FINAL TECHNICAL REPORT: East Sand Island Passive Integrated Transponder Tag Recovery and Avian Predation Rate Analysis, 2017




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East Sand Island Passive Integrated Transponder Tag Recovery and Avian Predation Rate Analysis, 2017

Final Technical Report

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EXECUTIVE SUMMARY

To address concerns of avian predation on Endangered Species Act (ESA) listed juvenile salmonids *Oncorhynchus spp.* in the Columbia River Estuary, management plans have been developed to reduce the number of Caspian terns *Hydroprogne caspia* and double-crested cormorants *Phalacrocorax auritus* nesting on East Sand Island (USFWS 2005; USACE 2015). The primary goal of work described herein was to provide the U.S. Army Corps of Engineers (USACE) with information to evaluate the effectiveness of these management plans in reducing predation rates (percentage of available fish consumed) on juvenile salmonids by terns and cormorants nesting on East Sand Island in 2017. The primary tasks were to (1) recover juvenile salmonid passive integrated transponder (PIT) tags from the tern and cormorant colonies on East Sand Island and (2) use those data to model predation rates on juvenile salmonids. More specifically, we generated population-specific (salmonid evolutionary significant units [ESU] or distinct population segments [DPS]) predation rates on ESA-listed juvenile salmonids that integrated multiple factors of uncertainty in the tag recovery process, including imperfect detection of tags on bird colonies, on-colony tag deposition probabilities that varied by bird species (tern, cormorant), and temporal changes in fish availability to avian predators nesting on East Sand Island in 2017. Predation rates from 2017 were then compared with smolt losses prior to reductions in colony size (number of nesting pairs) due to bird management actions on East Sand Island in years past. Predation rates were further evaluated based on the run-timing, abundance, rear-type (hatchery, wild), and outmigration history (in-river, transported) of each salmonid ESU/DPS, factors previously linked to variation in predation rates. To ensure relative comparability of predation rate results collected in 2017 to years past, we use the tag recovery and analytical methods Evans et al. (2012) and Hostetter et al. (2015), previously peer-reviewed methods that allow for direct comparisons of predation rates among predator species, salmonid ESUs/DPSs, and years.

PIT Tag Recovery

Following the nesting season, a total of 8,407 and 1,340 PIT tags from 2017 migration year smolts (Chinook salmon *O. tshawytscha*, coho salmon *O. kisutch*, sockeye salmon *O. nerka*, and steelhead trout *O. mykiss* tags combined) were recovered on the East Sand Island Caspian tern and double-crested cormorant colonies, respectively. PIT tags were detected by systematically scanning the entire area (referred to as a "pass") occupied by nesting birds during the breeding season, with a total of six passes conducted on the tern colony and three passes on the cormorant colony. Detection efficiency (proportion of deposited tags detected by researchers after the breeding season) was estimated at 73% (range = 40–88%) and 71% (range = 60–78%) on the tern and cormorant colonies, respectively. All newly detected PIT tags recovered on East Sand Island bird colonies were uploaded to the PIT Tag Information System (PTAGIS) on 18 December 2017, making the data readily available to other researchers, managers, and the public alike.

Predation Rates

Caspian terns – ESU/DPS-specific predation rates by Caspian terns nesting on East Sand Island in 2017 were some of the lowest ever recorded. Predation rates on salmon ESUs ranged from 0.2% (95% credible interval [CRI] = 0.1–0.5%) on Snake River Fall Chinook to 1.4% (95% CRI = 0.9–2.3%) on Upper Columbia River spring Chinook. By comparison, predation rates averaged 2.5% (95% CRI = 2.2–3.0%) and 3.9% (95% CRI = 3.4–4.6%) on Snake River Fall and Upper Columbia River spring Chinook, respectively, prior to reductions in the size of the tern colony on East Sand Island due to management actions. Predation rates on steelhead DPSs in 2017 ranged from 5.3% (95% CRI = 3.9–7.7%) on Snake River

steelhead to 8.4% (95% CRI = 5.6–13.1%) on Middle Columbia River steelhead. By comparison, predation rates average of 22.2% (95% CRI = 20.3–24.8%) and 14.9% (95% CRI = 13.1–17.6%) for Snake and Middle Columbia River steelhead DPSs, respectively, prior to reductions in the size of the tern colony on East Sand Island due to management actions. Reductions in tern predation rates were commensurate with reductions in tern colony size, indicating that Caspian tern management actions to reduce numbers of terns on East Sand Island are resulting in lower average annual predation rates on juvenile salmonids by this colony.

An investigation of predation rates in 2017 and years past (2006-2016) based on a fish's ESU/DPS, rear-type (hatchery, wild), outmigration history (in-river, transported), and abundance (density) indicated that multiple factors influence smolt susceptibility to Caspian tern predation. A relative comparison of impacts indicated that predation rates on steelhead DPSs were significantly higher than those of salmon ESUs. There was also evidence that hatchery spring/summer Chinook salmon were more susceptible to tern predation than their wild counterparts, although no statistically credible differences in susceptibility by rear-type were observed amongst steelhead DPSs. Weekly differences in smolt susceptibility based on the relative abundance of tagged smolts in the estuary were also observed, with tern predation rates decreasing as the number of steelhead smolts in the estuary increased. Taken together, results indicate that predator-prey interactions in the Columbia River Estuary were dynamic and that multiple factors are associated with variation in East Sand Island Caspian tern predation rates on juvenile salmonids.

In addition to the established Caspian tern colony on East Sand Island, where 3,500 nesting pairs were counted in 2017, Caspian terns also attempted to nest on Rice Island in the upper Columbia River Estuary in 2017. Nesting attempts on Rice Island were unsuccessful, but upwards of 1,000 pairs attempted to nests during the breeding season. The impact on smolts from birds that attempted but failed to successfully nest on Rice Island likely off-set, to an unknown degree, the record low rates of predation by terns that successfully nested on East Sand Island in 2017. Thus, to fully evaluate the efficacy of the Tern Management Plan for reducing predation rates on ESA-listed smolts throughout the Columbia River Estuary, an investigation of cumulative predation rates by all Caspian terns – those on East Sand Island and Rice Island – in the estuary is necessary, but was beyond the scope of this study.

Double-crested cormorants – Prior to 2016, the vast majority of double-crested cormorants in the Columbia River Estuary nested on East Sand Island, allowing for a holistic evaluation of predation rates based on recoveries of smolt PIT tags at just that single colony. In 2017, however, cormorants did not establish a nesting colony on East Sand Island during the peak smolt outmigration period of April to June, but rather dispersed from East Sand Island to other locations. A similar colony dispersal event occurred on East Sand Island in 2016. Rather than completely dispersing to colony sites outside of the Columbia River Estuary, large numbers of cormorants (at least 7,000 adults) remained in the estuary and continued to forage on juvenile salmonids to an unknown degree. As such, estimates of predation rates based on numbers of PIT-tags deposited by cormorants on East Sand Island in 2017 are minimum estimates and are not representative of smolt losses by all cormorants that remained in the Columbia River Estuary during the smolt outmigration period.

Predation rate estimates associated with double-crested cormorants which briefly attempted to nest on East Sand Island during the smolt outmigration period in 2017 ranged from 0.1% (95% CRI = 0–4.2%) of Snake River Fall Chinook to 1.4% (95% CRI = 0.8–2.7%) of Upper Columbia River steelhead. Insufficient sample sizes limited our ability investigate the relative susceptibility of fish to cormorant predation based on the fish's ESU/DPS, rear-type (hatchery, wild), outmigration history (in-river, transported), and abundance in 2017. Data from previous studies indicated that, unlike Caspian terns, East Sand Island double-crested cormorant predation rates were more similar between steelhead DPSs and salmon ESUs. Results also indicated that double-crested cormorants consumed smolts in proportion to their availability, with the highest predation rates observed when the largest numbers of PIT-tagged fish were available as prey in the estuary. Double-crested cormorants also showed little or no preference for fish based on their rear-type (hatchery, wild) or outmigration history (in-river, transport), indicating all smolts were equally susceptible to predation.

Due to the lack of cormorants on East Sand Island during the peak smolt outmigration period in 2016 and 2017, a relative comparison of predation rates prior to and following management actions could not be conducted as part of this study. An analysis of predation rates during 2003-2015 indicated that smolt losses to East Sand Island double-crested cormorants were substantial in most years, but also highly variable over time. For example, predation rate estimates by East Sand Island double-crested cormorants on Snake River steelhead ranged annually from 1.9% (95% CRI = 1.2–3.0%) to 16.6% (95% CRI = 12.0–25.7%) during 2003-2015 (years when normal nesting behavior on East Sand Island occurred). Analogous to the presence of Caspian terns on Rice Island, given the presence of large number of double-crested cormorants at sites other than East Sand Island in the estuary, future predation rate monitoring and evaluation studies may need to consider the cumulative impact of all cormorants in the estuary on ESA-listed smolts to fully evaluate the efficacy of management plans to reduce predation rates.

BACKGROUND

Avian predation on juvenile salmonids during outmigration to the Pacific Ocean is considered a limiting factor in the recovery of salmonid populations from the Columbia River Basin that are listed under the U.S. Endangered Species Act (ESA; NOAA 2008, 2010). Previous research has demonstrated that Caspian terns and double-crested cormorants nesting on East Sand Island in the Columbia River Estuary consume millions of juvenile salmonids annually (Roby et al. 2003; Lyons 2010). An evaluation of avian predation rates revealed that cormorants and terns nesting on East Sand Island consumed upwards of 10% and 20% of ESA-listed Chinook and steelhead populations, respectively, in some years (USACE 2015; Evans et al. 2016a). These impacts are especially alarming because avian predation in the estuary affects juveniles belonging to every Evolutionary Significant Unit (ESU) and Distinct Population Segment (DPS) of salmonid from the Columbia River Basin, fish that have survived freshwater migration through the Federal Columbia River Power System (FCRPS) and have a higher probability of survival to adulthood compared to those fish that have yet to complete outmigration (Roby et al. 2003).

While levels of tern and cormorant predation on some populations of juvenile salmonids have been high on average, there has also been substantial intra- and inter-annual variability in predation impacts. For instance, predation rates on the same salmonid ESU/DPS can vary significantly by year (Evans et al. 2012; Sebring et al. 2013) and by week within the same year (Evans et al. 2016b). Furthermore, even within the same salmonid population, differences in predation impacts based on a fish's rear-type (hatchery, wild), outmigration history (e.g., transported from the Snake River), and abundance have been observed (Ryan et al. 2003; Lyons et al. 2014a; Evans et al. 2016a; Roby et al. 2017). Results from these studies indicate that predation by Caspian terns and double-crested cormorants is not only a substantial source of smolt mortality, but also that predator-prey interactions are dynamic and may vary based on different biotic and abiotic conditions in the Columbia River Estuary (see Lyon et al. 2014 and Evans et al. 2016a for a more detailed review of biotic and abiotic factors known to influence fish susceptibility to tern and cormorant predation in the estuary).

Resource management agencies working in the Columbia River Basin recognize the importance of addressing avian predation in efforts to restore ESA-listed salmonids. As a result, two management plans are currently underway to reduce avian predation in the Columbia River Estuary, entitled "*Caspian Tern Management to Reduce Predation on Juvenile Salmonids in the Columbia River Estuary*" (USFWS 2005, 2006) and "*Double-crested Cormorant Management to Reduce Predation on Juvenile Salmonids in the Columbia River Estuary*" (USACE 2015). These management plans aim to reduce the number of Caspian terns and double-crested cormorants nesting on East Sand Island to reduce predation rates and, ultimately, increase the survival of juvenile salmonids migrating through the estuary. Efforts to reduce colony sizes have been primarily through lethal (i.e., culling and egg oiling) strategies for double-crested cormorants and the non-lethal strategies to disperse Caspian terns to alternative colony sites outside the Columbia River Basin. Management plans were developed in response to Reasonable and Prudent Alternatives (RPA) specified in Biological Opinions on operation of the FCRPS issued by NOAA Fisheries (NOAA 2008, 2010, 2014a). RPAs 66 and 67 specify annual monitoring of juvenile salmonid predation impacts by Caspian terns and double-crested cormorants in the Columbia River Estuary. More specifically, management plans require that salmonid PIT tags be recovered on the East Sand Island tern and cormorant colonies after the breeding season to document annual trends in predation rates (USACE 2015).

To address the monitoring requirements of these management plans, two tasks were conducted as part of this study in 2017: (1) recovery of smolt PIT tags on the Caspian tern and double-crested cormorant colonies on East Sand Island and (2) use those data to model predation rates on ESA-listed salmonid populations. As part of Task 2, predation rates from 2017 were compared with predation rates from years past to evaluate the effectiveness of management actions to reduce predation rates through reductions in colony size. To ensure relative comparability of predation rate results collected in 2017 to years past, we used the tag recovery and analytical methods of Evans et al. (2012) and Hostetter et al. (2015), previously peer-reviewed methods that allow for direct comparisons of predation rates among predator species (terns, cormorants), salmonid ESU/DPS, and years.

