine forage fishes (USACE 2001). We continued annual PIT-tag detection efforts on the estuarine colonies and expanded these efforts to colonies further upstream. These recovery efforts remained focused on evaluating the relative vulnerability of salmonids to avian predation. At present, detection efforts are focused primarily on the larger avian colonies responsible for the majority of predation on juvenile salmonids. This approach was intended to develop data for better evaluation of management alternatives for avian colonies.

In 2010, we continued this effort using PIT-tag technology originally developed for detection at dams (Prentice et al. 1990a,b) and later modified to recover juvenile salmonid PIT tags from avian colonies, using the techniques described by Ryan et al. (2001). In previous years, biologists from Oregon State University (OSU) and Real Time Research, Inc. (RTR) assisted with PIT-tag recovery efforts of the National Marine Fisheries Service (NMFS). Beginning in 2007, we divided PIT-tag recovery efforts among research groups stationed within different regions of the basin. We then pooled detection information for our respective analyses.

In this report, we summarize detection effort, methodology, and general vulnerabilities of juvenile salmonids to avian predators in 2010. Data obtained during this study contributed to analyses of smolt consumption rates, species-specific vulnerabilities of juvenile salmonids, and large-scale analyses of piscivorous colonial waterbird population dynamics, colony size, and nesting success in the Columbia River basin (Roby et al. 2011).

STUDY AREA

Our study area consisted of 13 distinct avian breeding colonies on 8 islands within the Columbia River Basin (Table 1). Detection effort began after the breeding season in summer and fall, when birds had completely vacated the nesting colonies. Locations of avian colonies ranged from East Sand Island in the estuary (rkm 8), to Twining Island in Banks Lake, a 43-km long reservoir approximately 959 km from the mouth of the Columbia River (Figure 1). Most PIT-tag detection efforts were concentrated on the largest avian predator colonies on islands in the estuary and on islands in Lake Wallula (McNary Dam reservoir) near the confluence of the Columbia and Snake Rivers.

Table 1. Location of avian breeding colonies sampled in 2010 and distance from Columbia River mouth.

River Reach and Island	Distance to Columbia River mouth (km)
Columbia River estuary	
East Sand Island	8
Lake Celilo (The Dalles reservoir)	
Miller Rocks Island	331
Lake Umatilla (John Day reservoir)	
Central Blaylock Island	441
Lake Wallula (McNary reservoir)	
Crescent Island	510
Badger Island	512
Foundation Island	518
Interior Columbia Plateau	
Goose Island (Potholes Reservoir)	665*
Twining Island (Banks Lake)	959*

* Approximate distances listed for sites not located on the Columbia River.

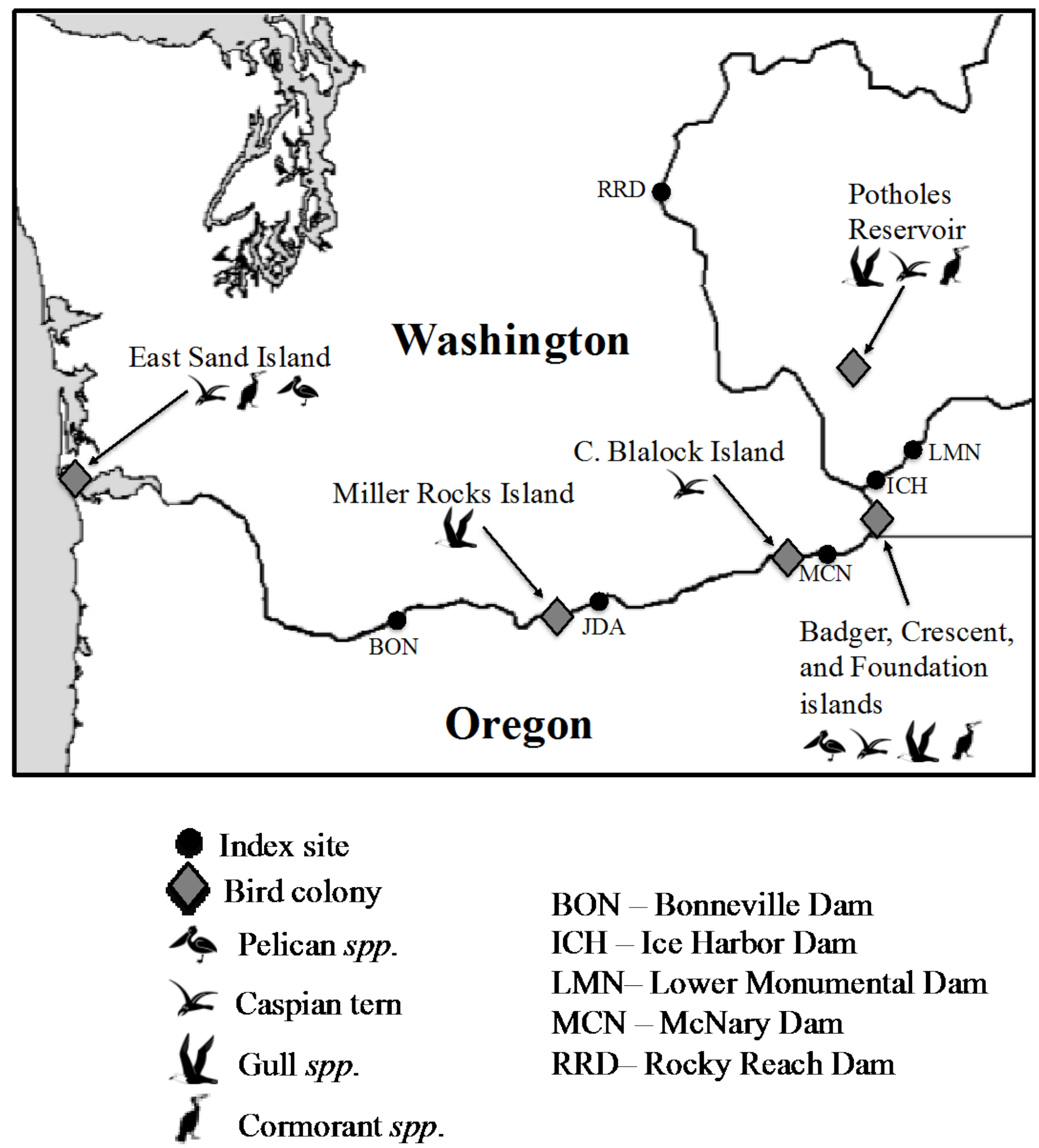

Figure 1. Location of bird nesting colonies sampled for PIT tags during 2010 and instream detection sites used to index fish available to birds within specific river reaches.

DATA ANALYSIS

Comparisons between various groups (by hatchery, origin, or migration history) were made using a two-tailed *t*-test ($\alpha < 0.05$). We calculated weekly predation rates by pooling hatchery and wild fish from each respective species or run type into a single group to obtain sample sizes of at least 100 fish for statistically valid comparisons (Ryan et al. 2003).

Predation rates on salmonids by double-crested cormorants and Caspian terns are known to vary throughout the season with changes in the availability of alternate prey and in the metabolic requirements of recently hatched young. Therefore, comparisons were generally limited to paired groups that had entered a given reach during the same week. For example, predation rates were compared among fish released to the lower river (downstream from Bonneville Dam), detected at Bonneville Dam, or released from transport barges during the same week.

We also compared predation rates between fish injected with only a PIT tag and those surgically implanted with both a PIT and acoustic tag. We calculated daily predation rates of PIT-tagged vs. double-tagged fish, although data for double-tagged fish were pooled with adjacent days when necessary to provide sufficient sample sizes for statistical comparisons.

We also compared weekly predation rates between tule and upriver bright stocks of subyearling fall Chinook salmon *O. tshawytscha* detected at Bonneville Dam or released from hatcheries into the lower Columbia River (LCR). Fall Chinook salmon migrate at different periods of the year, depending on where they originated within the Columbia River basin. Therefore, we compared weekly predation rates between groups on these fish even though they were not necessarily available to terns and cormorants in the LCR during concurrent periods. We compared predation rates of subyearling fall Chinook salmon originating from the interior Columbia River upstream of Bonneville Dam, those released from Spring Creek Hatchery, and those we tagged and released from hatcheries in the LCR.

COLLECTION OF TAGS FROM AVIAN COLONIES

Detection and Recovery Efforts

Methods

In 2010, PIT-tag detection and recovery efforts were conducted jointly with researchers from NMFS, OSU, and RTR. NMFS researchers primarily detected tags on East Sand Island and provided tractor-towed, flat-plate antenna systems to assist OSU and RTR in recovery of tags on Crescent Island. Recovery of PIT tags by OSU and RTR was focused on avian colonies upstream from the estuary, in the mid- and upper Columbia River.

Recovery data from previous years indicated that a large proportion of PIT tags would be located on Crescent, East Sand, and Foundation Island (Ryan et al. 2003, 2006, 2007). Substantial numbers of PIT tags have also been recovered from colonies on islands in Lake Celilo (The Dalles reservoir), Lake Umatilla (John Day reservoir), and Potholes Reservoir (Ryan et al. 2001, 2002).

To detect tags on the colonies, we used both a hand-held antenna, which was passed back and forth over the colony manually, and a flat-plate antenna, which was dragged over the colony using a tractor (Ryan et al. 2001). Avian colonies are generally occupied by a single species, which made a clear determination of which species was responsible for deposition of PIT tags. However, there are islands where multiple bird species nest within close proximity (i.e., Crescent Island). For these locations, we determined which species deposited PIT tags based on the boundaries of the breeding colony. Beyond these boundaries there existed the possibility that deposition of PIT tags was mixed among the bird species nesting on that island. Therefore, we designated PIT tags recovered from areas where we were not able to determine which species was responsible for deposition of PIT tags as “mixed avian species”.

In areas with high tag densities, such as the Crescent Island tern colony, the potential for tag-code collision was higher. Tag-code collision occurs when two or more PIT tags are present in the detection field simultaneously, causing interference between tag-code signals such that neither code is recorded (Brännäs et al. 1994). We used magnetized rakes to physically remove PIT tags from the Crescent Island tern colony before other detection techniques were used, and these collected tags were later read using a hand scanner.

Tern colonies on Crescent Island and East Sand Island were located on level, unobstructed terrain, which allowed towing of flat-plate antennas over the colony surface. With the towed flat-plate antenna, several individual passes were made over each colony in different directions. This method varied the orientation of the antenna to the tags, which improved the likelihood that any given PIT tag would be at the optimal angle for detection while within detection range of the antenna. Hand-held antennas were used for colonies on rugged or obstructed terrain, where use of the flat-plate antenna was not feasible.