METHODS

PIT Tag Recovery

We used the previously established methods of Evans et al. (2012, 2016a) to recover (detect) PIT tags on the East Sand Island Caspian tern and double-crested cormorant colonies in 2017. Below is a summary of those methods by colony site:

East Sand Island Caspian tern colony – A custom built eight-coil flat-plate PIT tag detection system attached to an all-terrain vehicle (ATV) was used to detect PIT tags *in situ* on the East Sand Island Caspian tern colony after nesting birds dispersed from the colony in September of 2017. PIT tags were detected by systematically scanning the entire area (referred to as a "pass") occupied by nesting terns during the breeding season (*Figure 1*). Additional passes were conducted until the number of newly identified, previously undetected tags were less than 5% of the total number found during all previous passes, which resulted in a total of six complete passes of the tern colony in 2017. Passes were conducted in varying directions, a technique that results in higher detection efficiency (Ryan et al. 2003), and at consistent speed and antenna height to optimize antenna performance (see Evans et al. 2016a for additional details). Hand-held PIT tag detection systems (*Biomark*, model HPR) were also used to detect PIT tags in areas inaccessible to the ATV (e.g., areas adjacent to dissuasion fencing and vegetated habitat; see *Figure 2*). PIT tag transceivers were optimized to detect ISO FDXB tags, the most common type of PIT tag implanted in juvenile salmonids from the Columbia River Basin in 2017 (PSFMC 2017).

In addition to electronic detection of PIT tags using the flat-plate and hand-held antenna systems, PIT tags were also physically removed from the Caspian tern colony using a tow behind sweeper magnet (*Bluestreak,* model Hog series) attached to the ATV (*Figure 1*). The physical removal of PIT tags reduces tag collision, a phenomenon that renders PIT tags in close proximity to each other undetectable using electronics. The physical removal of PIT tags, and subsequent hand scanning of each tag to acquire its unique code, increases tag detections at sites like the East Sand Island tern colony where tag densities are very high (Evans et al. 2016a). Both physical and electronic PIT tag recovery were conducted concurrently, when conditions permitted (i.e., use of magnet required dry substrate).

PIT tag codes stored locally on the flat-plate system's transceiver were uploaded to a central storage drive at the completion of each scanning session, along with metadata regarding the date and pass number. After each scanning day, tag data were uploaded to a cloud-based server for redundancy. Following validation and removal of duplicate records, newly detected tag codes, including codes from tags physically removed with the sweeper magnet, were uploaded to PTAGIS on 18 December 2017, using guidelines and protocols established by the PIT-tag Steering Committee (PSFMC 2017). Tag codes can be downloaded directly from PTAGIS as Raw Data Files, Raw Tagging Files, under the 2017 APD (Avian Predation Detection) Directory (PSMFC 2017).

<u>*East Sand Island double-crested cormorant colony*</u>: Hand-held PIT tag detection systems (*Biomark*, model HPR) were used to detect PIT tags *in situ* on the East Sand Island double-crested cormorant colony after nesting birds dispersed from the island following the breeding season in October. Analogous to scanning on the Caspian tern colony, PIT tags were recovered by systematically scanning the entire area occupied by nesting cormorants during 2017 with additional passes conducted until the number of newly identified previously undetected tags were less than 5% of the total number found during all previous passes, which resulted in a total of three passes of the cormorant colony in 2017. In addition to scanning areas occupied by double-crested cormorants, we independently scanned nesting areas exclusively used by Brandt's cormorants *P. penicillatus* during the breeding season, a non-managed predator species on East Sand Island. This was necessary because Brandt's cormorants nested adjacent to double-crested cormorants and efforts to delineate tags deposited by the two species were needed to minimize potential bias in predation rate estimates from double-crested cormorants (i.e., erroneously attributing tags consumed by Brandt's cormorants to those of double-crested cormorants; see Evans et al. 2016a for additional details).

Data from aerial and ground-surveys during the breeding season were used to distinguish where cormorants nested or attempted to nest on East Sand Island in 2017 (*Figure 2*). Results of these surveys indicated nesting attempts during the peak smolt outmigration were limited to just two discrete weeks; one in mid-May and one in mid-June (see *Results*). Following the peak smolt outmigration period in July, cormorants were able to successfully establish a small colony on the western tip of East Sand Island (*Figure 2*; see also Turecek et al. 2018). PIT tag codes stored locally on each transceiver were uploaded to a central storage drive at the completion of each scanning session, along with metadata regarding the scan date, species (double-crested, Brandt's), and pass number. After each scanning day, tag data were uploaded to a cloud-based server for redundancy. Following validation and removal of duplicate records, newly detected tag codes were uploaded to PTAGIS on 18 December 2017. Tag codes can be downloaded directly from PTAGIS as Raw Data Files, Raw Tagging Files, under the 2017 APD (Avian Predation Detection) Directory (PSMFC 2017).

Predation Rate Calculations

Following previously established methods (Hostetter et al. 2015), a Bayesian hierarchical model was used to estimate predation rates based on recoveries of smolt PIT tags on the East Sand Island Caspian tern and double-crested cormorant colonies in 2017. Predation rate estimates were derived using the proportion of juvenile salmonid PIT tags found on each bird colony from the available population of PIT-tagged fish (i.e., smolt availability), and then adjusting by the probability that a consumed PIT tag was subsequently deposited on that colony (i.e., deposition probability) and later detected by researchers following the nesting season (i.e., detection probability; *Figure 3*).

The predation rate model used in 2017 was the same model used to estimate predation rates on smolts by East Sand Island Caspian terns during 2000-2016, East Sand Island double-crested cormorants during 2000-2015, and the same model used in the Affected Environment Analysis of the *Double-crested Cormorant Management Plan in the Columbia River Estuary* (USACE 2015). The one exception to the use of standard method to calculate avian predation rates was for the East Sand Island double-crested cormorant colony in 2016, where a different analytical approach was used to estimate hypothetical rates of cormorant predation (see Skalski et al. 2017). To maintain comparability among predation rate estimates across nesting seasons, we do not present or otherwise compare East Sand Island cormorant results from 2016 to those of other years.

Smolt Availability – Smolt availability to birds nesting in the Columbia River Estuary was based on detections of live PIT-tagged fish last interrogated passing Bonneville Dam (Rkm 234 on the lower Columbia River) and Sullivan Dam (Rkm 203 on the lower Willamette River), referred to as "in-river fish". Bonneville and Sullivan dams are considered the upper most reaches of the Columbia River Estuary as defined by the USACE for the purposes of evaluating avian predation rates (USACE 2015; *Map 1*). In addition to in-river migrants, PIT-tagged smolts that were loaded into barges at dams on the lower Snake River and transported and released below Bonneville Dam near Skamania Landing (Rkm 225; *Map 1*) were also included in predation rate analyses, referred to as "transported fish". Availability of transported fish was based on fish interrogated (detected alive) at the Lower Granite Dam (Rkm 695), Little Goose Dam (Rkm 635), or Lower Monumental Dam (Rkm 589) Juvenile Bypass Systems (JBS) and subsequently loaded into a fish barge. Fish were classified as being collected for transportation based on a unique combination of the interrogation site antennas (e.g., detected entering a raceway) and date at each JBS. Downstream interrogation histories, JBS facility collection reports, and other sources (e.g., NOAA, USACE, and FPC Technical Reports) were used to validate and otherwise proof classifications to ensure accurate assignment of each fish's outmigration history (in-river, transported). Due to small numbers of PIT-tagged fish (generally < 500), smolts collected at JBS facilities and transported using trucks during the study period were not included in study results (see also Evans et al. 2016a).

For both in-river and transported groups of fish, smolt availability was defined as those fish last detected or released (for transported fish) between 1 March and 31 August each year, which reflects the annual periods of overlap in active PIT-tagged smolt out-migration and Caspian tern and double-crested cormorant nesting activity on East Sand Island (Evans et al. 2012; Adkins et al. 2014). PIT-tagged fish were then grouped by salmonid ESU/DPS, representing a unique combination of species (steelhead trout, Chinook salmon, or sockeye salmon), run-type (spring, summer, fall), and river-of-origin

(Columbia, Snake, or Willamette). The designation of ESU/DPS followed that of NOAA (2014b) and was largely based on the tagging and release location of each PIT-tagged fish relative to the geographic boundary of each ESU/DPS. Fish within each ESU/DPS were further grouped by rear-type (hatchery, wild), outmigration history (in-river, transport for Snake River ESUs/DPSs), and week.

Not all ESA-listed salmonid ESUs/DPSs in the Columbia River Basin were included in predation rate analyses, as populations that originate wholly or partially below Bonneville and Sullivan dams were excluded. These populations were excluded because spatially- and temporally-explicit detections of live fish during outmigration were not available for these ESUs/DPSs and because sufficient sample sizes of tagged fish from these ESUs/DPSs were generally lacking in 2017 (see also Lyons et al. 2014b). These ESUs/DPSs were: (1) Lower Columbia River steelhead, (2) Lower Columbia River Chinook, (3) Lower Columbia River coho, and (4) Columbia River chum *O. keta*. In addition to ESA-listed salmonids, non-listed juvenile salmonids and other fishes (e.g., Pacific lamprey *Lampetra tridentate* and Eulachon *Thaleichthys pacificus*) were also available as prey to Caspian terns and double-crested cormorants nesting on East Sand Island; fish that are of cultural, economic, and/or conservation concern (Lyons et al. 2014b). Including these other fishes was beyond the scope of this study, but efforts to reduce the number of terns and cormorants nesting on East Sand Island will presumably also benefit these other fishes (USACE 2015a).

Deposition and Detection Probabilities – Not all smolt PIT tags that are ingested by colonial waterbirds are subsequently deposited on their nesting colony (Hostetter et al. 2015). A portion of PIT tags implanted in depredated fish are damaged and rendered unreadable following digestion, or are regurgitated off-colony at loafing, staging, or other off-colony areas used by birds during the nesting season. Deposition probability (i.e., probability that a tag consumed by a nesting bird will be deposited on its breeding colony) was previously estimated by feeding PIT-tagged fish to Caspian terns and double-crested cormorants and subsequently recovering those tags on East Sand Island (see Hostetter et al. 2015 for details). The distribution of the median deposition probability derived from these studies was 0.71 (95% CRI = 0.51–0.89) for Caspian terns and 0.51 (95% CRI = 0.34–0.70) for double-crested cormorants (see also *Results*). Deposition probabilities measured during these previous experiments were used to infer deposition probabilities for data collected in 2017. Use of deposition probabilities from data collected in years past was deemed appropriate because results of deposition experiments indicated that deposition probabilities did not vary significantly within or between years for each predator species evaluated (see Hostetter et al. 2015 for additional details).

Not all PIT tags deposited by birds on their nesting colony are subsequently found by researchers after the nesting season (Evans et al. 2012; Sebring et al. 2013; Hostetter et al. 2015). For example, tags can be blown off the colony during wind storms, washed away during flooding events, or otherwise damaged or lost during the nesting season. Furthermore, the detection methods used to find PIT tags on bird colonies are not 100% efficient, with some proportion of detectable tags missed by researchers during the scanning process. Unlike deposition probabilities, detection probabilities (i.e., probability that a tag deposited by a bird on the colony is detected by researchers after the nesting season) often vary significantly within and between breeding season, variation that necessitates a direct measure of detection probabilities in each study year, for each colony (Hostetter et al. 2015). To address this in 2017, PIT tags with known tag codes were intentionally sown on the East Sand Island tern and cormorant colonies (hereafter referred to as "control tags") prior to, during (terns only), and following the nesting season to quantity PIT tag detection probability. Control tags were the same size and type as those used to mark juvenile salmonids from the Columbia River Basin (12 mm, ISO FDXB). During each discrete sowing period, control tags were haphazardly sown throughout the area occupied by nesting birds during the breeding season (see *Figure 2*). Detections (i.e., recoveries) of control tags during scanning efforts after the nesting season were then used to model the probability of detecting tags that are deposited at different times during the nesting season via logistic regression (see *Predation Rates* below for details). Equal number of control tags were sown during each discrete period and sample sizes (n = 300 on the tern colony and n = 400 on the cormorant colony) were selected by considering historic releases (see Evans et al. 2016a). This allows direct comparisons of independent detection probabilities, with similar precision between years.

Predation Rates – Following the methodology of Hostetter et al. (2015), predation rates were modeled independently for each salmonid ESU/DPS, bird colony (Caspian tern, double-crested cormorant) and year. The probability of recovering a PIT tag from a smolt on each colony was modelled as the product of the three probabilities described above, the probability that (1) the fish was consumed (θ), (2) the PIT tag was deposited on-colony (ϕ), and (3) the PIT tag was detected on-colony after the breeding season (ψ_i; see also *Figure 3*):

$$k_i \sim Binomial(n_i, \theta_i * \phi * \psi_i)$$

where k_i is the number of smolt PIT tags recovered from the number available (n_i) in week *i*. The detection probability (ψ_i) and predation probability (θ_i) were each modeled as a function of time. The probability, ψ_i, that a tag, consumed in week *i* and then deposited on the colony and detected, is assumed to be a logistic function of week. That is:

$$logit(\psi_i) = \beta_0 + \beta_1 * i$$

where β_0 and β_1 are both derived from non-informative priors (normal [0, 1000]).

Predation rates nearer together in time are more similar than those further apart in time (Evans et al. 2016a). To reflect this, variation in weekly predation probabilities, θ_i, was modeled as a random walk process with mean μ_θ and variance σ_θ^2, where:

$$logit(\theta_i) = \mu_\theta + \sum_{w \le i} \varepsilon_w$$

and $\varepsilon_w \sim normal(0, \sigma_\theta^2) \; \forall \, w$. We placed non-informative priors on these two hyperparameters: logit^{-1} (μ_θ) $\sim uniform(0,1)$ and $\sigma_\theta^2 \sim uniform(0,20)$. This allows each week (*i*) to have a unique predation probability (θ_i), while still sharing information among weeks improving precision.

Informative Beta (α, β) priors were used to model deposition probability(ϕ). The shape parameters are dependent on the predator species (cormorants, terns) and are assumed to be mutually independent from colony to colony. For terns, we assumed α = 16.20 and β = 6.55 and for cormorants, we assumed α = 15.98 and β = 15.29 (see Hostetter et al. 2015 for details).

Weekly predation estimates were defined as the estimated number of PIT-tagged smolts consumed divided by the total number last detected passing Bonneville Dam, Sullivan Dam, or released from barges in the tailrace of Bonneville Dam each week. Annual predation rates were derived as the sum of the estimated number of PIT-tagged smolts consumed each week divided by the total number of PIT-tagged smolts last detected at Bonneville Dam, Sullivan Dam, or released from barges:

$$\sum_{i \in breeding\ season} (\theta_i * n_i) \Big/ \sum_{i \in breeding\ season} (n_i)$$

Summation of weekly consumption estimates is necessary to accurately reflect weekly variation and autocorrelation of predation rates and thus to create unbiased annual rates with accurate assessments of precision (Butler and Stephens 1993; Hamilton 1994).

Rear-type and outmigration history comparisons: We calculated, compared, and contrasted (based 95% confidence intervals) predation rates for different ESUs/DPSs by rear-type (hatchery, wild) and migration history (in-river, transported). Results were used to evaluate trends in ESU/DPS-specific predation rates in the context of factors known to influence variation in predation rates (Evans et al. 2016a). Inclusion of these subsets was achieved through a re-parameterization such that:

$$k_{iv} \sim Binomial(n_{iv}, \theta_{iv} * \phi * \psi_i)$$

where k_{iv} is the number of smolt PIT tags in category *v* recovered from the number available (n_{iv}) in week *i*. This approach allows a common estimate of deposition and detection across categories which facilitates increased precision (i.e., smaller bounds around the estimate). Annual and weekly predation probabilities for each category can then be calculated using the methods described above.

Building on this approach, analyses across the study period (weekly, annual) to make comparisons between categories were developed. We let ρ represent the average proportional difference in the odds of predation over the study period, with a value less than or greater than 1.0 indicating a preference for a group or category of fish and a value of 1.0 showing no preference. We tested for statistically significant differences using logistic regression. The weekly estimates of predation were treated as mutually independent, allowing the focus to be limited to the proportion of recovered tags from each colony (corrected for detection and deposition probabilities) from those available to each colony. Therefore:

$$k_{iv_0} \sim Binomial(n_{iv_0}, \theta_{iv} * \phi * \psi_i)$$

and

$$k_{iv_1} \sim Binomial\left(n_{iv_1}, \rho * \theta_{iv} * \phi * \psi_i\right)$$

and we tested the hypothesis H_0: ρ = 1.0. Confidence intervals that overlapped 1 were not statistically significant. This test was applied to all appropriate ESUs/DPSs for each comparison.

Predation impacts prior to and following management actions: If given enough time and a significant decrease in the number of nesting birds, it is expected that the management of Caspian terns and double-crested cormorants on East Sand Island will have a measurable effect on the level of predation. For the Caspian tern colony on East Sand Island, comparisons of predation rates by management period were defined as those during 2000-2010 (pre-management) and those during 2011-2015 (management). The management time period was considered to have started in 2011 (as opposed to 2008 when efforts to reduce nesting habitat were first initiated) because this was the first year that reductions in nesting habitat at East Sand Island resulted in a significant reduction in the number of terns below the pre-management average (Evans et al. 2016a; BRNW 2017).

For the double-crested cormorant colony on East Sand Island, management time periods were defined as 2003-2015 (pre-management) and 2016-2017 (management). Although cormorants have nested on East Sand Island since the late 1980's, the steady increase in the number of nesting cormorants and predation rates was first considered to be a significant threat to salmonid recovery by the federal government in 2003 (referred to as the "current period"; NOAA 2014; USACE 2015). The first year of management actions on the East Sand Island cormorant colony were initiated in 2015. Management activities in 2015, however, were limited in scope and started after most PIT-tagged fish passed Bonneville and Sullivan's dams that year. For instance, only 158 adult cormorants (< 1% of the estimated 12,150 nesting pairs on East Sand Island in 2015) were culled between 22 May and 31 August 2015 (USACE 2015), a number too small to influence predation rates in a meaningful way that year (Evans et al. 2016a). As such, impacts from the 2015 East Sand Island cormorant colony on PIT-tagged juvenile salmonids should be considered more comparable to the pre-management impacts, than impacts during the management period.

To monitor the effectiveness of avian predation management plans to reduce predation rates by reducing colony size, we compared estimates of ESU/DPS-specific predation rates and peak colony sizes (number of nesting pairs) across study years, to the extent possible (e.g., where sufficient data existed for the analysis). Per capita (per nesting pair) predation rates were calculated by dividing the annual ESU/DPS-specific predation rate by the peak measure of colony size each year:

$$Annual\ Per\ Capita\ Predation\ Rate_y = {\sum_w (\theta_{wy} * n_{wy}) / \sum_w (n_{wy})} \Big/ {C_y}$$

where C_y is the peak colony size in year, *y.* The relationship between colony size and predation rates across years was further evaluated by generating a posterior distribution of least squares regression lines, calculated from random samples of per capita predation rates taken from the posterior distributions associated with the above defined estimates. The strength and direction of the relationship can be inferred from the median value of the resulting posterior distribution associated with the slope of the resulting posterior distribution with the 95% CRI defined as the 2.5th and 97.5th quantiles. Statistical credibility was identified by the credibility interval of the slope parameter not overlapping with zero.

Modelling software and assumptions: All predation rate models were implemented using the software JAGS (Plummer 2003) accessed through R version 3.1.3 (R Core Team 2015) using the R2jags (Su and Yajima 2012) and dclone (Solymos 2010) R packages. Three parallel chains were run for 80,000 iterations each, after an initial 10,000 iteration burn-in, to diagnose and confirm convergence. Chain convergence was tested using the Gelman-Rubin statistic ($\hat{R}$; Gelman et al. 2004). A single "long-run" of 150,000 Markov Chain Monte Carlo (MCMC) iterations were run to produce the final posterior distribution from which estimates were derived (Raferty 1992). Chains were thinned by 20 to reduce autocorrelation inherent to successive MCMC samples. Results were reported as posterior medians along with the 2.5 and 97.5 percentiles, which are referred to as 95% credible intervals. Annual predation rates were calculated for salmonid ESUs/DPSs where ≥ 500 PIT-tagged individuals were available to birds to avoid imprecise results that may occur from small sample sizes of available PIT-tagged smolts (Evans et al. 2012). In addition, predation rates had to be at 1% per group for comparisons of impacts based rear-type and outmigration history; rates potentially large enough to be biologically relevant to salmon survival.

A detailed list of predation rate model assumptions (A) and procedures used to evaluate the validity of those assumptions is provided in Hostetter et al. (2015) and Evans et al. (2016a). Briefly, the predation model assumed that (A1) PIT tag interrogation data obtained at dams from PTAGIS were accurate, (A2) PIT-tagged fish passing dams were available to birds nesting downstream, (A3) predation, detection, and deposition were independent variables, and in the case of detection and deposition, were accurately measured in field studies, (A4) PIT-tagged fish were consumed in a relatively short (one week) period following interrogation at upstream dams, and (A5) PIT-tagged fish were representative of non-tagged fish belonging to the same ESU/DPS and passing the same detection (dam) or release (barge) sites. All assumptions were validated to the extent possible, or possible violation of the assumption (e.g., predation within a week of detection/release) had little influence on predation rates (see Hostetter et al. 2015 and Evans et al. 2016a for additional details).

RESULTS AND CONCLUSIONS

PIT Tag Recovery

East Sand Island Caspian tern colony – Following the nesting season, 8,407 PIT tags from 2017 migration year smolts (Chinook salmon, coho salmon, sockeye salmon, and steelhead combined) were recovered on the East Sand Island Caspian tern colony (*Table 1*). The number of smolt tags recovered from the tern colony in 2017 was the lowest recorded since the colony was first scanned in 2000. The number of tags recovered in 2017 was slightly lower than that in 2016 (9,930 tagged smolts) and substantially lower than in other years (annual range = 13,059 to 44,947 tagged smolts).

Recoveries of control PIT tags sown on the East Sand Island tern colony (n = 300) indicated that estimated detection efficiency averaged 73% (seasonal range = 40–88%) during the 2017 nesting season (*Table 2*). Estimated average detection efficiency in 2017 was lower than that observed in 2016 (average = 82%) and 2015 (average = 87%) but similar to efficiency rates estimated from 2011 to 2014 (range of averages = 64–77%; Evans et al. 2016a). Increases in detection efficiency on the Caspian tern colony in 2015 and 2016 were likely due to the physical removal PIT tags via magnet (see *Methods*), a technique that was first initiated as part of the standard scanning protocol on East Sand Island in 2015. Since being implemented, the magnet has removed over 25,000 functional PIT tags each year, tags that would have otherwise contributed to collision effects and reduced detection efficiency (Evans et al. 2016a). Given the magnet was again used in 2017, it was thus surprising that detection efficiency was not similar to that observed in 2015 and 2016. One possible explanation for the lower than anticipated detection efficiency in 2017 was a reduction in colony surface preparations on East Sand Island. In most years since 2000, the entire tern colony on East Sand Island was tilled to a depth of 6 inches or more prior to the arrival of terns. Tilling efforts may have destroyed previously deposited PIT tags or moved them deeper into the soil where they were not as easily detected with surface antennas, thus further reducing tag collision effects in years past. In 2017, only the vegetated areas of the prepared 1.0 acre colony area were tilled, leaving about 2/3 of the colony surface hard packed and undisturbed.

Based on previous studies that empirically measured deposition rates for Caspian terns nesting on East Sand Island, deposition rates were estimated to be 71% (95% CRI = 51–89%; *Table 2* and Hostetter et al. 2015).

East Sand Island double-crested cormorant colony – Following the nesting season, 1,340 PIT tags from 2017 migration year smolts (Chinook salmon, coho salmon, sockeye salmon, and steelhead combined) were recovered on the East Sand Island double-crested cormorant colony (*Table 1*). The number of smolt PIT tags recovered on the double-crested cormorant colony in 2017 was substantially lower than that recovered in years past (annual range = 9,047 to 31,984 tagged smolts), years when cormorants nested on East Sand Island throughout the entire smolt outmigration period. As noted in the *Methods*, nesting cormorants were not present on East Sand Island during the majority of the 2017 smolt outmigration period (see *Predation Rate Results* below) and as a result, a record low number of smolt PIT tags were deposited by double-crested cormorants on East Sand Island in 2017.

A total of just 42 PIT tags from 2017 migration year smolts (Chinook salmon, coho salmon, sockeye salmon, and steelhead combined) were recovered on the East Sand Island Brandt's cormorant colony following the nesting season in 2017 (*Table 1*). Analogous to double-crested cormorants, very few Brandt's cormorants attempted to nest on East Sand Island during the peak smolt outmigration period from April to June, 2017. Tags recovered from the Brandt's cormorant colony were not used in predation rate analyses, but tag codes were reported to PTAGIS as avian mortalities (see *Methods*).

Control PIT tags sown to measure detection efficiency on the double-crested cormorant colony (n = 400) indicated that estimated detection efficiency averaged 71% (range = 60–78%) during the nesting season in 2017 (*Table 2*). Detection efficiency estimates in 2017 were higher than those reported for 2016 (average = 60%; Skalski et al. 2017) but similar to estimates for 2011 to 2015 (range = 70–81%; Evans et al. 2016a).