Results

Using physical and electronic recovery techniques, we collected approximately 107,000 PIT-tag codes with no previous detection history on avian breeding colonies (Appendix Table 1). Over 84,000 of these recoveries were from fish released for migration in 2010 (Table 2). These recoveries included PIT tags detected at bird colonies

Table 2. Number of PIT-tag codes recovered from salmonids released for migration in 2010 and the proportion recovered on each avian colony.

	American White Pelican	Brandt's Cormo-rant	Caspian Tern	Double-crested Cormo-rant	Gull species	Mixed avian species	Total PIT-tags detected N	Total PIT-tags detected (%)
Columbia Estuary								
East Sand Island		196	34,634	23,455			58,285	68.9
Lake Celilo (The Dalles reservoir)								
Miller Rocks Island					3,715		3,715	4.4
Lake Umatilla (John Day reservoir)								
Central Blalock Island			1,085				1,085	1.3
Lake Wallula (McNary reservoir)								
Foundation Island				5,228			5,228	6.2
Crescent Island			5,954		3,098	219	9,271	11.0
Badger Island	2,202						2,202	2.6
Interior Columbia Plateau								
Twining Island (Banks Lake)			108				108	0.1
Goose Island (Potholes Res)			4,359			352	4,711	5.6
Total PIT-tags detected								
N	2,202	196	46,140	28,683	6,813	571	84,605	
(%)	2.6	0.2	54.5	33.9	8.1	0.7		

of known species, as well as those detected at locations where multiple bird species potentially deposited PIT tags (i.e., mixed avian species). Data from these recoveries provide minimum estimates of predation because detection efficiency on the colonies was below 100%, and we could not adjust estimates for tags deposited at off-colony locations.

Detection Efficiency

Methods

As in previous years, NMFS collaborated with researchers from OSU and RTR to evaluate detection efficiency on each avian colony. For these evaluations, pre-identified "control" PIT tags were distributed on the colonies by OSU and RTR at various intervals throughout the breeding season. Control PIT tags were sown on all bird colonies at least twice: once immediately before the breeding season and once after. Control tags were deposited on all tern colonies on at least three occasions throughout the nesting season, with the exception of the Caspian tern colony in Lake Umatilla. Control tags could not generally be deposited within the breeding season for cormorants due to their sensitivity to disturbance.

Over the years, we have used several different methods to estimate detection efficiency on the double-crested cormorant colony on East Sand Island because of its large size and variation in nesting substrates (Sebring et al. 2010a). However, detection efficiency at this colony has increased in recent years due to improvements in the technology and in sampling techniques (Sebring et al. 2009, 2010a,b). Therefore, in 2010 we adjusted detection efficiency on this colony in the same manner as for other avian colonies, by calculating the mean proportion of PIT tags detected (D^1, D^2, …D^N) from the number of PIT tags of each release group (R^1, R^2, …R^N) (see equation 1).

$$\text{Detection efficiency} = (D^1, D^2, \ldots D^N) \div (R^1, R^2, \ldots R^N) \qquad \text{Equation 1}$$

In previous years, we have observed temporal changes in detection efficiency at the Crescent and Goose Island tern colonies (Sebring et al. 2010a). To more accurately estimate predation rates for these bird colonies we used linear regression models to interpolate weekly detection efficiencies throughout the migration season. We generated linear regression models by calculating proportions of control tags detected from release groups on each bird colony. The linear models were used to interpolate weekly detection efficiencies between periods when control tags were released for bird colonies not having a uniform distribution of control tag recoveries. We used detection efficiency rates from post-season control tags as the maximum weekly value for predation rate adjustments because the final release of control tags occurred within days of our electronic recovery efforts.

Results

On colonies where the majority of PIT tags were detected, mean detection efficiency ranged from 52 to 84% (Table 3). In general, these efficiencies were similar to those measured during recent years (Ryan et al. 2007; Sebring et al. 2009, 2010a,b). We found that recovery of control tags on the Crescent and Goose Island tern colonies was non-uniformly distributed (Appendix Figure 1). Linear regression models were used only to interpolate detection efficiency between weeks when control tags were dispersed on the Crescent and Goose Island tern colonies.

Table 3. Number of control PIT tags planted and number detected on colonies of various avian species throughout the Columbia River basin during 2010. Recoveries sites and avian colonies are listed in ascending order of distance from the Pacific Ocean.

Recovery site	Avian colony	Controls tags detected (N)	Controls tags planted (N)	Detection efficiency (%)
Columbia River Estuary				
East Sand Island	Brandt's cormorant	83	100	83
	Double-crested cormorant	304	400	76
	Caspian tern	336	400	84
Lake Celilo (The Dalles reservoir)				
Miller Rocks Island	Gull	150	200	75
Lake Umatilla (John Day reservoir)				
Central Blaylock Island	Caspian tern		No measurement	
Lake Wallula (McNary reservoir)				
Badger Island	American White Pelican	149	200	75
Crescent Island	Caspian tern	303	400	76
	Gull	158	200	79
Foundation Island	Double-crested cormorant	252	400	63
Columbia Plateau				
Twining Island (Banks Lk)	Caspian tern	60	100	60
Goose Island (Potholes Res)	Caspian tern	207	400	52

In contrast, we found that recovery of control tags released on the East Sand Island tern colony was uniformly distributed across the nesting period at this location. Therefore, we used the mean detection efficiency of control tags (84%) to adjust predation rates for the East Sand Island tern colony. We did not record a detection efficiency measurement for birds nesting on Central Blalock Island because we had not released preseason control tags there. Instead, preseason control tags had been released on Rock Island, a nearby location that had hosted terns nesting in Lake Umatilla during previous years. The initiation of nesting activity by terns on Central Blalock Island prevented the opportunity to release control tags at this location due to possible disturbance of nesting activity.

ESTIMATES OF PREDATION

Index of Seasonal Predation

Methods

We generated indices of seasonal predation by calculating mean weekly predation rates. We grouped PIT-tagged fish by species, run, and origin, forming virtual release groups from detections of fish at the nearest interrogation site upstream from the colony of interest. Detection information was downloaded from PTAGIS and pooled into weekly "release" groups based on detection date (usually in the juvenile bypass system of dams). Fish detected at one of these interrogation sites and subsequently detected on a colony were used to calculate weekly predation rates.

The majority of PIT-tagged fish are released far upstream from avian colonies in the mid and lower Columbia River and estuary, and considerable mortality can occur between the point of release and the point at which fish come within range of foraging avian predators. For this reason, we used virtual release groups, which were comprised of fish known to have survived to an interrogation site closer to the colony. Some interrogation sites (i.e., Ice Harbor Dam and Lower Monumental Dam) were located within foraging range of an avian colony, meaning birds could have consumed some of these fish prior to "release." For these colonies, we estimated annual predation using two interrogation sites (both upstream from the colony). From the two interrogation sites, we formed three detection history groups: fish observed only at the upstream site, fish observed only at the downstream site, and fish observed at both sites.

Comparison of predation estimates based on these groups provided a seasonal index of the species or run-types most vulnerable to avian predators in a given area. Because these indices were based upon fish assumed to be vulnerable to predation, they could be used for non-biased interannual comparisons of predation within a given reach. However, we calculated separate indices for fish originating from different river reaches. For example, separate indices were calculated for Upper Columbia and Snake River fish, even though both were consumed by birds nesting in Lake Wallula. However, comparisons among fish originating from different river reaches, (i.e., Upper Columbia River and Snake River fish consumed by birds nesting within Lake Wallula), are not appropriate because the comparison would be based on two index sites expected to have different mortality rates between index site and predation event.

We estimated predation rates in four areas that contained avian colonies within reasonable proximity to an upstream interrogation site and where large numbers of PIT tagged fish have been detected in previous years. These areas were Potholes Reservoir, Lake Wallula, Lake Celilo, and the Columbia River estuary. We used detections of fish at Rocky Reach Dam (rkm 763) to evaluate predation of upper Columbia River fish on avian colonies in Potholes Reservoir because more than 81,000 were detected at this location in comparison to Rock Island Dam, where only approximately 1,200 fish were detected during 2010 (PTAGIS; PSMFC 2010). Numbers of fish detected at Rocky Reach Dam were also used to evaluate predation of upper Columbia River fish to birds nesting in Lake Wallula.

Birds nesting in Lake Wallula are known to forage in the forebay of Ice Harbor Dam. Therefore, to estimate predation on Snake River fish by birds from Lake Wallula colonies, we used virtual releases comprised of fish detected at either Ice Harbor (rkm 538) or Lower Monumental Dam (rkm 589), or both (using two interrogation sites, as explained above). Similarly, we used detections of fish at both John Day (rkm 347) and McNary Dam (rkm 470) to form virtual release groups of fish available to predation by gulls nesting on Miller Rocks Island. For estimates of predation in the Columbia River estuary, two separate release groups were used: one was a virtual release comprised of fish previously detected at Bonneville Dam (rkm 235), and a second was comprised of fish actually released from hatcheries in the Lower Columbia or Willamette River.

Results

Potholes Reservoir—Mean annual predation by Caspian terns nesting on Goose Island was estimated at less than 1% for spring/summer Chinook *O. tshawytscha* and coho salmon *O. kisutch* detected at the Rocky Reach Dam index site (Table 4). However, estimates of predation by Caspian terns averaged about 8% for hatchery steelhead *O. mykiss* and 5% for wild steelhead, and these estimates were considerably higher than those of other species from the upper Columbia River.

Table 4. Numbers of tags recovered from the Goose Island Caspian tern colony and estimated rates of predation on in-river migrating PIT-tagged salmonids from the 2010 migration year. Predation rates were adjusted for detection efficiency rates, which were interpolated using linear regression equations (see Appendix Figure 1) and presented by species, run, rear-type, and origin only for groups with at least 100 detections at Rocky Reach Dam.

	Goose Island Caspian tern colony			
Upper Columbia River species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
Spring/Summer Chinook salmon				
Hatchery	50,365	144	290	0.6
Wild	804	3	6	0.7
Coho salmon				
Hatchery	3,994	19	26	0.7
Steelhead				
Hatchery	21,739	764	1,633	7.5
Wild	1,408	29	63	4.5

Lake Wallula (McNary Dam Reservoir)—Mean weekly predation rates for birds nesting in Lake Wallula were estimated based on colonies of terns and gulls on Crescent Island, cormorants on Foundation Island, and pelicans on Badger Island (Tables 5-8). For these avian colonies, mean weekly predation was generally 2% or less (Tables 5-8).