Based on previous studies that empirically measured deposition rates for double-crested cormorants nesting on East Sand Island, deposition rates were estimated to be 51% (95% CRI = 34–70%; *Table 2* and Hostetter et al. 2015).

Predation Rates

East Sand Island Caspian terns – Predation rate estimates varied significantly by salmonid ESU/DPS in 2017 (*Table 3).* Results indicated that steelhead DPSs were the most susceptible to predation by Caspian terns nesting on East Sand Island, with predation rates ranging from 5.3% (95% CRI = 3.9–7.7%) on Snake River steelhead to 8.4% (95% CRI = 5.6–13.10%) on Upper Columbia River steelhead (*Table 3*). By comparison, predation rates on salmon ESUs were significantly lower than those on steelhead DPSs, ranging from just 0.2% (95% CRI = 0.1–0.5%) on Snake River Fall Chinook salmon to 1.4% (95% CRI = 0.9–2.3%) on Upper Columbia River spring Chinook salmon (*Table 3*). Differences in steelhead susceptibility relative to salmon susceptibility observed in 2017 were very similar to those observed in years past, with Caspian tern predation rates on steelhead populations often 5 to 10 times greater than those on salmon populations (*Appendix A, Table A1*). Higher avian predation impacts by Caspian terns on juvenile steelhead compared with salmon is well documented in the published literature (Collis et al. 2001; Ryan et al. 2003; Evans et al. 2012; Evans et al. 2016b). Differences in the relative size (fork length) and behavior of steelhead compared with salmon species are two possible explanations. For instance, Beeman and Maule (2006) observed that steelhead smolts were more surface-oriented compared with salmon smolts and surface orientation is believed to render fish more vulnerable to predation by Caspian terns, a plunge diving species that forages in the top meter of the water column (Cuthbert and Wires 1999). Hostetter et al. (2012) and Evans et al. (2016a) noted size-selectivity amongst avian predators, with larger fish typically predated at higher rates than smaller fish (see *Impacts by rear-type and outmigration history* below for additional discussion).

For most salmonid ESUs/DPSs evaluated, there was complete or near complete overlap between the availability of tagged fish last detected passing Bonneville Dam and the presence of Caspian terns on East Sand Island (*Figure 4*), indicating that most tagged fish passing through the estuary were susceptible to tern predation in 2017. An investigation of weekly predation rates by East Sand Island Caspian terns indicates that estimated predation rates were generally lower when the largest number or greater density of PIT-tagged smolts were available as prey in the estuary (*Figure 5*). For instance, estimated impacts on steelhead DPSs were the lowest during the peak of the run in May and higher before (April) and after (June) the peak. Hostetter et al. (2012) theorized that the inverse relationship between prey density and Caspian tern predation rates was due to prey swamping, with the probability of an individual fish being consumed decreasing as the number of available prey increases (see also Ims 1990). A multiyear analysis of weekly East Sand Island Caspian tern predation rates and smolt abundance estimates in the estuary conducted by Roby et al. (2017) indicated that the trend of decreasing estimated tern predation rates at higher level of smolt availability was statistically significant across weeks and years (2006-2016), with the odds of predation declining by a factor 0.82 (95% CRI = 0.75-0.89) for each 10% increase in the relative availability of tagged smolts.

Impacts by rear-type and outmigration history: There was no evidence that hatchery fish were more susceptible to predation by East Sand Island Caspian terns compared with their wild counterparts in 2017 (*Table 4*). Comparisons in 2017, however, were constrained by small sample sizes. A more robust investigation of weekly and annually trends over the course of the last decade (2006-2016) indicated that hatchery Snake River spring/summer Chinook and hatchery Upper Columbia River spring Chinook were consistently more susceptible to East Sand Island tern predation than their wild counterparts (*Table 4*; see also Roby et al. 2017). There was no long-term trend, however, in the relative susceptibility of hatchery and wild Snake and Upper Columbia River steelhead to East Sand Island Caspian tern predation, with both rear-types equally susceptible to predation (*Table 4;* see also Roby et al. 2017). Data from other studies indicates that both behavior and physical traits associated with hatchery-raised juvenile salmonids may enhance susceptibility to predation (Olla and Davis 1989, Fritts et al. 2007, Hostetter et al. 2012). Evans et al. (2016a) attributed difference in the vulnerability of hatchery spring/summer Chinook salmon to Caspian tern predation to differences in the size (mm; fork length) of hatchery (mean = 144 mm) and wild (mean = 111 mm) Chinook salmon smolts last detected passing Bonneville Dam during 2006-2015. An analysis of length data (based on lengths collected within the same month fish were interrogated passing Bonneville Dam) indicated that the odds of Caspian tern predation on spring/summer Chinook salmon increased by 12% (95% CRI = 11.9–12.6%) for every 10-mm increase in fork-length (Evans et al. 2016a). Hostetter et al. (2012) also found evidence of size-selectivity in Caspian terns nesting at Crescent Island in McNary Reservoir (Columbia River), with larger PIT-tagged fish more likely to be preyed upon than smaller PIT-tagged fish up to about 175 mm, at which point fish were equally susceptible to tern predation up to about 225 mm. Tern predation rates on fish > 225 mm then rapidly decreased as fish reached or exceeded the maximum prey size for Caspian terns of about 275 mm (Cuthbert and Wires 1999; Lyons 2010). The majority (> 80%) of hatchery and wild PIT-tagged steelhead last detected passing Bonneville Dam were between 175-225 mm, fish with similar length-dependent selectivity profiles (Roby et al. 2017).

There was no evidence that Caspian terns disproportionately consumed transported Snake River steelhead relative to in-river migrants from the Snake River in 2017 (*Table 4*). Insufficient sample sizes prevented comparisons amongst other Snake River ESUs/DPSs in 2017. An investigation of the transported vs. in-river migrant data over the course of the last decade indicated that odds-ratios were close to 1.0 (no preference) for most ESUs/DPSs in most weeks and years (see Roby et al. 2017 for weekly and annual comparisons during 2006-2016). Overall (all years combined) there was some evidence that in-river steelhead and in-river spring/summer Chinook salmon were more susceptible to East Sand Island Caspian tern predation than transported migrants (*Table 4*), but again differences were not consistently observed across all weeks and years and the magnitude of difference was generally small (as determined by the proximity of the estimate to 1.0). Roby et al. (2017) theorized that differences in the relative susceptibility of in-river versus transported fish were due to differences in run-timing (arrival times in estuary) and how run-timing coincided with the nesting chronology of Caspian terns on East Sand Island. Regardless of the mechanism, differences were generally not great enough to be considered biologically significant (Roby et al. 2017).

Impacts prior to and following management actions: Predation rate estimates in 2017 were the lowest ever recorded for Caspian terns nesting on East Sand Island (*Appendix A, Table A1 and A3; see also* Evans et al. 2016a). An investigation of predation impacts prior to and following management actions indicates that predation rates were, on average, significantly lower following management actions during 2011-2017, compared with predation rates prior to management during 2000-2010 (*Table 5*). For instance, average annual predation rates on Snake River steelhead during 2000-2010 were estimated to be 22.2% (95% CRI = 20.3–24.8%), compared with 9.5% (95% CRI = 8.4–10.3%) following management actions that reduced the number of terns on East Sand Island. Insufficient samples sizes prohibited comparisons across all ESUs/DPSs in all study years, but the reductions in predation rates following management actions observed in Snake River steelhead were observed in all other ESA-listed ESUs/DPSs evaluated (*Table 5*), to varying degrees.

Addressing high rates of steelhead predation by Caspian terns was the primary impetus of the Caspian Tern Management Plan (USFWS 2008). Average estimated predation rates following management on steelhead DPSs were roughly one-third to a half (depending on the DPS) lower than those observed during the pre-management period (*Table 5*). In 2017, estimated steelhead predation rates were a half to one-fourth (depending on the DPS) of those observed during the management period (*Table 3*). In all three steelhead DPSs evaluated, reductions in Caspian tern predation rates were in proportion to reductions in colony size (*Figure 6*). Comparisons suggest a linear relationship between annual predation rates and colony sizes ($p < 0.01$ in all steelhead DPS evaluated; *Figure 6*). Results indicate that Caspian tern management initiatives aimed at reducing the number of Caspian terns nesting on East Sand Island are resulting in reduced annual predation rates on steelhead DPSs. This was particularly evident in 2017, when the lowest number of Caspian terns ever recorded on East Sand Island (3,500 nesting pairs) coincided with the lowest estimated predation rates (*Figure 6*). Prior to management actions that reduced the size of the colony, the East Sand Island Caspian tern colony averaged 9,221 nesting pairs (range = 8,283–10,668 nesting pairs during 2000-2010; BRNW 2017).

The number of Caspian terns on East Sand Island in 2017 (3,500 nesting pairs) nearly reached the 3,125 nesting pair target goal identified in the Caspian Tern Management Plan (USFWS 2006). Based on an analysis of ESU/DPS-specific per capita (per nesting pair) predation rate estimates (*Table 6*), an East Sand Island tern colony of 3,125 nesting pairs would, on average, consume an estimated 6.9% (95% CRI =5.9–10.3%), 5.6% (95% CRI = 4.7–8.1%), and 4.7% (95% CRI = 3.7–7.2%) of Snake River, Upper Columbia River, and Middle Columbia River steelhead, respectively. If achieved, rates would represent a two-thirds reduction in steelhead predation rates relative to average pre-management predation rates; another stated goal of the Caspian Tern Management Plan (USFWS 2006). It is important to note that predation rate results presented herein are specific to Caspian terns that successfully nested on East Sand Island, but upwards of 1,000 pairs of Caspian terns attempted but failed to nest on Rice Island (Rkm 34; *Map 1*) in the upper Columbia River estuary from April through June 2017 (USACE, unpublished data). The impact of Caspian terns that attempted but failed to nest on Rice Island on smolt survival in

2017, however, is currently unknown. Roby et al. (2002) reported that juvenile salmonids were more prevalent in the diet of Caspian terns nesting on Rice Island compared with terns nesting on East Sand Island in years past, with salmonids comprising 77% and 90% of the diet of terns on Rice Island in 1999 and 2000 compared with 46% and 47% juvenile salmonids in the diet of terns on East Sand Island in 1999 and 2000. It is unknown if similar differences in smolt susceptibility to Rice Island and East Sand Island tern predation existed in 2017. Regardless, because Caspian tern were observed on both East Sand Island and Rice Island, an investigation of cumulative predation rates would be necessary to characterize the total or net impact of all terns on ESA-listed smolts in the estuary in 2017.

East Sand Island double-crested cormorants – Prior to 2016, the vast majority (> 95%) of double-crested cormorants present in the Columbia River Estuary nested on East Sand Island during the smolt outmigration period (Lyons et al. 2014a; Evans et al. 2016a). In 2017, however, cormorants did not establish a nesting colony on East Sand Island during the peak smolt outmigration period of April to June (*Figure 4*). A similar event occurred in 2016, where cormorants completely dispersed from East Sand Island from 17 May to 27 June before returning to re-nest in July (Anchor 2017). Rather than completely dispersing to colony sites outside of the Columbia River Estuary, large numbers of cormorants (at least 7,000 adults; Turecek et al. 2018) remained in the estuary and continued to forage on juvenile salmonids to an unknown degree. As such, estimates of predation rates based on the number of PIT-tags deposited by cormorants on East Sand Island in 2017 are minimum estimates of the number of fish consumed and are thus not representative of smolt losses by all cormorants present in the Columbia River Estuary. Relative comparisons of predation rates by cormorants that attempted to nest on East Sand Island in 2017 compared to those that successfully nested on East Sand Island in years past (when cormorant remained on East Sand Island throughout the smolt outmigration period) are also biased low to an unknown degree. For these reasons, we avoid direct comparisons of predation rates by East Sand Island cormorants in 2017 to those from previous years.

Predation rates by double-crested cormorants that briefly attempted to nest on East Sand Island during the smolt outmigration period in 2017 ranged from 0.1% (95% CRI = 0–4.2%) of Snake River Fall Chinook to 1.4% (95% CRI = 0.8–2.7%) of Upper Columbia River steelhead (*Table 4*). Predation rate estimates were similar between steelhead and salmon ESUs/DPSs in 2017. An analysis of historic data indicates that cormorant predation rates were often, but not always, higher on steelhead DPSs compared with salmon ESUs (*Appendix A*, *Table A2*). Significant annual variation in ESU/DPS-specific predation rates by cormorants on juvenile salmonid populations were also evident in years past, with differences in predation rates often greater between years within the same ESU/DPS than differences between ESUs/DPSs in the same year. For instance, predation rates by cormorants on Snake River spring/summer Chinook ranged from just 1.7% (95% CRI =1.1–2.7%) in 2007 to 14.5% (10.5–22.4%) in 2015 (*Appendix A, Table A2*).

An investigation of weekly ESU/DPS-specific predation rates indicated that predation rates were at or near zero (0) in most weeks during 2017 (*Figure 7*). The one exception were predation rate estimates in mid-May, when rates greater than 1% were observed in some ESUs/DPSs (e.g., Snake River steelhead and sockeye; *Figure 7*). These slightly elevated estimated rates of predation coincided with the week when double-crested cormorants were counted on East Sand Island during the peak smolt outmigration period in May (*Figure 4*). Using a more robust dataset from East Sand Island in years past, Roby et al. (2015) and Evans et al. (2016a) observed that predation rates by East Sand Island double-crested cormorants increased in concert with the number of available PIT-tagged smolts in the estuary, with the highest rates observed during the peak outmigration period for each ESU/DPS evaluated. Results indicated that as more fish became available, double-crested cormorants consumed a larger proportion;

a finding that suggests that larger numbers of smolts were not able to swamp double-crested cormorants to avoid predation (Ims 1990; Hostetter et al. 2012). The trend observed in cormorants was the opposite of that observed in East Sand Island Caspian terns, where estimated predation rates decreased as more PIT-tagged fish became available (*Figure 5*). Unlike Caspian terns, double-crested cormorants are pursuit divers that can consume multiple fish in a single foraging bout (Hatch and Weseloh 1999) and as such, highly concentrated prey may be especially vulnerable to predation by cormorants in the Columbia River Estuary (Lyons 2010; Evans et al. 2016a).

Impacts by rear-type and outmigration history: Insufficient sample sizes prevented a meaningful comparison of predation impacts based on a fish's rear-type (hatchery, wild) and outmigration history (in-river, transport) to East Sand Island double-crested cormorants in 2017. A summary of cormorant predation rate estimates by rear-type and outmigration history from data collected during 2006-2015 are provided in *Table 4* and Evans et al. (2016a). Results indicated that there were no consistent trends in the relative susceptibility of fish by rear-type to East Sand Island double-crested cormorant predation in years past. There was limited evidence that wild Snake River steelhead were more susceptible to cormorant predation than their hatchery counterparts, but differences were not consistent across weeks and years (see Evans et al. 2016a). Collectively, results indicated that hatchery and wild smolts last detected passing Bonneville Dam had no appreciable difference in susceptibility to double-crested cormorants nesting on East Sand Island. Other studies have also observed small and inconsistent differences in predation rates between hatchery and wild juvenile salmonids to cormorant predation in the Columbia River Estuary (Collis et al. 2001; Ryan et al. 2003). A more detailed discussion of mechanisms that potentially explain differences (or the lack thereof) in the relative susceptibility of smolts based on their rear-type to cormorant predation is provided in Evans et al. (2016a).

Like comparisons by rear-type, insufficient samples prevented a meaningful comparison of cormorant impacts based on fish's outmigration history (in-river, transport) in 2017. From the limited data available, predation rates on transported groups of fish were similar to those of in-river fish. A multiple year summary of comparisons also showed no consistent trend between the relative susceptibility of in-river versus transported fish to cormorant predation in the estuary, with impacts varying by week, year, and salmonid ESU/DPS (*Table 4;* see Evans et al. 2016a for weekly and year-specific results). There was some evidence that transported Snake River fall Chinook salmon and transported Snake River sockeye salmon were more likely to be consumed by cormorants than in-river migrants and some evidence that in-river Snake River spring/summer Chinook salmon and in-river Snake River steelhead were more likely to be predated by cormorants compared with transported fish (*Table 4*). Sample sizes of available fish for comparisons in years past were large (generally > 20,000 PIT-tagged fish per year) and data were available in most weeks and years throughout the ten-year study period (2006-2015). Given the robust datasets used for relative comparisons in years past, tests were readily able detect significant differences, even if the magnitude of difference in predation rates between in-river and transported fish were small (e.g., < 2% difference in predation rates between in-river and transported smolts; Evans et al. 2016a). As such, although results were statistically significant in some ESUs/DPSs, the biological significance of these differences should be considered when interpreting results.

Impacts prior to and following management actions: Because double-crested cormorants dispersed from East Sand Island during the peak smolt outmigration period in both 2016 and 2017 – years of management actions – a relative comparison of smolt losses by management period could not be conducted as part of this study. Based on data collected prior to 2016 (when normal cormorant nesting behavior on East Sand Island occurred), average annual steelhead predation rates were estimated at

5.1% (95% CRI = 4.1–6.1%), 8.3% (95% CRI = 6.8–10.1%), and 9.3% (95% CRI = 8.0–11.0%) of Upper Columbia River, Middle Columbia River, and Snake River steelhead, respectively (*Table 7*). Average annual predation rate estimates were also appreciable on some salmon ESUs, particularly Snake River spring/summer Chinook, with an estimated 5.2% (95% CRI = 4.4–6.1%) of available fish consumed by East Sand Island cormorants during 2003-2015. The average size of the East Sand Island double-crested cormorant colony during 2003-2015 was estimated to be 12,744 nesting pairs (range = 10,646 –14,916 nesting pairs; BRNW 2017). Per capita (per nesting pair) predation rate estimates indicate that an East Sand Island double-crested cormorant colony of 5,600 nesting pairs – a target goal of Cormorant Management Plan (USACE 2015) – may result in average annual steelhead predation rates of 2.9% (95% CRI = 2.6–3.4%), 3.2% (95% CRI = 2.8–4.3%), and 3.4% (95% CRI = 2.9–4.0%) of Upper Columbia, Middle Columbia, and Snake River steelhead, respectively. If achieved, rates would represent a half to two-thirds reduction in steelhead predation rates relative to average pre-management predation rates during 2003-1015. Given how highly variable annual rates of predation have been in years past (*Appendix A, Table A2*), however, the benefits of reducing the number of double-crested cormorants on East Sand Island may vary greatly by year.

Analogous to impacts from Caspian terns presented in this report, predation rates by double-crested cormorant presented herein apply only to cormorants that attempted to nest on East Sand Island in 2017. The impact of cormorants that dispersed from East Sand Island during the peak smolt outmigration period but remained in the estuary to forage on salmonids is unknown, but could be substantial given the large numbers of cormorants observed throughout the estuary during the 2017 smolt outmigration period. Thus, future efforts to quantify the cumulative or total impact of all double-crested cormorants present in the Columbia River Estuary on ESA-listed smolts may be necessary to fully evaluate the efficacy of the management plan to reduce predation rates.

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LITERATURE CITED

Adkins, J.Y., D.D. Roby, D.E. Lyons, K.N. Courtot, K. Collis, H.R. Carter, W.D. Shuford, and P.J. Capitolo. 2014. Recent population size, trends, and limiting factors for the double-crested cormorant in western North America. The Journal of Wildlife Management DOI:10.1002/jwmg.737.

Anchor. 2017. Double-crested cormorant (DCCO) monitoring report. Final technical report submitted to the U.S. Army Corps of Engineers. Available from the U.S. Army Corps of Engineers, Portland District, Portland, OR.

Beeman, J.W., and A.G. Maule. 2006. Migration depths of juvenile Chinook Salmon and steelhead relative to total dissolved gas supersaturation in a Columbia River reservoir. Transactions of the American Fisheries Society 135:584–594.

Bird Research Northwest (BRNW). 2017. East Sand Island Caspian tern and double-crested cormorant colony sizes. Available online at: http://www.birdresearchnw.org/project-info/project-data/.

Collis, K., D.D. Roby, D.P. Craig, B.A. Ryan, and R.D. Ledgerwood. 2001. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia River Estuary: Vulnerability of different salmonid species, stocks, and rearing types. Transactions of the American Fisheries Society 130:385–396.

Cuthbert, F.J., and L.R. Wires. 1999. Caspian Tern (*Sterna caspia*), The Birds of North America Online (A. Poole, Ed.). Ithaca, Cornell Lab of Ornithology. Available online at http://bna.birds.cornell.edu/bna/species/403.

Evans, A.F, Q. Payton, B.M. Cramer, K. Collis, D.E. Lyons, and P.J. Loschl. 2016a. Predation Impacts on Juvenile Salmonids by Double-crested Cormorants and Caspian Terns Nesting on East Sand Island in the Columbia River Estuary. Final technical report submitted to the U.S. Army Corps of Engineers in partial fulfillment of Contract No. W912EF-14-D-0004, Task Order No. 0004.

Evans, A.F., Q. Payton, A. Turecek, B.M. Cramer, K. Collis, D.D. Roby, P.J. Loschl, L. Sullivan, J. Skalski, M. Weiland, and C. Dotson. 2016b. Avian predation on juvenile salmonids: Spatial and temporal analysis based on acoustic and Passive Integrated Transponder tags. Transactions of the American Fisheries Society 145:860-877.

Evans, A.F., N.J. Hostetter, D.D. Roby, K. Collis, D.E. Lyons, B.P. Sandford, R.D. Ledgerwood, and S. Sebring. 2012. Systemwide evaluation of avian predation on juvenile salmonids from the Columbia River based on recoveries of passive integrated transponder tags. Transactions of the American Fisheries Society 141:975–989.

Fritts, A.L., J.L. Scott, and T.N. Pearsons. 2007. The effects of domestication on the relative vulnerability of hatchery and wild origin spring Chinook salmon (*Oncorhynchus tshawytscha*) to predation. Canadian Journal of Fisheries and Aquatic Sciences 64:813–818.

Gelman, A., J.B. Carlin, H.S. Stern, and D.B. Rubin. 2004. Bayesian Data Analysis, Second Edition. CRC Press.

Hatch, J.J., and D.V. Weseloh. 1999. Double-crested cormorant (*Phalacrocorax auritus*). The Birds of North America Online (A. Poole, Ed.). Ithaca, Cornell Lab of Ornithology. Available on-line at http://bna.birds.cornell.edu/bna/species/441.

Hostetter, N.J., A.F. Evans, B.M. Cramer, K. Collis, D.E. Lyons, D.D. Roby. 2015. Quantifying avian predation on fish populations: Integrating predator-specific deposition probabilities in tag-recovery studies. Transactions of the American Fisheries Society 144:410–422.

Hostetter, N.J., A.F. Evans, D.D. Roby, and K. Collis. 2012. Susceptibility of juvenile steelhead to avian predation: the influence of individual fish characteristics and river conditions. Transactions of the American Fisheries Society 141:1586–1599.

Ims, R.A. 1990. On the adaptive value of reproductive synchrony as a predator swamping strategy. American Naturalist 136:485–498.

Lyons, D.E., A.F. Evans, N.J. Hostetter, A. Piggott, L. Weitkamp, T.P. Good, D.D. Roby, K. Collis, P.J. Loschl, and B. Cramer. 2014a. Factors influencing predation on juvenile salmonids by double-crested cormorants in the Columbia River Estuary: A retrospective analysis. A report to the U.S. Army Corps of Engineers Portland District. Bird Research Northwest. Available on-line at www.birdresearchnw.org.

Lyons, D.E., D.D. Roby, A.F. Evans, N.J. Hostetter, K. Collis. 2014b. Benefits to Columbia River anadromous salmonids from potential reductions in predation by double-crested cormorants nesting at East Sand Island in the Columbia River Estuary. A report to the U.S. Army Corps of Engineers Portland District. Bird Research Northwest. Available on-line at www.birdresearchnw.org.

Lyons, D.E. 2010. Bioenergetics-based predator-prey relationships between piscivorous birds and juvenile salmonids in the Columbia River Estuary. Unpublished Ph.D. dissertation, Oregon State University, Corvallis, Oregon. Available on-line at www.birdresearchnw.org.

NOAA (NOAA Fisheries). 2014a. Supplemental Consultation on Remand for Operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a) (I) (A) Permit for Juvenile Fish Transportation Program. National Marine Fisheries Service, Northwest Region.

NOAA (National Oceanic and Atmospheric Administration). 2014b. Updated status of federally listed ESUs of West Coast salmon and steelhead. Available at on-line at http://www.nwr.noaa.gov/Publications/Biological-Status-Reviews/Salmon.cfm.

NOAA (National Oceanic and Atmospheric Administration). 2010. Endangered Species Act section 7(a)(2) consultation supplemental biological opinion: Supplemental consultation on remand for operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a)(I)(A) permit for Juvenile Fish Transportation Program. Seattle, WA.

NOAA (National Oceanic and Atmospheric Administration). 2008. Biological opinion, Endangered Species Act section 7(a)(2) consultation: consultation on remand for operation of the federal Columbia River power system, 11 Bureau of Reclamation projects in the Columbia basin and ESA section 10(a)(1)(A) permit for juvenile fish transportation program. NOAA National Marine Fisheries Service, Northwest Region, Seattle, Washington.