We do not have data to estimate survival from the respective virtual release sites to Lake Wallula for either upper Columbia or Snake River fish. Therefore, estimated rates of avian predation between fish originating from these two locations are not comparable. For most salmonid species, mean weekly predation rates by double-crested cormorants were approximately 1%, whereas those by American white pelicans and California gulls were generally less than 0.5%. The Crescent Island Caspian tern colony had the greatest impact on survival of migrating salmonids in Lake Wallula; and these terns preyed more heavily on steelhead in particular than did other birds in the area. Mean weekly predation rates by Crescent Island terns ranged 3-4% for Snake River steelhead and 0.3-1.0% for Upper Columbia River steelhead (Table 6).

Table 5. Numbers of tags recovered from the double-crested cormorant colony on Foundation Island and estimated rates of predation on in-river migrating PIT-tagged salmonids from the 2010 migration year. Colony detection data were adjusted using a mean detection efficiency rate of 63%. Predation rates were estimated by species, run, rear type, and origin for groups having at least 100 detections per week at Rocky Reach Dam (for Columbia River fish) or at Ice Harbor and Lower Monumental Dam (for Snake River fish).

	Foundation Island double-crested cormorant colony			
Species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
	Upper Columbia River stocks			
Spring/Summer Chinook salmon				
Hatchery	50,365	1	2	<0.1
Wild	804	7	11	<0.1
Coho salmon				
Hatchery	3,994	0	0	0.0
Steelhead				
Hatchery	21,739	12	19	<0.1
Wild	1,408	0	0	0.0
	Snake River stocks			
Spring/Summer Chinook salmon				
Hatchery	12,569	57	90	0.7
Wild	4,532	32	51	1.1
Fall Chinook salmon				
Hatchery	51,758	240	381	0.7
Unknown Chinook salmon				
Hatchery	4,946	35	56	1.1
Wild	2,811	21	33	1.2
Unknown	268	1	2	0.6
Steelhead				
Hatchery	18,761	223	354	1.9
Wild	4,322	40	63	1.5
Sockeye salmon				
Hatchery	717	9	14	2.0

Table 6. Numbers of tags recovered from the Crescent Island Caspian tern colony and estimated rates of predation on in-river migrating PIT-tagged salmonids from the 2010 migration year. Colony detection data were adjusted for detection efficiency rates, which were interpolated using linear regression equations (see Appendix Figure 1). Mean weekly predation rates were estimated by species, run, rear type, and origin only for groups with at least 100 detections upstream at Rocky Reach Dam (for Columbia River fish) or at Ice Harbor and Lower Monumental Dam (for Snake River fish).

	Crescent Island Caspian tern colony			
Species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
	Upper Columbia River stocks			
Spring/Summer Chinook salmon				
Hatchery	50,365	65	96	0.3
Wild	804	1	2	0.4
Coho salmon				
Hatchery	3,994	33	46	1.2
Steelhead				
Hatchery	21,739	158	250	1.2
Wild	1,408	1	2	0.3
	Snake River stocks			
Spring/Summer Chinook salmon				
Hatchery	12,569	20	32	0.7
Wild	4,532	19	30	0.6
Fall Chinook salmon				
Hatchery	51,758	273	340	0.8
Unknown Chinook salmon				
Hatchery	4,946	17	27	0.7
Wild	2,811	14	16	0.7
Unknown	268	6	12	4.5
Steelhead				
Hatchery	18,761	396	554	3.0
Wild	4,322	75	106	2.5
Sockeye salmon				
Hatchery	717	5	7	1.0

Table 7. Numbers of tags recovered on the Crescent Island California gull colony and estimated rates of predation on PIT-tagged salmonids migrating in 2010. Colony detection data were adjusted using a mean detection efficiency rate of 79%. Mean weekly predation rates were estimated by species, run, rear type, and origin only for groups with at least 100 detections upstream at Rocky Reach Dam (for Columbia River fish) or at Ice Harbor and Lower Monumental Dam (for Snake River fish).

	Crescent Island California gull colony			
Species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
	Upper Columbia River stocks			
Spring/Summer Chinook salmon				
Hatchery	50,365	16	25	<0.1
Wild	804	0	0	0.0
Coho salmon				
Hatchery	3,994	4	5	0.1
Steelhead				
Hatchery	21,739	213	270	1.2
Wild	1,408	6	8	0.6
	Snake River stocks			
Spring/Summer Chinook salmon				
Hatchery	12,569	8	10	<0.1
Wild	4,532	3	4	<0.1
Fall Chinook salmon				
Hatchery	51,758	15	19	<0.1
Unknown Chinook salmon				
Hatchery	4,946	7	9	0.2
Wild	2,811	3	4	0.1
Unknown	268	0	0	<0.1
Steelhead				
Hatchery	18,761	93	118	0.6
Wild	4,322	13	16	0.4
Sockeye salmon				
Hatchery	717	0	0	0.0

Table 8. Numbers of tags recovered from the American white pelican colony on Badger Island and estimated predation on PIT-tagged salmonids migrating in 2010. Colony detection data were adjusted by the mean detection efficiency of 75%. Mean weekly predation rates were estimated by species, run, rear type, and origin only for groups with at least 100 detections upstream at Rocky Reach Dam (for Columbia River fish) or at Ice Harbor and Lower Monumental Dam (for Snake River fish).

	Badger Island American white pelican colony			
Species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
	Upper Columbia River stocks			
Spring/Summer Chinook salmon				
Hatchery	50,365	9	12	**<0.1**
Wild	804	0	0	**0.0**
Coho salmon				
Hatchery	3,994	3	4	**0.1**
Steelhead				
Hatchery	21,739	17	23	**0.1**
Wild	1,408	0	0	**0.0**
	Snake River stocks			
Spring/Summer Chinook salmon				
Hatchery	12,569	2	3	**<0.1**
Wild	4,532	1	1	**<0.1**
Fall Chinook salmon				
Hatchery	51,758	20	27	**<0.1**
Unknown Chinook salmon				
Hatchery	4,946	0	0	**<0.1**
Wild	2,811	0	0	**<0.1**
Unknown	268	0	0	**<0.1**
Steelhead				
Hatchery	18,761	49	66	**0.4**
Wild	4,322	4	5	**0.1**
Sockeye salmon				
Hatchery	717	0	0	**<0.1**

Lake Celilo (The Dalles Dam reservoir)—Avian colonies nesting in Lake Celilo made a negligible contribution to predation compared to other avian colonies throughout the Columbia River basin. Predation by the gull colony on Miller Rocks Island was less than 1% for most salmon species (Table 9). Miller Rocks gulls did not appear to prefer salmonids of any particular origin, but preyed upon steelhead somewhat more frequently than other salmonids.

Columbia River estuary—Annual predation rates in the estuary were estimated both for fish detected at Bonneville Dam and for those released from lower Columbia River hatcheries. Predation rates by Caspian terns and double-crested cormorants nesting on East Sand Island were generally greater than those of avian predators elsewhere in the basin for all salmon species (Tables 10 and 11).

In most cases, predation rates were similar within salmonid species, regardless of origin or rearing type. For example, Caspian terns generally consumed 8-9% of all available steelhead, regardless of origin, whereas double-crested cormorants generally consumed steelhead at rates of 3-4%.

Table 9. Tag recoveries from the Miller Rocks Island gull colony with estimated mean weekly predation rates of PIT-tagged salmonids migrating in 2010. Estimates were adjusted by the mean detection efficiency of 75% and were calculated only for groups with at least 100 upstream detections per week.

	Miller Rocks Island gull colony			
Species/rear type	Detections upstream from colony	Colony detections	Adjusted colony detections	Estimated mean weekly predation (%)
Mid-Columbia River stocks				
Spring/Summer Chinook salmon				
Hatchery	4,693	12	16	0.3
Wild	3,296	5	7	0.2
Fall Chinook salmon				
Hatchery	2,976	6	8	0.3
Coho salmon				
Hatchery	1,167	5	7	0.6
Steelhead				
Hatchery	1,138	7	9	0.8
Wild	1,495	8	11	0.7
Upper Columbia River stocks				
Spring/Summer Chinook salmon				
Hatchery	12,847	26	35	0.3
Wild	2,982	0	0	0.0
Fall Chinook salmon				
Hatchery	149	0	1	0.3
Coho salmon				
Hatchery	1,453	8	11	0.7
Steelhead				
Hatchery	5,045	39	52	1.0
Wild	595	7	9	1.5
Unknown	268	5		3.0
Sockeye salmon				
Hatchery				
Wild	1,196	4	5	0.4
Unknown	949	4	5	0.6
Snake River stocks				
Spring/Summer Chinook salmon				
Hatchery	47,955	102	136	0.3
Wild	11,564	24	32	0.3
Fall Chinook salmon				
Hatchery	20,474	29	39	0.2
Unknown Chinook salmon				
Hatchery	6,833	20	27	0.4
Wild	5,517	10	13	0.2
Unknown	260	2	3	1.0
Steelhead				
Hatchery	20,871	210	280	1.3
Wild	4,048	36	48	1.2
Unknown				
Sockeye salmon				
Hatchery	1,218	11	15	1.0
Wild	47,955	102	136	0.3

Table 10. Number of tags recovered from the Caspian Tern colony on East Sand Island with estimated mean weekly predation rates of PIT-tagged salmonids migrating in 2010. Data shown are adjusted for detection efficiency (DE) (84%) by species and origin (hatchery, wild, and unknown) for groups with at least 100 fish released per week from LCR hatcheries or detected at the Bonneville Dam index site.

	East Sand Island Caspian tern colony											
	Lower Columbia River			Mid-Columbia River			Upper Columbia River			Snake River		
Rear type	Colony detections	Hatchery released	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)
Spring/Summer Chinook salmon												
Hatchery	93	15,546	**0.3**	382	15,001	**3.0**	209	15,606	**1.6**	701	33,644	**2.5**
Wild	15	7,673	**0.2**	38	2,558	**1.8**	9	1,402	**0.8**	38	5,480	**0.8**
Unknown	41	1,494	**3.3**	4	127	**3.7**	3	144	**2.5**			
Fall Chinook salmon												
Hatchery	646	21,348	**3.6**	83	5,117	**1.6**	0	172	**0**	83	17,812	**0.6**
Wild				1	199	**0.6**						
Unknown Chinook salmon												
Hatchery				13	666	**2.3**				431	18,120	**2.8**
Wild	20	8,397	**0.3**							24	3,159	**0.9**
Unknown				5	503	**1.2**				3	245	**1.5**
Coho salmon												
Hatchery	231	8,830	**3.1**	51	1,635	**3.7**	110	3,509	**3.7**			
Steelhead												
Hatchery	212	4618	**5.5**	519	6,931	**8.9**	944	11,826	**9.5**	2,752	35,233	**9.3**
Wild	11	180	**7.3**	276	4,526	**7.3**	59	906	**7.8**	487	5,680	**10.2**
Unknown				18	260	**8.2**						
Sockeye salmon												
Hatchery							3	819	**0.4**	12	1,367	**1.0**
Unknown							2	379	**0.6**			

Table 11. Number of tags recovered from the double-crested cormorant colony located on East Sand Island with mean weekly predation rates of PIT-tagged salmonids migrating in 2010. Data shown are adjusted for colony-specific detection efficiency (76%) by species and origin (hatchery, wild, and unknown) for paired groups with at least 100 fish released per week from LCR hatcheries or detected at the Bonneville Dam index site.

	East Sand Island double-crested cormorant colony											
	Lower Columbia River			Mid-Columbia River			Upper Columbia River			Snake River		
Rear type	Colony detections	Hatchery released	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)	Colony detections	Bonneville detections	Mean predation (%)
Spring/Summer Chinook salmon												
Hatchery	104	15,546	**0.2**	213	15,001	**1.9**	208	15,606	**1.8**	639	33,644	**2.5**
Wild	15	7,673	**0.5**	38	2,558	**2.0**	13	1,402	**1.2**	104	5,480	**2.5**
Unknown	41	1,494	**4.5**	2	127	**2.1**	1	144	**0.9**	1	50	**2.6**
Fall Chinook salmon												
Hatchery	1,974	21,348	**16.2**	307	5,117	**7.9**	0	172	**0**	251	17,812	**1.9**
Wild				6	199	**4.0**						
Unknown Chinook salmon												
Hatchery				197	11,022	**2.5**				378	18,120	**2.7**
Wild	20	8,397	**0.8**							56	3,159	**2.3**
Unknown				97	5,733	**2.4**				4	245	**2.1**
Coho salmon												
Hatchery	231	8,830	**10.6**	35	1,635	**2.8**	38	3,509	**1.4**			
Steelhead												
Hatchery	212	4,618	**3.6**	181	6,931	**3.4**	290	11,826	**3.2**	898	35,233	**3.4**
Wild	11	180	**2.9**	120	4,526	**3.5**	21	906	**3.0**	193	5,680	**4.5**
Unknown				7	260	**3.5**						
Sockeye salmon												
Hatchery							17	819	**2.7**	12	1,367	**1.2**
Wild							7	449	**2.1**			
Unknown							3	379	**1.0**			

Temporal Trends in Seasonal Predation

Methods

In addition to estimates of mean seasonal predation by bird colony and by fish species and origin, we also examined temporal trends in these estimates for avian colonies with substantial rates of predation. These evaluations allowed us to discern changes in predation rates during the spring migration season, which generally runs from April through July. We examined temporal predation rates for all avian colonies except those on Twining Island in Banks Lake and on Central Blaylock Island in Lake Umatilla. These were excluded due to lack of an appropriate upstream detection site with which to form virtual releases, or because we could not estimate detection efficiency on the colony. For weekly estimates of avian predation, we used fish with previous detections at the same upstream locations used in the seasonal estimates.

For colonies on East Sand Island in the Columbia River estuary, we also compared weekly predation rates between groups of transported and inriver migrating fish. For these comparisons, we used transport groups comprised of fish released from barges at Skamania Landing (rkm 224) and inriver-migrant groups comprised of fish detected at Bonneville Dam (rkm 235). We calculated predation rates only for weeks during which a minimum of 100 fish were available from each migration history category (detected at Bonneville Dam or released from transport barges). All species codes (i.e., for Chinook salmon, coho, steelhead, etc.) and run codes (spring, summer, fall, winter, unknown) were obtained from PTAGIS (PSMFC 2010).

Results

Upper Columbia River stocks—The majority of upper Columbia River fish consumed by Caspian terns were detected at Rocky Reach Dam during May (Figure 2). Caspian terns nesting on Crescent Island and Goose Island accounted for the majority of predation of upper Columbia River fish, especially steelhead. Predation by terns Goose Island terns was far higher for steelhead than for other salmonid species and weekly estimates exceeded 10% for several weeks and reached 15% late in the migration season. Predation rates of gulls nesting on Crescent Island during late April and early May (mean 1.5%) was also notable. On Goose Island, for all avian species combined, the predation rate on coho salmon was less than 5% over the entire migration season.

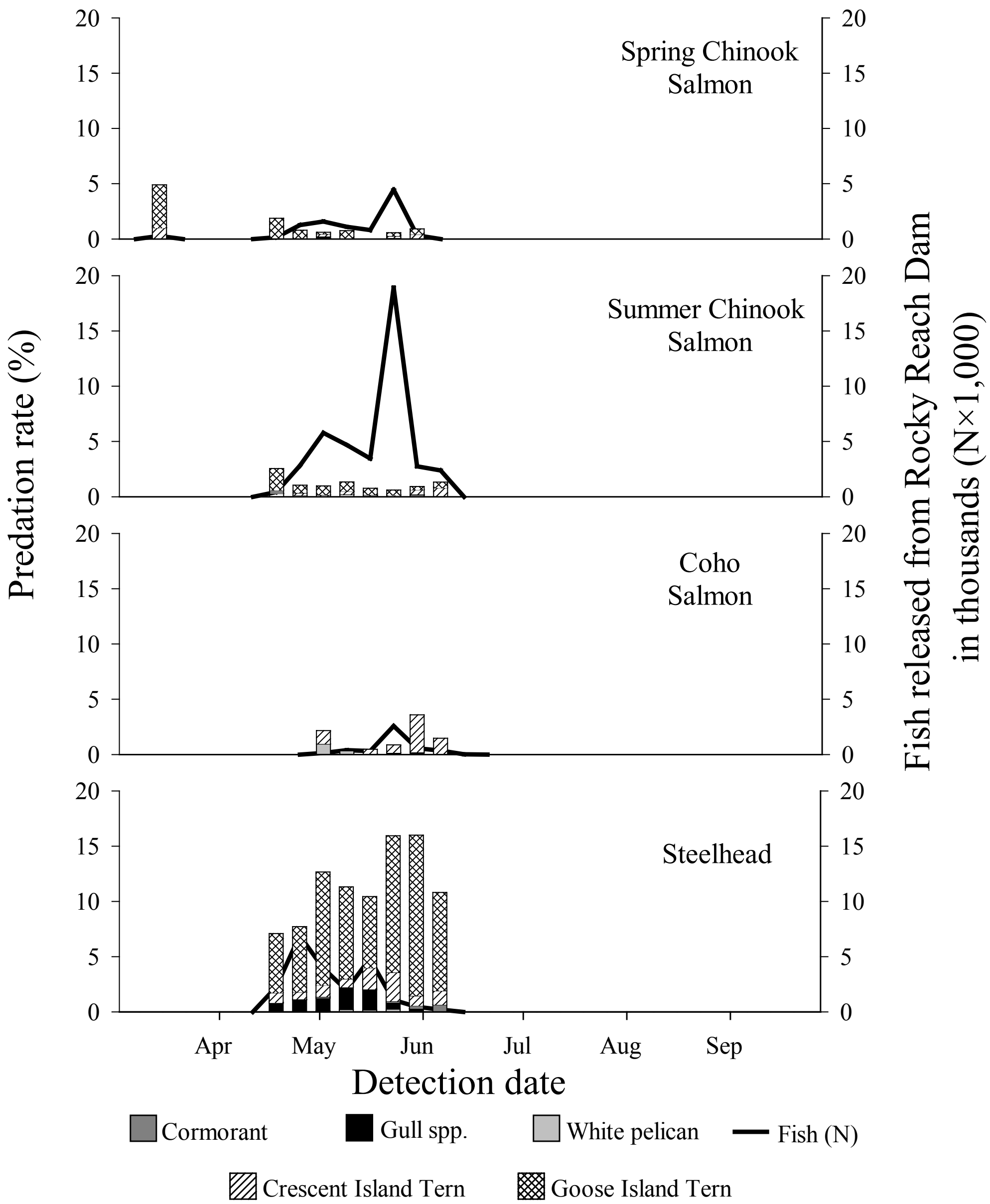

Figure 2. Temporal trends in predation (adjusted for detection efficiency; see Appendix Figure 1) of PIT-tagged upper Columbia River salmonids detected at Rocky Reach Dam index site by avian species nesting in Lake Wallula or Potholes Reservoir.

Snake River stocks—Predation rates of salmonids detected at lower Snake River dams by birds nesting in Lake Wallula were generally 5% or less for all species except steelhead (Figure 3). The majority of Snake River fish was preyed upon by Crescent Island terns and Foundation Island cormorants. Predation rates of spring/summer Chinook salmon and steelhead by these avian species increased later in the migration season. Consumption of Snake River fish by gulls and pelicans was negligible, although they did consume notable proportions of steelhead. Combined consumption of steelhead by terns and cormorants exceeded 5% during most weeks.

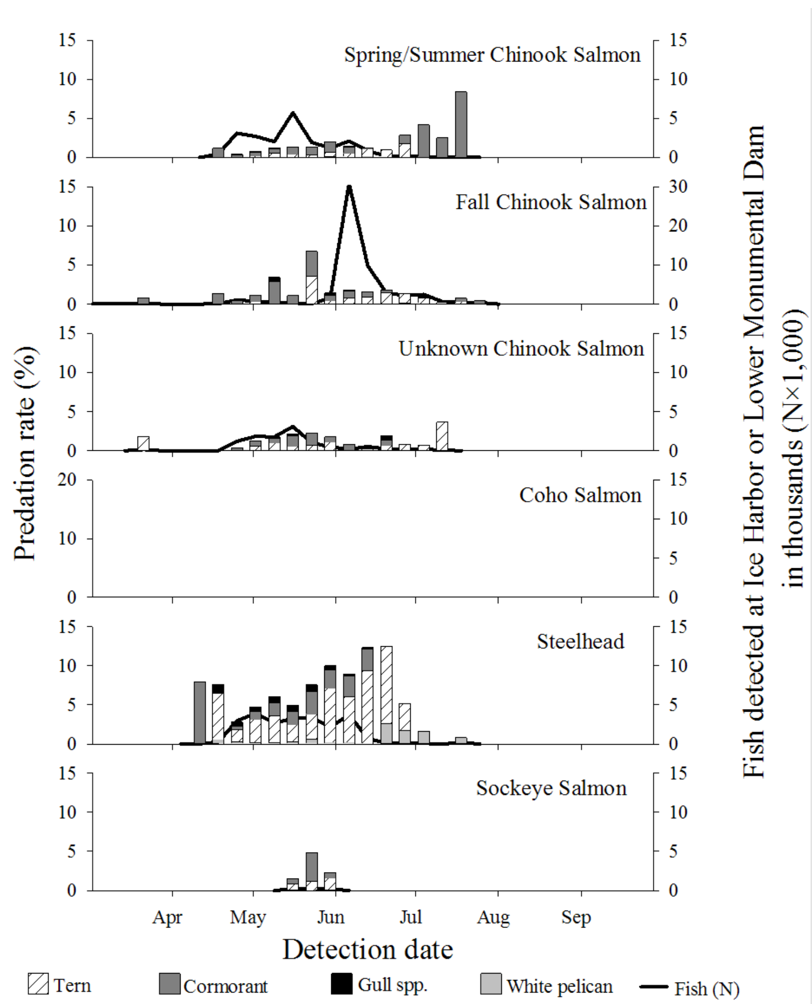

Figure 3. Temporal trends in predation of PIT-tagged Snake River salmonids (detected at Ice Harbor or Lower Monumental Dam) by avian colonies recovered on located in Lake Wallula on Badger, Crescent, and Foundation Islands.