Olla, B.L., and M.W. Davis. 1989. The role of learning and stress in predator avoidance of hatchery-reared coho salmon (*Oncorhynchus kisutch*) juveniles. Aquaculture 76:209–214.

PSMFC (Pacific States Marine Fisheries Commission). 2017. PIT Tag Information Systems (PTAGIS). Available online: https://www.psmfc.org/program/pit-tag-information-systems-ptagis

R Development Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raftery, A.E., and S.M. Lewis. 1992. [Practical Markov Chain Monte Carlo]: comment: one long run with diagnostics: implementation strategies for Markov Chain Monte Carlo. Statistical Science:493–497.

Roby, D.D., K. Collis, D.E. Lyons, D.P. Craig, J. Adkins, A.M. Myers, and R.M. Suryan. 2002. Effects of colony relocation on diet and productivity of Caspian terns. Journal of Wildlife Management 66:662–673.

Roby, D.D., D.E. Lyons, D.P. Craig, K. Collis, and G.H. Visser. 2003. Quantifying the effect of predators on endangered species using a bioenergetics approach: Caspian terns and juvenile salmonids in the Columbia River Estuary. Canadian Journal of Zoology 81:250–265.

Roby D.D, K. Collis, D.E. Lyons, T. Lawes, Y. Suzuki, P.J. Loschl, K. Bixler, K. Kelly, A. Peck-Richardson, A. Piggott, O. Bailey, H.McKinnon, A. Laws, J. Mulligan, S. Toomey, A. Munes, E. Schniedermeyer, A. Wilson, G. Smith, K. Saunders, L. Hanwacker, A. Evans, B. Cramer, A. Turecek, Q. Payton, M. Hawbecker, and D. Kuligowski. 2015. Research, monitoring, and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River. 2014 Final Annual Report. Submitted to Bonneville Power Administration, U.S. Army Corps of Engineers, Grant County Public Utility District, and the Priest Rapids Coordinating Committee. Available on-line at www.birdresearchnw.org.

Roby, D.D, K. Collis, D.E. Lyons, T. Lawes, Y. Suzuki, P.J. Loschl, K. Bixler, K. Kelly, E. Schniedermeyer, A.F. Evans, B. Cramer, J. Morella, A. Turecek, Q. Payton, and M. Hawbecker. 2017. Evaluation of Foraging Behavior, Dispersal, and Predation on ESA-listed Salmonids by Caspian Terns Displaced from Managed Colonies in the Columbia Plateau Region. 2016 Final Annual Report. Submitted to the Grant County Public Utility District and the Priest Rapids Coordinating Committee. Available on-line at www.birdresearchnw.org.

Ryan, B.A., S.G. Smith, J.M. Butzerin, and J.W. Ferguson. 2003. Relative vulnerability to avian predation of juvenile salmonids tagged with passive integrated transponders in the Columbia River Estuary, 1998-2000. Transactions of the American Fisheries Society 132:275–288.

Sebring, S.H., M.C. Carper, R.D. Ledgerwood, B.P. Sandford, G.M. Matthews, and A.F. Evans. 2013. Relative vulnerability of pit-tagged subyearling fall Chinook salmon to predation by Caspian terns and double-crested cormorants in the Columbia River Estuary. Transactions of the American Fisheries Society 142:1321–1334.

Skalski, J.R., R.L. Townsend, and J. Murauskas. 2017. Predation rates of double-crested cormorants on Columbia and Willamette River Salmonids, 2016. Final technical report submitted to the U.S. Army Corps of Engineers. Available from the U.S. Army Corps of Engineers, Portland District, Portland, OR.

Sólymos, P. 2010. dclone: Data Cloning in R. The R Journal, 2(2), 29-37. URL http://CRAN. R-project. org/package= dclone

Su, Y.S., and M. Yajima. 2012. R2jags: A Package for Running jags from R. R package version 0.03-08, URL http://CRAN. R-project. org/package= R2jags.

Turecek, A., J. Tennyson, K. Collis, and B. Cramer. 2017. Double-crested cormorant monitoring on East Sand Island, 2017. DRAFT technical report submitted to the U.S. Army Corps of Engineers – Portland District in partial fulfillment of Contract No. W912EF-14-D-0004, Task Order DT02.

USACE (U.S. Army Corps of Engineers). 2015. Double-crested Cormorant Management Plan to Reduce Predation on Juvenile Salmonids in the Columbia River Estuary: Final Environmental Impact Statement, February 2015. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

USFWS (U.S. Fish and Wildlife Service). 2005. Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary: Final Environmental Impact Statement, January 2005. U.S. Fish and Wildlife Service, Migratory Birds and Habitat Program, Portland, Oregon.

USFWS (U.S. Fish and Wildlife Service). 2006. Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary: Record of Decision, November 2006. U.S. Fish and Wildlife Service, Migratory Birds and Habitat Program, Portland, Oregon.

MAPS

Map 1. Columbia and Snake rivers depicting Lower Granite, Little Goose, and Lower Monumental dams (sites where PIT-tagged smolts were loaded into transportation barges) and Bonneville and Sullivan dams (interrogation sites for in-river fish) and Skamania landing (release site for transported fish). Interrogation and release sites were used to determine the availability of PIT-tagged fish to terns and cormorants nesting on East Sand Island in the Columbia River estuary.

FIGURES

Figure 1. PIT tag detection equipment used on East Sand Island in 2017, including a hand-held portable system (top left), an eight-coil flat-plate attached to an ATV (top right), and a towable sweeper magnet attached to an ATV (bottom right and left).

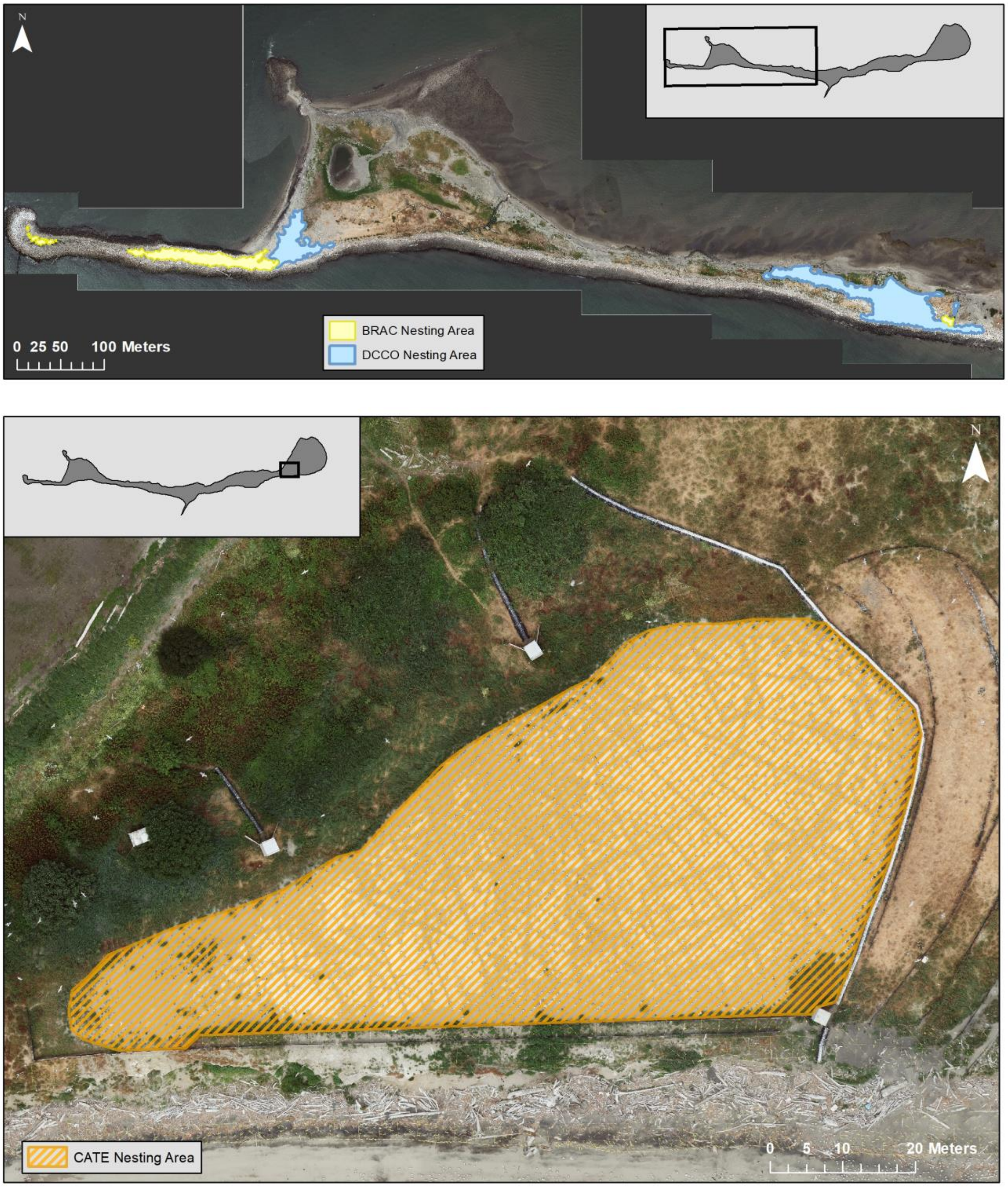


Figure 2. Areas scanned for PIT tags deposited by nesting double-crested cormorants (DCCO; top), Brandt's cormorants (BRAC: top), and Caspian terns (CATE: bottom) on East Sand Island in 2017.

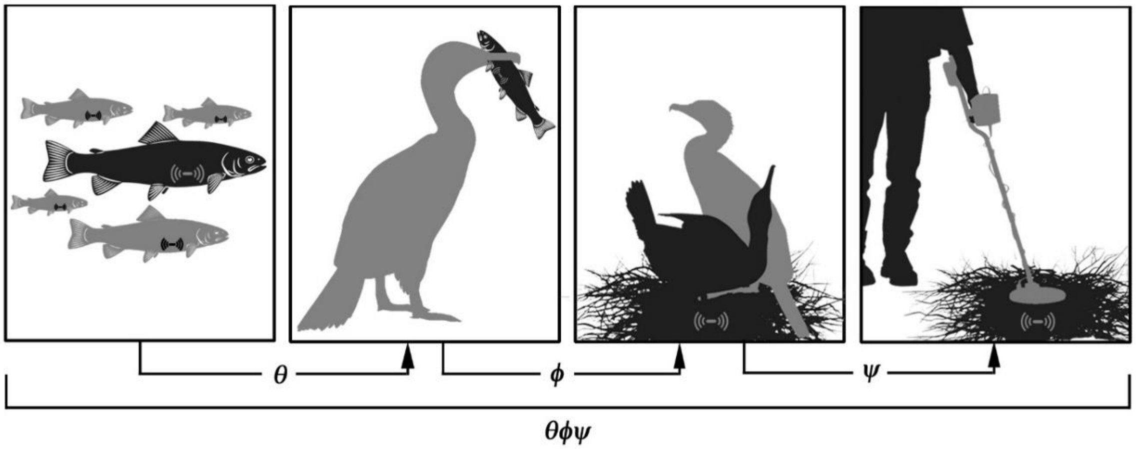
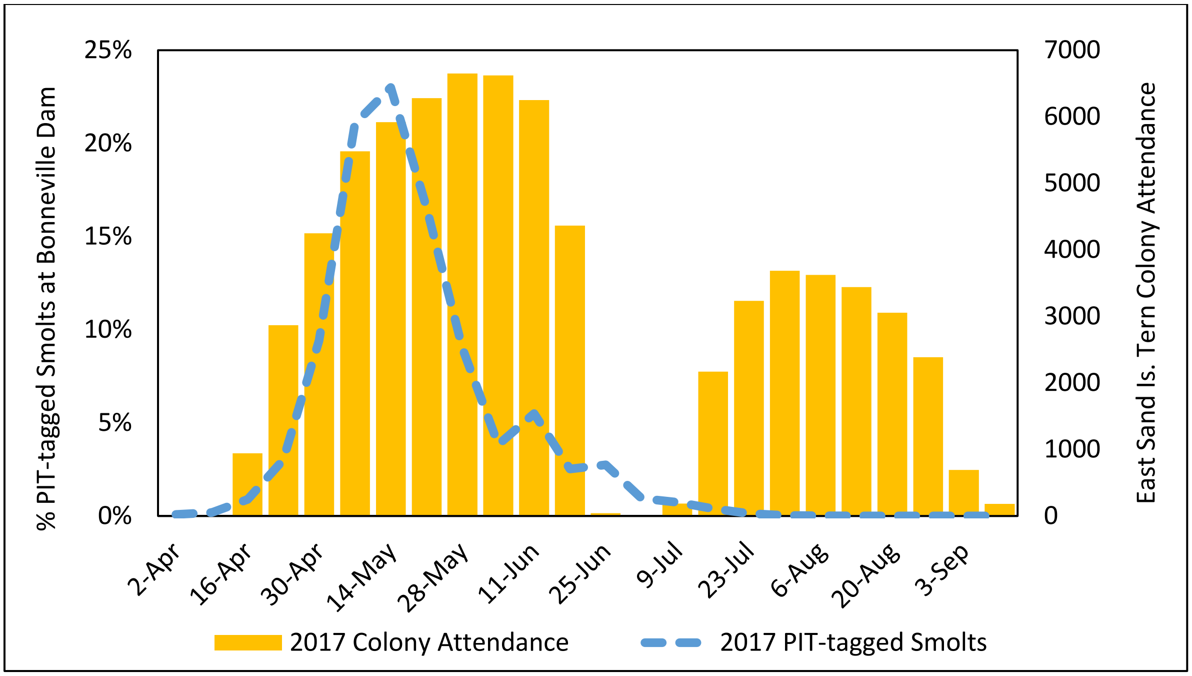


Figure 3. Conceptual model of the tag-recovery process in studies of avian predation. The probability of recovering a fish tag on a bird colony is the product of three probabilities: a fish was consumed (predation probability, ϑ), deposited on the nesting colony (deposition probability, ϕ), and detected by researchers (detection probability, ψ). Figure from Hostetter et al. (2015).