Miller Rocks Island—Gulls nesting on Miller Rocks Island had a consistently low predation rate on all species of salmonids detected at John Day or McNary Dam. Predation rates by Miller Rocks gulls on fish detected at these dams were generally consistent, at 1% or less (Figure 4). However, predation rates on steelhead by these gulls exceeded 1% during nearly every week of the migration season.

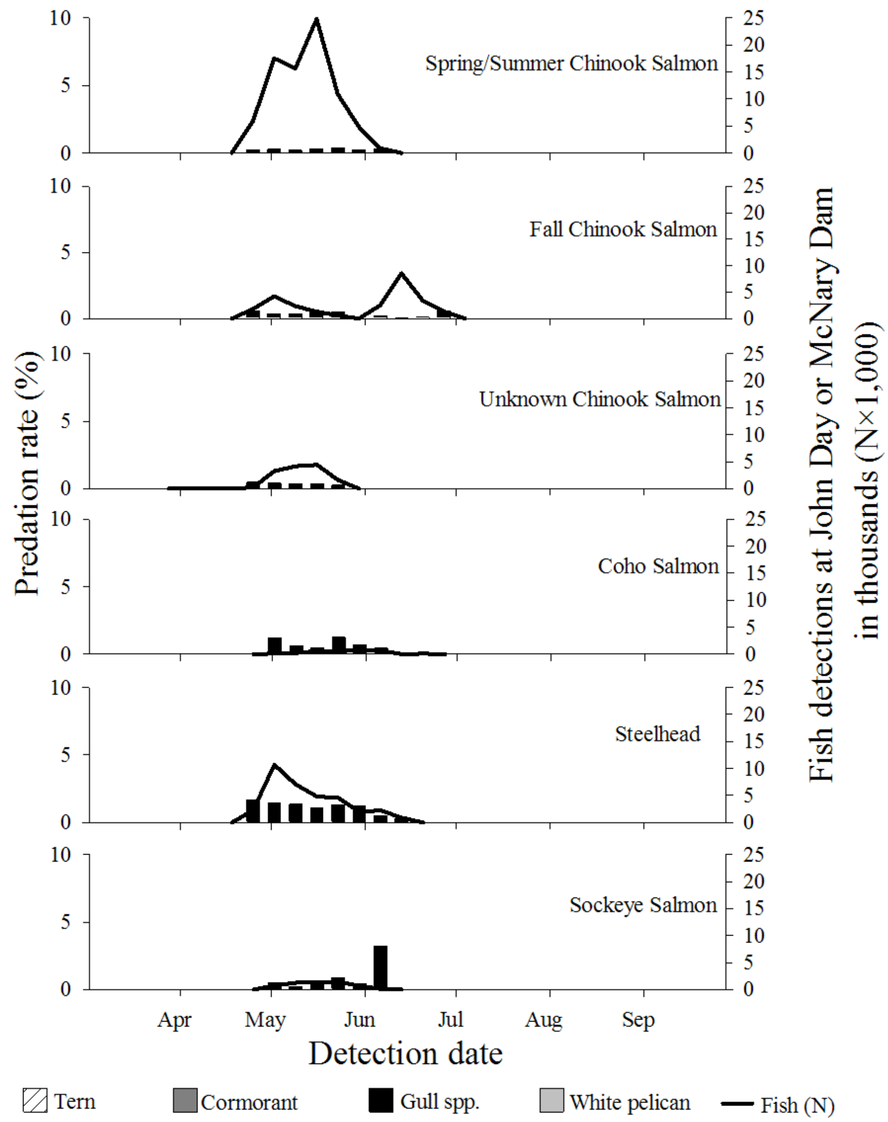

Figure 4. Temporal trends in weekly predation by Miller Rocks Island Gulls (estimates adjusted for a colony detection efficiency of 75%) on PIT-tagged salmonids detected at John Day or McNary Dam.

East Sand Island—For birds nesting on East Sand Island, predation rates on salmonids detected at Bonneville Dam were approximately 5% throughout most of the migration season, regardless of species (Figure 5). In general, predation was evenly split between Caspian terns and double-crested cormorants; however, cormorants consumed the majority of fall Chinook salmon, whereas terns consumed the majority of steelhead. Predation rates by terns and cormorants did not follow a consistent pattern during the migration season for most salmonid species. However, predation rates exceeded 10% for two groups of subyearling fall Chinook salmon released from Spring Creek Hatchery in early April and May. In contrast, predation rates were less than 5% for all other groups of subyearling Chinook salmon. We did not observe groups of fish from any other virtual or actual release site with a similar disparity in vulnerability to predation.

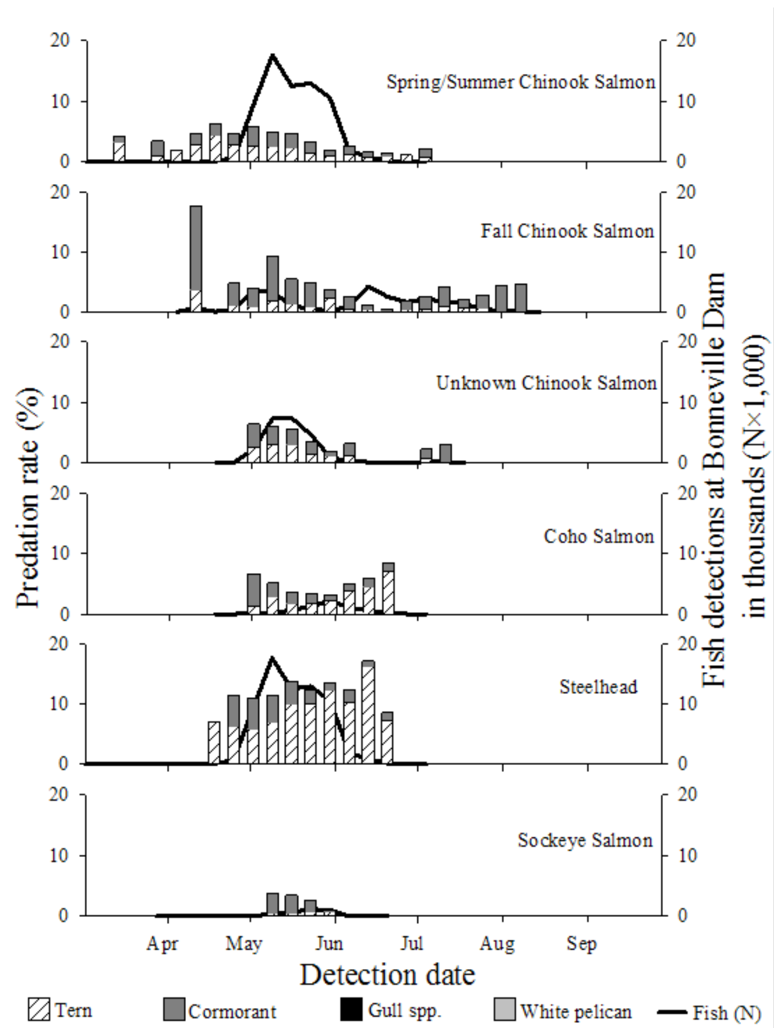

Figure 5. Estimated weekly predation rates (adjusted for detection efficiency; tern 84%, cormorant 76%) for salmonids with PIT tags detected at the Bonneville Dam index site and subsequently recovered from the East Sand Island Caspian tern and double-crested cormorant colonies.

Comparison by Migration History—We used weekly numbers of fish detected at Bonneville Dam and released from transport barges to examine temporal trends in of predation by migration history. Data for comparison was available only for East Sand Island Caspian tern and double-crested cormorant colonies. Predation rates ranged 2-8% for all fish species/run combinations released from transport barges at Skamania Landing with the exception of steelhead, for which predation rates ranged 11-15% (Figure 6). Predation rates of transported salmonids, regardless of species, were not significantly different than those of inriver migrants (Table 12).

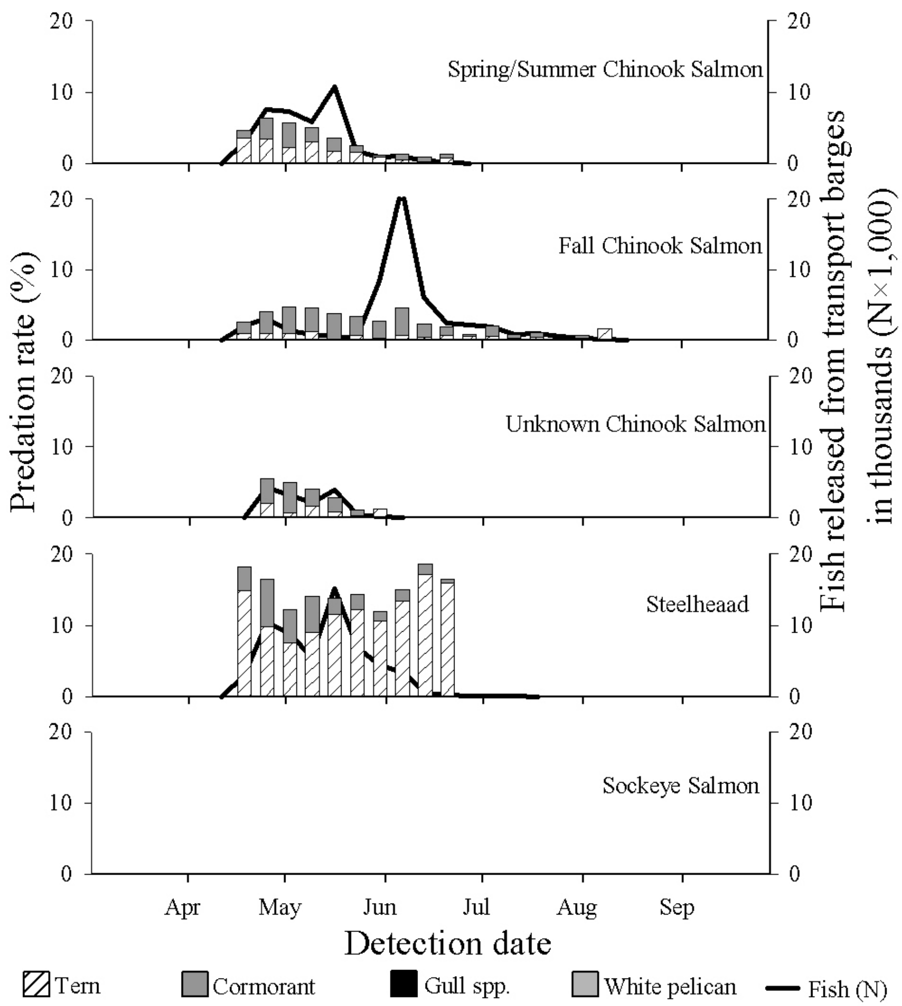

Figure 6. Estimated weekly predation rates (adjusted for detection efficiency; tern 84%, cormorant 76%) for salmonids with PIT tags released from transport barges and subsequently recovered from the East Sand Island Caspian tern and double-crested cormorant colonies.

Table 12. Mean weekly predation rates of fish detected at Bonneville Dam and those released concurrently from transport barges at Skamania Landing (adjusted for mean detection efficiencies of 84% on the tern colony and 76% on the cormorant colony). We pooled wild and hatchery fish for all comparisons. Mean weekly predation rates between inriver and transported fish were compared using a *t*-test.

		Spring/summer Chinook	Fall Chinook	Unknown Chinook	Steelhead
		Inriver migrants			
Total colony detections	Tern	1,328	150	481	4,918
	Cormorant	1,193	500	456	1,678
Adjusted predation rate (%)	Tern	2.0	0.8	2.2	9.3
	Cormorant	1.7	2.9	2.5	3.2
	Total	3.7	3.6	4.7	12.4
		Transported migrants			
Total colony detections	Tern	798	260	80	3,897
	Cormorant	643	1,080	200	976
Adjusted predation rate (%)	Tern	1.8	0.6	0.9	10.7
	Cormorant	1.4	1.9	1.9	3.0
	Total	3.3	2.5	2.9	13.6
		P-value			
		0.63	0.08	0.25	0.11

Predation on Lower Columbia River Chinook Salmon

Methods

During 2010, we continued tagging hatchery subyearling Chinook to evaluate avian predation on the lower Columbia River fall Chinook Salmon ESU (evolutionarily significant unit). This ESU contains both upriver bright and tule stocks (Narum et al. 2004), and is represented by few PIT-tagged individuals. Using techniques described in Ryan et al. (2006), we PIT-tagged over 12,000 subyearling tule Chinook during spring and early summer at four Lower Columbia River hatcheries.

Tagging was conducted at Big Creek Hatchery (rkm 49), Deep River Net Pens (rkm 37), North Toutle Hatchery (rkm 135), and Warrenton High School Hatchery (rkm 14). Groups of fish released from these four hatcheries were also used to examine whether predation rates of subyearling fall Chinook salmon released near the estuary were similar to those of stocks released further upstream. Fish tagged at Warrenton High School Hatchery were transported approximately 3 km downstream in oxygenated tanks of recirculating hatchery water. Fish were then released into the Skipanon River 2 km from its confluence with the Columbia River.

At three of these hatcheries, we also tagged and released 3,000 coho salmon. Coho salmon from Big Creek Hatchery, Deep River Net Pens, and Warrenton High School Hatchery were used to compare predation rates between lower Columbia River fish and those originating upstream from Bonneville Dam. Similar to comparisons of Chinook salmon, these comparisons were based on paired groups of fish released from Lower Columbia River hatcheries and detected at Bonneville Dam during the same week. Records of transported fish were not included for this analysis.

Results

We PIT-tagged a total of 12,251 subyearling fall Chinook salmon at the four lower Columbia River (LCR) hatcheries from early May through mid-June 2010 (Table 13). Records obtained from PTAGIS showed that a total of 14,579 PIT-tagged hatchery subyearling Chinook salmon were detected at Bonneville Dam from April through September 2010.

The mean adjusted seasonal predation rate for lower Columbia River hatchery subyearlings by avian predators nesting on East Sand Island, was 20.6%, similar to rates estimated in previous years (Ryan et al. 2006, 2007; Sebring et al. 2009, 2010). For subyearling fall Chinook salmon detected at Bonneville Dam, estimated seasonal predation was considerably lower than for LCR hatchery subyearlings, at 5.8%, and the difference was significant (P = 0.003). The ratio of fish consumed by terns and cormorants nesting on East Sand Island was not significantly different between LCR hatchery subyearlings (24% tern:76% cormorant) and subyearlings detected at Bonneville Dam (17% tern: 83% cormorant; P = 0.30).

Table 13. Numbers released and estimated predation rate of PIT-tagged subyearling Chinook and coho salmon. Fish were either released to the lower Columbia River from hatcheries or net pens or detected at Bonneville Dam. Predation rates were adjusted by detection efficiency at each colony (tern 84%, cormorant 76%).

		Recovered (N)		Estimated predation (%)		
Release or detection site	Detected or released (N)	Caspian tern	Double-crested cormorant	Caspian tern	Double-crested cormorant	Total
	Subyearling fall Chinook salmon					
Hatchery releases						
Big Creek Hatchery	3,051	99	521	3.9	21.6	25.5
Deep River Net Pens	3,085	206	405	7.9	16.6	24.6
North Toutle Hatchery	3,073	72	286	2.8	11.8	14.6
Warrenton HS Hatchery (Skipanon R)	3,042	137	301	5.4	12.5	17.9
Bonneville Dam detection	14,579	90	335	1.0	4.8	5.8
	Coho salmon					
Hatchery releases						
Big Creek Hatchery	3,002	104	333	4.1	14.0	18.2
Deep River Net Pens	2,770	111	327	4.8	14.9	19.7
Warrenton HS Hatchery (Skipanon R)	3,058	16	55	0.6	2.3	2.9
Bonneville Dam detection	6,479	233	108	5.1	2.9	8.1

For Spring Creek Hatchery tule stocks detected at Bonneville Dam early in the migration season, predation rates were significantly different than those of upriver bright stocks detected later in the season ($P < 0.001$; Figure 7). However, there was no significant difference in the mean proportion of fish consumed by Caspian terns vs. double-crested cormorants between tule (20 vs. 80%) and upriver bright stocks (17 vs. 83%; $P = 0.78$).

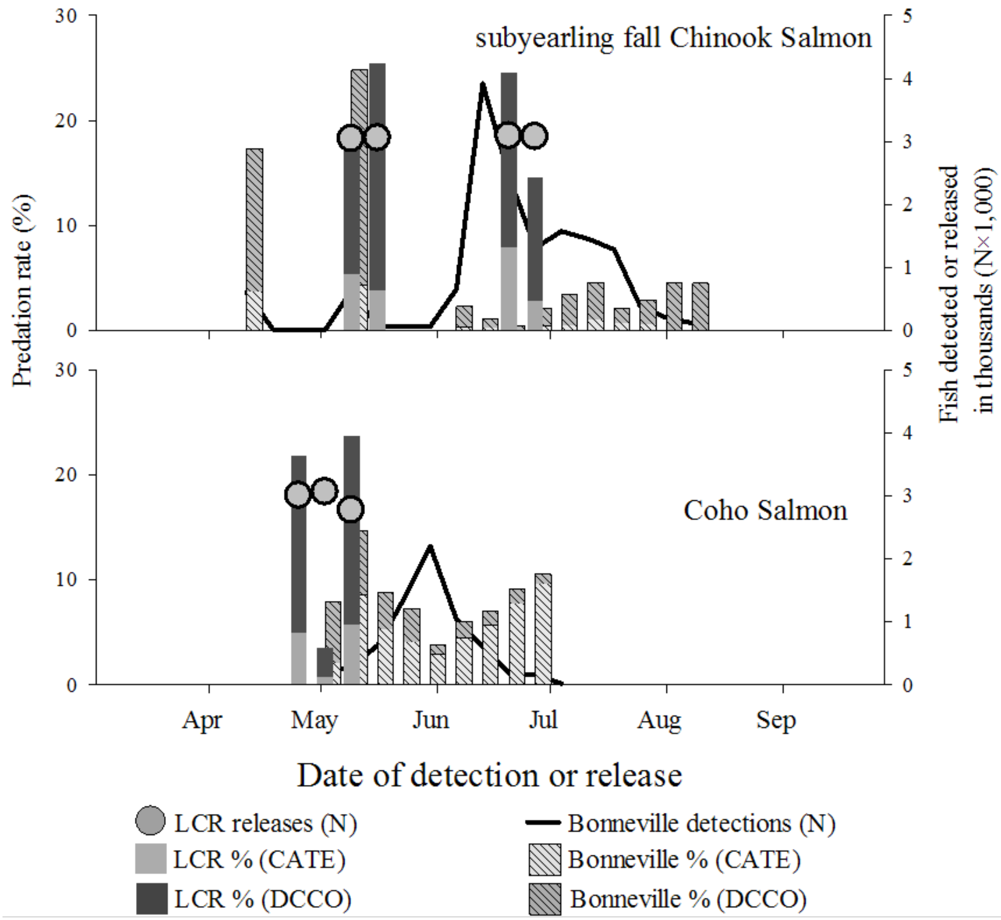

Figure 7. Seasonal predation rates by East Sand Island Caspian terns (CATE) and double-crested cormorants (DCCO) on subyearling Chinook salmon and coho salmon released from LCR hatcheries or detected at Bonneville Dam during 2010.

For coho salmon, the mean avian predation rate of LCR hatchery releases was approximately 13.6% (Table 13), which was not significantly different than the mean predation rate of coho salmon detected at Bonneville Dam (8.1%; $P = 0.15$). However, we observed substantial variation in predation rates among coho released from Warrenton High School Hatchery (3%) vs. those released from Big Creek Hatchery (18.2%) and Deep River Net Pens (19.7%). There was also a significant difference in the mean ratio consumed by Caspian terns vs. double-crested cormorants between coho salmon released from LCR hatcheries (tern 23%: cormorant 77%) and those detected at Bonneville Dam (tern 65%: cormorant 35%; $P = 0.01$).

Comparison of Predation by Tag Type

Methods

In addition to comparisons of avian predation by species and migration history, we compared predation on fish injected with a PIT-tag vs. those surgically implanted with both a PIT and an acoustic tag (double-tagged fish). For this comparison, we used fish with a PIT-tag detected at Bonneville Dam and later recovered on an East Sand Island tern or cormorant colony. This comparison was made only for Caspian tern and double-crested cormorant colonies because numbers of tag recoveries on other colonies were insufficient for analysis.