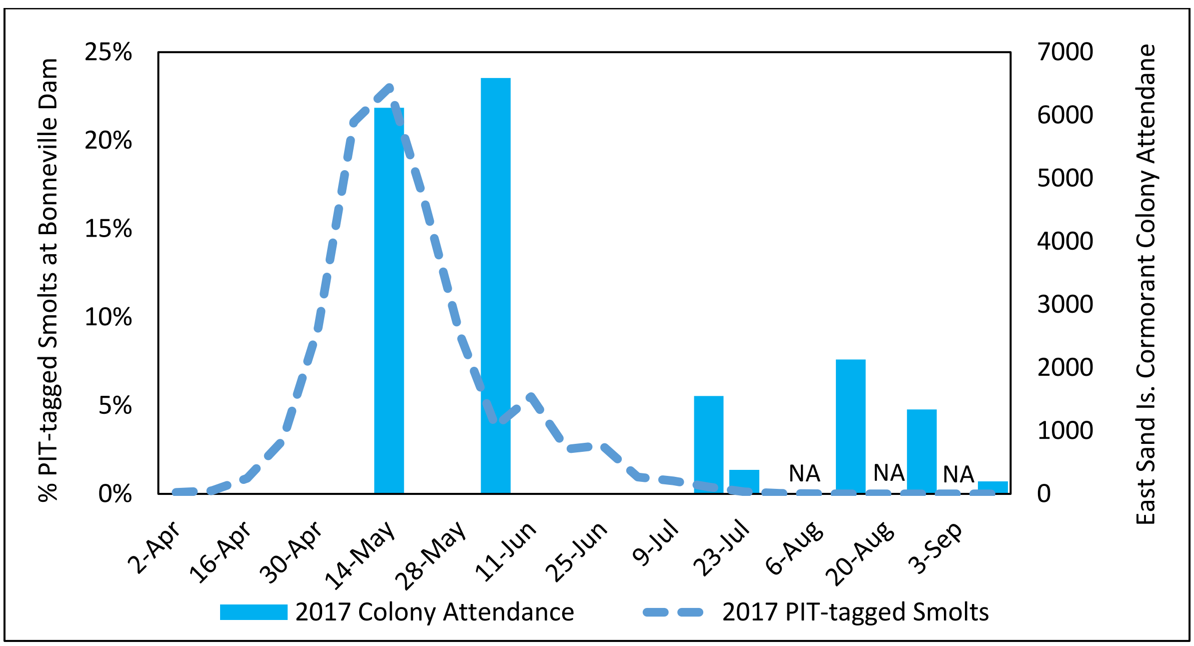


Figure 4. Attendance of Caspian terns (top; yellow bars) and double-crested cormorants (bottom; blue bars) on East Sand Island and the run-timing of PIT-tagged juvenile salmonids last detected passing Bonneville Dam in 2017 (top and bottom; blue dotted line). NA denotes that birds were present but that no counts were conducted that week.

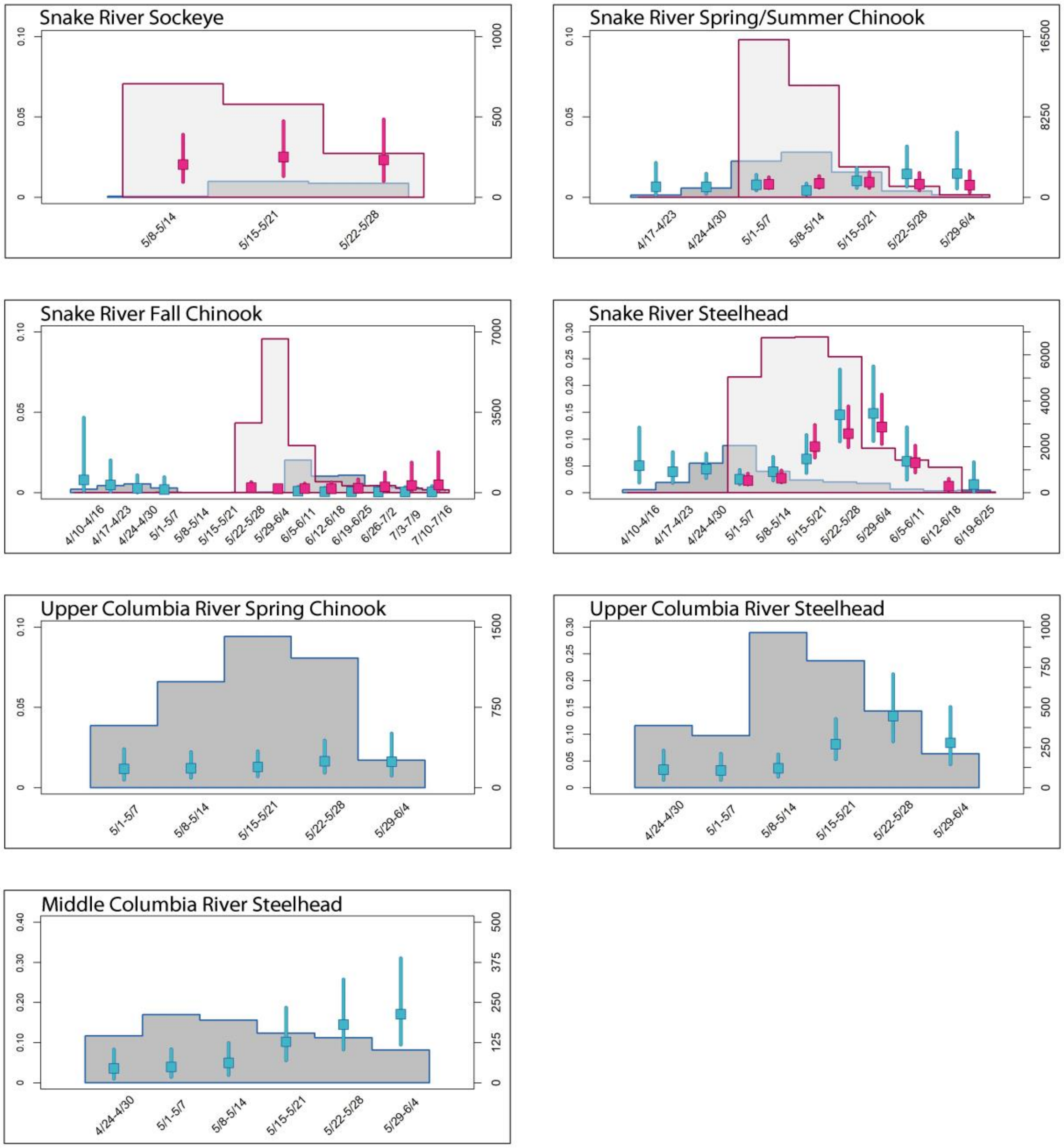


Figure 5. Estimated weekly predation rates (y_1; proportion of fish consumed) on in-river (blue squares) and transported (red squares) PIT-tagged juvenile salmonids last detected passing Bonneville or Sullivan dams (y_2; number available, dark gray bars) or transported from the lower Snake River (y^2; number available; light gray bars) by Caspian terns on East Sand Island during 2017. Error bars represent 95% credible intervals for predation rates.

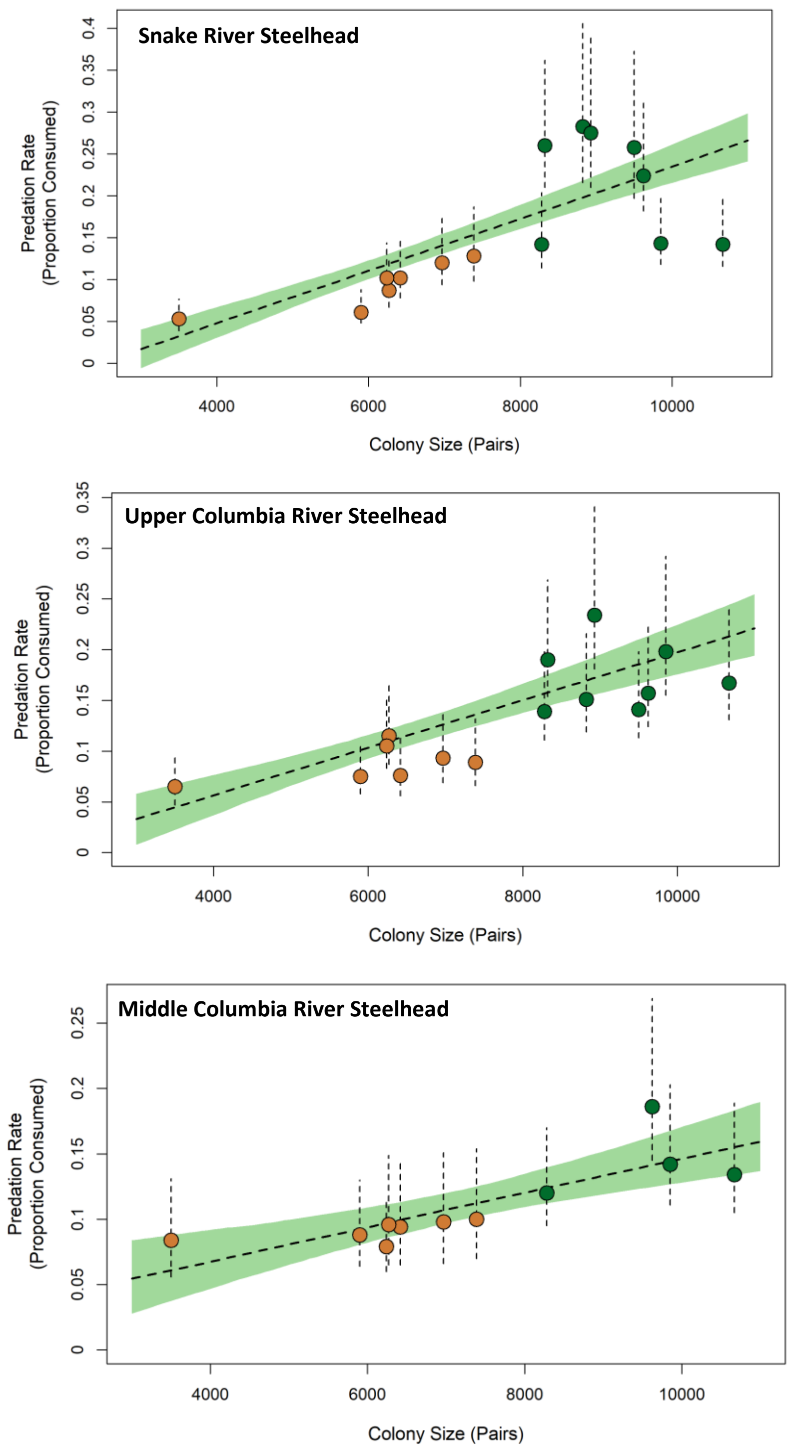


Figure 6. Estimated annual predation rate (95% credible intervals) and Caspian tern colony size (nesting pairs) prior to (green dots) and following (orange dots) management actions on East Sand Island. Predation rates are on PIT-tagged Upper Columbia River, Snake River, and Middle Columbia River steelhead last detected passing Bonneville Dam during 2003-2017 (for years with adequate sample sizes of tagged fish; see Methods).