Comparisons were limited to periods during which fish with both tag types were being detected at Bonneville Dam each day. Daily detections both at Bonneville Dam and on the colonies were pooled into 3-d blocks for analysis because detections of double-tagged fish at the dam were often low (i.e., < 10/d). We assumed that after detection at Bonneville Dam, the probability of subsequent detection on a colony would be equal between fish with different tag types.

Results

A total of 809 Chinook salmon and 1,017 steelhead implanted with both an acoustic and a PIT tag (double-tagged fish) were detected passing Bonneville Dam during May 2010 (PSMFC 2010). Predation rates of these fish were compared to those of the more numerous PIT-only fish, and no apparent differences in daily mean predation were found between the two tag groups during May 2010 (Figure 8). We restricted our comparison to fish migrating during May because this was the only period for which there were consistent daily detections of PIT-tagged and double-tagged fish at Bonneville Dam (Appendix Figure 2).

The estimated mean predation rate was 9.9% for pooled groups (hatchery and wild) of double-tagged steelhead; this was not significantly different than the 10.7% rate estimated for steelhead implanted with only a PIT tag (10.7%; $P = 0.36$). Similarly, for yearling Chinook salmon, the estimated mean predation rate for double-tagged fish was 3.3% and was not significantly different than the 4.1% estimated for salmon with only a PIT tag ($P = 0.75$).

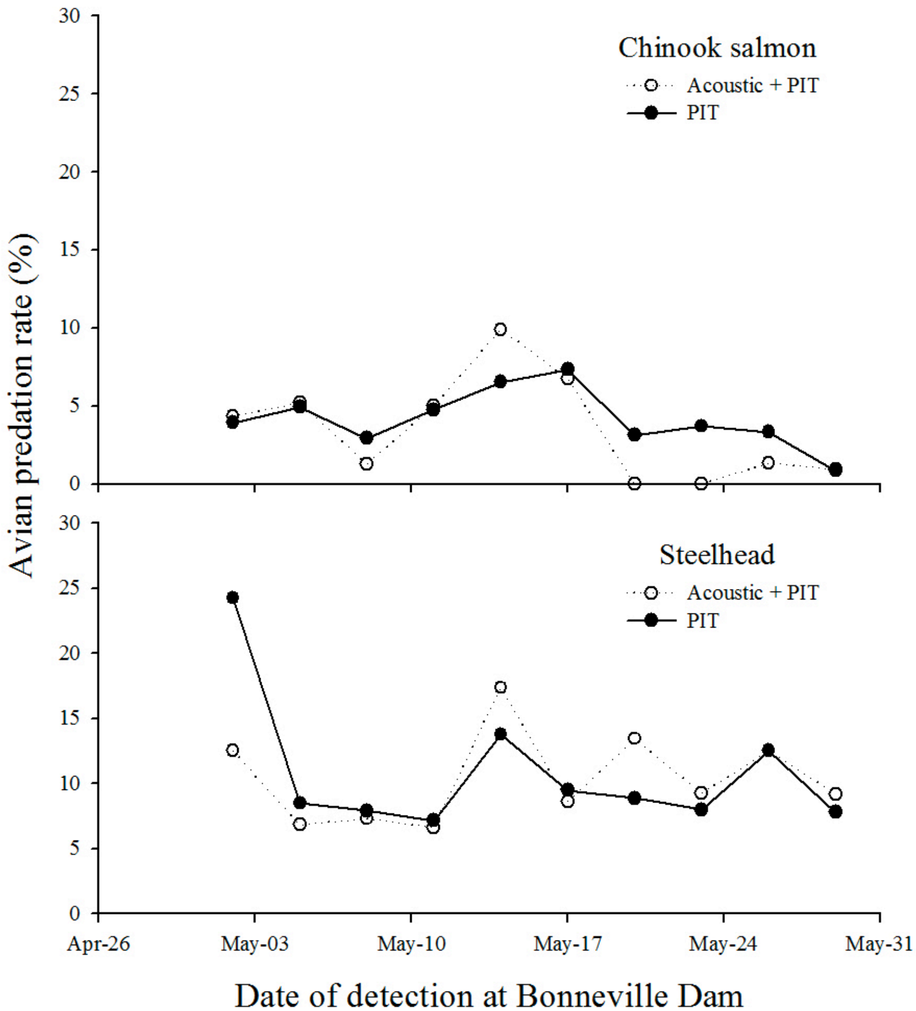

Figure 8. Relative comparison of avian predation rates on Chinook salmon and steelhead detected at Bonneville Dam that were surgically implanted with an acoustic and PIT tag or injected with a PIT tag. Fish were pooled into 3-d groups. Differences in predation rates between tag groups were not significant for either Chinook salmon (*P* = 0.36) or steelhead (*P* = 0.75).

DISCUSSION

Since 1998, we have provided recovery data from juvenile salmonid PIT-tags for use in annual assessments of avian predation throughout the Columbia River Basin (Ryan et al. 2001, 2002, 2003, 2007; Glabek et al. 2003; Sebring et al. 2009, 2010). In 2010, we continued to provide annual PIT-tag recovery data and to summarize predation rates by avian species and colony and by fish species and migration history. While continuing to monitor for any relevant change in patterns of predation, in recent years we have focused recovery effort on the specific avian colonies that have had the greatest impact on migrating juvenile salmon. These colonies were located on islands in the estuary and near the confluence of the Snake and Columbia Rivers. Data from PIT tags on these colonies provide an annual index of predation, which has been useful in determining the success or failure of management strategies to reduce the impact of avian predators on juvenile salmonids.

Our detection efficiency estimates in 2010 were consistent with those measured during previous years, given the variations in weather and substrate that can affect efficiency. Our efforts to reduce tag collision on avian colonies with large densities of PIT tags using shielding and a modified coil design were successful. Detection efficiency measurements for the cormorant colonies on East Sand Island in particular were the highest reported to date (Appendix Table 3). Detection efficiency estimates on Caspian tern colonies on Crescent and East Sand Islands generally remained consistent with those from previous years. Detection efficiency on the Goose Island Caspian tern colony was approximately 50%, and was low in comparison to other tern colonies. Additional tag data collection effort may be necessary at Goose Island in the future due to increasing numbers of terns nesting at this location.

Predation rates on LCR hatchery subyearling fall Chinook and coho salmon by Caspian terns and double-crested cormorants nesting on East Sand Island were considerably greater than conspecifics originating from the interior Columbia River basin that were detected at Bonneville Dam. In addition, greater proportions of both LCR subyearling Chinook and coho salmon were consumed by double-crested cormorants than by Caspian terns. For two of the three groups of PIT-tagged hatchery coho salmon, we observed generally high predation rates that were similar to those of subyearling Chinook salmon. The ratio of fish consumed by terns and cormorants was also significantly different between coho salmon originating from hatcheries in the LCR and those originating from the interior Columbia River detected passing Bonneville Dam.

PIT tag recovery data from East Sand Island indicates that vulnerability to avian predation of lower Columbia River stocks is considerably higher than that of stocks originating upriver, a finding similar to those reported from previous study years (Ryan et al. 2006; Sebring et al. 2009, 2010, 2010a). The disparity in vulnerability to predation may reflect differences in behavior, release timing, and length of estuary residency of LCR fish in comparison to those originating from the interior Columbia River. Factors contributing to these differences could be evaluated using acoustic transmitters and mobile tracking of lower Columbia River fish.

We also found differences in vulnerability to avian predators in the estuary for subyearling fall Chinook salmon originating upstream of Bonneville Dam. In 2010, weekly predation rates on subyearling fall Chinook salmon from Spring Creek National Fish Hatchery, located approximately 40 rkm upstream of Bonneville Dam, were generally higher than those measured during 2009 (21 vs. 6%; Sebring et al. 2010b). A portion of Spring Creek Hatchery-reared subyearlings have been shown to rear in the estuary for extended periods prior to ocean entry (Teel et al. 2009). We speculate that interannual differences in predation rates on these fish may result from differences in seasonal conditions (river flow, presence of marine forage fishes, turbidity, and wind stress) or other factors (disease and degree of smoltification). These conditions influence the proportion, duration, and type of habitat used by these fish in the estuary; many of these conditions also influence the foraging success of birds. Though management decisions frequently focus on threatened salmonid stocks in the upper Columbia and Snake River basins, it is also important to consider lower river stocks, which appear acutely vulnerable to avian predation. Management action to relocate avian colonies outside the estuary may benefit all salmonid migrants in the Columbia River Basin.

The use of surgically implanted acoustic tags as a method to investigate spatially explicit migration behavior of juvenile fish has increased in recent years. This has also led to greater scrutiny of the effects of acoustic tags on fish behavior (Adams et al. 1998a; b; Martinelli et al. 1998; Hockersmith et al. 2003) and survival (Lacroix et al. 2004; Hall et al. 2009; Rub et al. 2009), either due to the presence of tags or associated implantation procedures.

Studies to evaluate tag effects have included some comparisons of predation rates between Chinook salmon implanted with both acoustic and PIT tags vs. those with only a PIT tag. Cohorts were released at Lower Granite Dam, but the numbers of these fish found on avian colonies provided small sample sizes for evaluation and did not reveal significant differences in rates of avian predation between tag types (Rub et al. 2009). In our evaluations of predation rates between double-tagged and PIT-tagged fish in the estuary, we compared data from 2008-2010 on a daily basis throughout the migration season when both groups were present. In 2008, recoveries of PIT-only versus double-tagged fish suggested that fish implanted with both an acoustic and PIT tag were significantly more vulnerable to avian predators on East Sand Island than fish implanted with only a PIT tag (Sebring et al. 2010). For that analysis, we pooled daily groups of double-tagged fish detected passing Bonneville Dam with groups of double-tagged fish released at the dam. In subsequent years, no releases of double-tagged groups were made at Bonneville Dam, thus we re-analyzed all years (2008-2010) to equally compare treatment types (acoustic and PIT tag vs. PIT tag only) using only detections of fish passing Bonneville Dam. We found no significant differences in predation rates between tag types for any species in any year after excluding fish tagged and released at Bonneville Dam (Sebring et al. 2010b).

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APPENDIX

Detection Data Tables and Figures

Appendix Table 1. Numbers and proportions of all PIT tags recovered on avian colonies in 2010. Totals include tags with no prior colony detection and those of fish released to migrate during 2010 and in prior years.

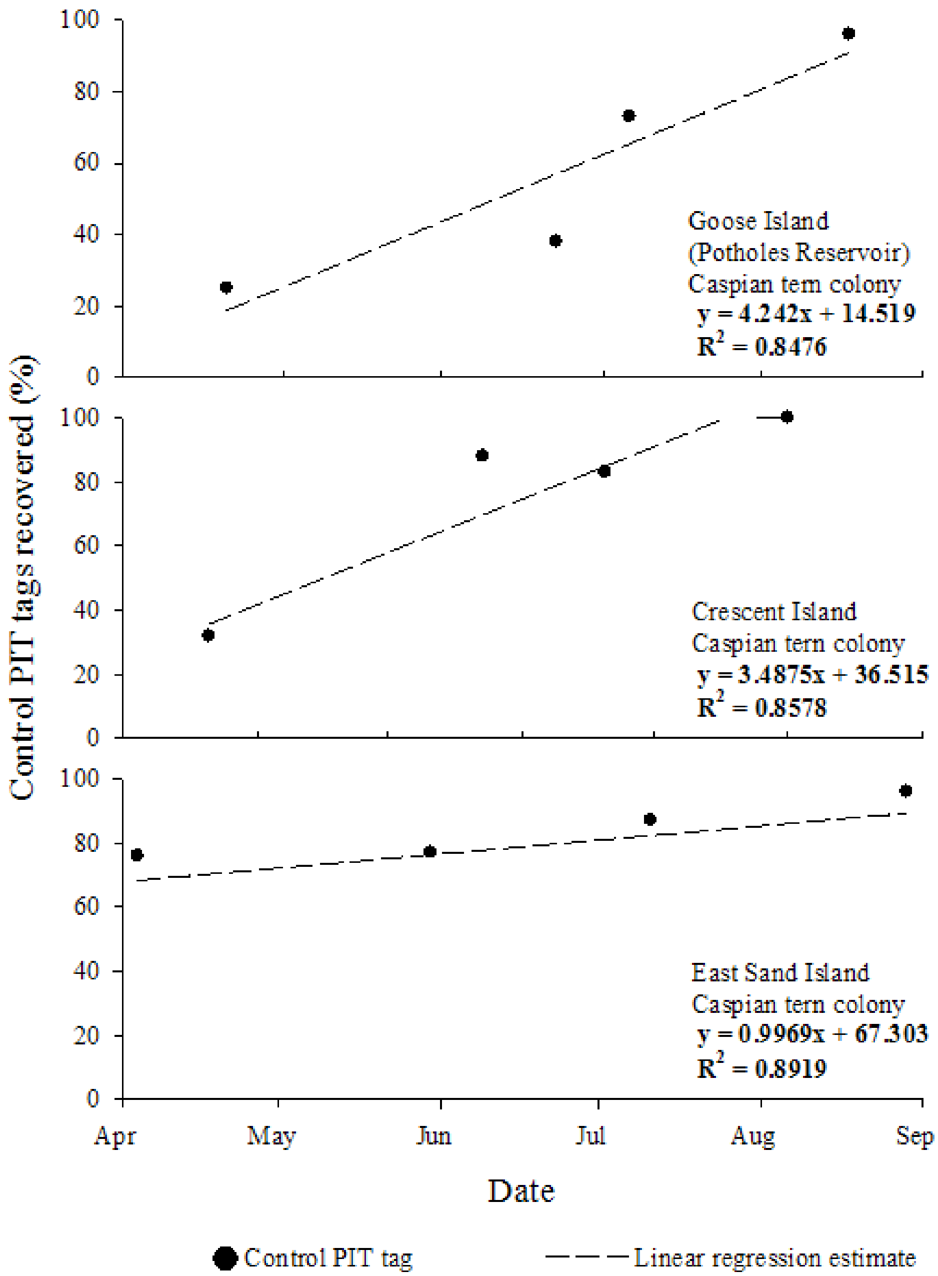
Area and island	American White Pelican	Brandt's Cormorant	Caspian Tern	Double-crested cormorant	Gull species	Mixed avian species	Total (N)	Percent (%)
Columbia Plateau								
Twining Island (Banks Lk)			117				117	0.1
Goose Island (Potholes Res)			4,595			445	5,040	4.7
Lake Wallula								
Crescent Island			6,576		3,826	312	10,714	10.0
Badger Island	2,653						2,653	2.5
Foundation Island				7,612			7,612	7.1
Lake Umatilla								
Central Blalock Isl			1,130				1,130	1.1
Lake Celilo								
Miller Rocks Island					4,892		4,892	4.6
Columbia Estuary								
East Sand Island		201	42,053	32,560			74,814	69.9
Total (N)	2,653	201	54,471	40,172	8,718	757	106,972	
Percent (%)	2.5	0.2	50.9	37.6	8.1	0.7		

Appendix Table 2. Number of tags recovered from the combined Caspian tern and double-crested cormorant colonies on East Sand Island with estimated predation rates for PIT-tagged salmonids transported in 2010. Data are presented only for species and rear types with more than 100 fish released from transport barges.

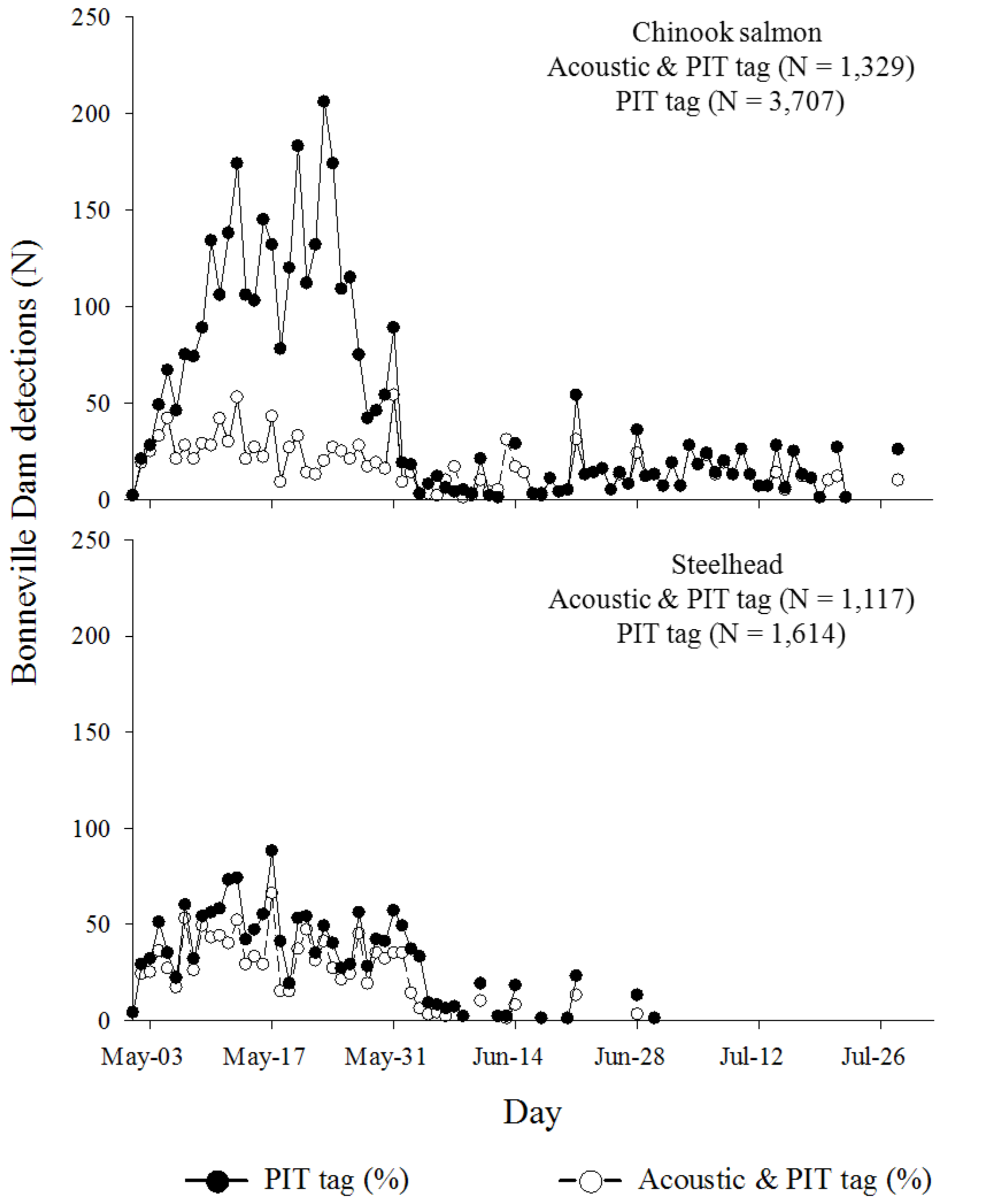
		East Sand Island Caspian tern and double-crested cormorant colonies						
		Colony recovery (N)			Estimated predation rate (%)			
Rear type	Transport barge releases	Brandt's cormorant	Caspian Tern	Double-crested cormorant	Brandt's cormorant	Caspian Tern	Double-crested cormorant	Total
Spring/Summer Chinook salmon								
Hatchery	32,450	8	761	560	0.03	2.79	2.27	5.1
Wild	6,720	1	37	80	0.02	0.66	1.57	2.2
Fall Chinook Salmon								
Hatchery	53,228	16	277	1,099	0.04	0.62	2.72	3.4
Unknown run Chinook salmon								
Hatchery	207	1	2	6	0.58	1.15	3.81	5.5
Wild	13,858	1	138	294	0.01	1.19	2.79	4.0
Unknown	415	0	17	11	0	4.88	3.49	8.4
Steelhead								
Hatchery	44,246	11	4,471	1,113	0.03	12.03	3.31	15.4
Wild	13,977	4	780	467	0.03	6.64	4.40	11.1

Appendix Table 3. Proportion of control PIT tags recovered on East Sand Island avian breeding colonies from 2002-2010 that were intentionally sown on the colony surface to measure detection efficiency. The number of control PIT tags sown on each colony is listed in parentheses.

	Percent of control PIT tags recovered (sown)	
Year	Double-crested cormorant	Caspian tern
2002	35 (300)	95 (300)
2003	45 (300)	85 (300)
2004	36 (600)	92 (1,100)
2005	55 (800)	83 (1,200)
2006	52 (600)	64 (1,200)
2007	58 (200)	89 (600)
2008	69 (600)	92 (600)
2009	70 (600)	90 (600)
2010	76 (400)	84 (400)
Mean	55	86



Appendix Figure 1. Proportion of control PIT tags released at four intervals that were detected on Goose, Crescent, and East Sand Island tern colonies. Linear regression was used evaluate potential change in detection efficiencies over the migration season.



Appendix Figure 2. Numbers of Chinook salmon and steelhead implanted with acoustic and PIT tag or PIT tag only that were detected at Bonneville Dam during May through July of 2010.