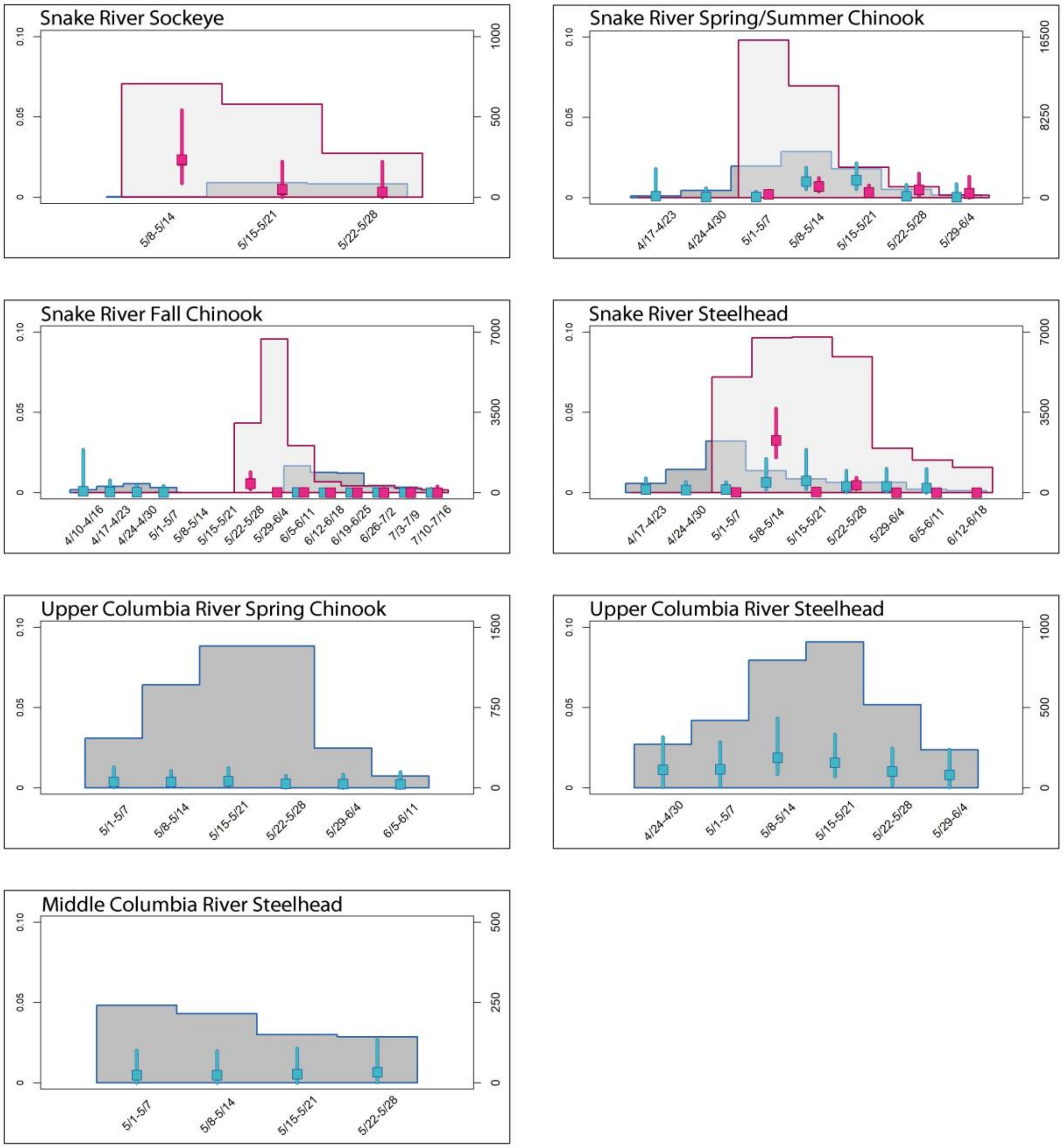


Figure 7. Estimated weekly predation rates (y_1; proportion of fish consumed) on in-river (blue squares) and transported (red squares) PIT-tagged juvenile salmonids last detected passing Bonneville or Sullivan dams (y_2; number available, dark gray bars) or transported from the lower Snake River (y^2; number available; light gray bars) by double-crested cormorants on East Sand Island during 2017. Error bars represent 95% credible intervals for predation rates.

TABLES

Table 1. Number of 2017 migration year PIT-tagged juvenile salmonids (Chinook salmon, coho salmon, sockeye salmon, and steelhead combined) recovered (electronic detections and physical removal; see Methods) on bird colonies on East Sand Island following the 2017 breeding season.

Location	Colony	Tags Recovered
East Sand Island	Caspian tern	8,407
	Double-crested cormorant	1,340
	Brandt's cormorant	42

Table 2. Average deposition (95% credible interval) and detection (range; first-to-last week of nesting season) probability estimates for PIT tags on the East Sand Island Caspian tern and double-crested cormorant colonies in 2017. Results were used to estimate the proportion of PIT-tagged smolt consumed by birds that were deposited on their nesting site and the proportion of deposited tags subsequently detected by researchers after the nesting season (see Methods). Deposition estimates are those reported by Hostetter et al. (2015).

Location	Colony	Deposition	Detection
East Sand Island	Caspian terns	0.71 (0.51-0.89)	0.73 (0.40-0.88)
	Double-crested cormorants	0.51 (0.34-0.70)	0.71 (0.60-0.78)

Table 3. Estimated predation rates (95% credible interval) of PIT-tagged salmonid smolts last detected at Bonneville Dam on the Columbia River or Sullivan Dam on the Willamette River (In-river) or released from transportation barges (Transported) below Bonneville Dam by Caspian terns or double-crested nesting on East Sand Island in 2017. Predation rates were adjusted to account for tag loss due to on-colony PIT tag detection efficiency and deposition rates (see Table 2). The number (N) of in-river and transported PIT-tagged smolts and current U.S. Endangered Species Act (ESA) status of each evolutionarily significant unit (ESU) or distinct population segment (DPS) of PIT-tagged fish are provided. Only fish originating from and collected for transport on the Snake River (SR) were used in this analysis. Due to the limited use of East Sand Island by double-crested cormorants in 2017 (see Figure 4) predation rates on available smolts are biased low to unknown degree.

		N		Caspian terns		Double-crested cormorants	
ESU/DPS[1]	ESA[2]	In-river	Transported	In-river	Transported	In-river	Transported
SR Sockeye	E	256	1,589	-	2.3% (1.3-4.0)	-	1.4% (0.6-3.0)
SR Spr/Sum Chinook	T	13,151	32,395	0.8% (0.5-1.2)	0.8% (0.6-1.3)	0.7% (0.4-1.1)	0.4% (0.3-0.7)
UCR Spr Chinook	E	4,622	-	1.4% (0.9-2.3)	-	0.4% (0.1-0.8)	-
SR Fall Chinook	T	4,635	13,205	0.2% (0.1-0.5)	0.3% (0.2-0.5)	0.1% (0-0.2)	0.2% (0.1-0.3)
UWR Spr Chinook	T	89	-	-	-	-	-
SR Steelhead	T	6,497	28,964	5.3% (3.9-7.7)	6.4% (5.0-9.2)	0.4% (0.2-0.8)	0.9% (0.6-1.4)
UCR Steelhead	T	3,275	-	6.5% (4.7-9.6)	-	1.4% (0.8-2.7)	-
MCR Steelhead	T	1,069	-	8.4% (5.6-13.1)	-	0.7% (0.1-2.1)	-

[1] MCR = Middle Columbia River, SR = Snake River, UCR = Upper Columbia River, UWR = Upper Willamette River
[2] E = Endangered, T = Threatened

Table 4. Relative susceptibility of PIT-tagged smolts by rear-type and outmigration history to predation by Caspian terns and double-crested cormorants nesting on East Sand Island during 2006-2016 (average across all years) and in 2017. Values represent the odds-ratio of predation, with values < 1 indicating greater predation odds for hatchery fish and in-river fish and values > 1 indicating greater predation odds for wild fish and transported fish (see Methods). Dashed lines denote that insufficient sample sizes (< 500 PIT-tagged fish of each category) or extremely low rates of predation rates (< 1.0% of each category) prevented comparisons in 2017. An asterisk denotes a statistical significance difference. See Evans et al. (2016) for weekly and year-specific results during 2006-2015 and Roby et al. (2017) for weekly and year-specific results in 2016. Salmonid populations included fish from the Snake River (SR) and Upper Columbia River (UCR), with runs of spring (Sp) and summer (Su) fish.

	Caspian Terns		Double-crested Cormorants	
	2006-2016	2017	2006-2015 [1]	2017
Hatchery versus Wild				
SR Sp/Su Chinook	0.38 (0.31-0.46)*	-	0.95 (0.84-1.08)	-
UCR Sp Chinook	0.34 (0.22-0.54)*	-	0.76 (0.55-1.04)	-
SR Steelhead	1.03 (0.98-1.09)	0.85 (0.61-1.19)	1.25 (1.14-1.38)*	-
UCR Steelhead	0.94 (0.79-1.08)	-	1.01 (0.83-1.22)	-
Transport versus In-river				
SR Sp/Su Chinook	0.86 (0.81-0.91)*	-	0.79 (0.76-0.83)*	-
SR Fall Chinook	0.92 (0.83-1.01)	-	1.52 (1.40-1.65)*	-
SR Sockeye	0.84 (0.61-1.17)	-	1.46 (1.15-1.87)*	-
SR Steelhead	0.88 (0.84-0.91)*	0.86 (0.69-1.08)	0.80 (0.76-0.84)*	-

[1] Cormorant predation rates in 2016 were excluded from the time series because predation rates were generated using a different analytical framework (see Skalski et al. 2017)

Table 5. Average annual predation rates (95% credible intervals) by Caspian terns nesting on East Sand Island prior to and following periods of management. Salmonid populations (ESU/DPS) with runs of spring (Sp), summer (Su), and fall (Fall) fish were evaluated, where applicable. Asterisks denotes statistically credible differences between management periods (see Methods).

	Pre-management Period	Management Period
Salmonid ESU/DPS	2000-2010	2011-2017
Snake River Sockeye [1]	1.5% (0.9-2.2)	1.4% (1-1.8)
Snake River Spr/Sum Chinook	4.8% (4.3-5.4)	1.5% (1.3-1.8)*
Upper Columbia River Spr Chinook	3.9% (3.4-4.6)	1.6% (1.3-2.0)*
Snake River Fall Chinook	2.5% (2.2-3.0)	0.8% (0.6-0.9)*
Upper Willamette River Spr Chinook [2]	2.5% (1.9-3.3)	1.0% (0.6-1.4)*
Snake River Steelhead	22.2% (20.3-24.8)	9.5% (8.4-10.8)*
Upper Columbia River Steelhead [3]	17.2% (15.7-19.3)	9.0% (7.9-10.3)*
Middle Columbia River Steelhead [4]	14.9% (13.1-17.6)	9.3% (7.9-10.8)*

[1] Predation rate estimates were not available in 2000-2008 and in 2016-2017 due to insufficient sample sizes

[2] Predation rate estimates were not available in 2000-2006 and in 2017 due to insufficient sample sizes

[3] Predation rate estimates were not available in 2000-2002 due to insufficient sample sizes

[4] Predation rate estimates were not available in 2000-2006 due to insufficient sample sizes

Table 6. Average annual per capita (nesting pair) predation rates (95% credible intervals) by Caspian terns and double-crested cormorants nesting on East Sand Island. Salmonid populations (ESU/DPS) with runs of spring (Sp), summer (Su), and fall (Fall) fish were evaluated, where applicable.

Salmonid ESU/DPS	Caspian Terns	Double-crested Cormorants
	2000-2017	2003-2015 [5]
Snake River Sockeye [1]	0.0002% (0.0001-0.0003)	0.0003% (0.0002-0.0004)
Snake River Sp/Su Chinook	0.0004% (0.0004-0.0007)	0.0004% (0.0004-0.0005)
Upper Columbia River Sp Chinook	0.0004% (0.0003-0.0006)	0.0003% (0.0003-0.0004)
Snake River Fall Chinook	0.0002% (0.0002-0.0004)	0.0003% (0.0002-0.0003)
Upper Willamette River Sp Chinook [2]	0.0002% (0.0001-0.0003)	0.0001% (0.0001-0.0002)
Snake River Steelhead	0.0022% (0.0019-0.0033)	0.0006% (0.0005-0.0007)
Upper Columbia River Steelhead [3]	0.0018% (0.0015-0.026)	0.0005% (0.0004-0.0006)
Middle Columbia River Steelhead [4]	0.0015% (0.0012-0.0023)	0.0006% (0.0005-0.0008)

[1] Predation rate estimates were not available in 2000-2008 and 2016-207 due to insufficient sample sizes

[2] Predation rate estimates were not available in 2000-2006 and 2017 due to insufficient sample sizes

[3] Predation rate estimates were not available in 2000-2002 due to insufficient sample sizes

[4] Predation rate estimates were not available in 2000-2006 due to insufficient sample sizes

[5] Predation rate estimates from 2016 and 2017 were excluded because cormorants dispersed from East Sand Island during the peak smolt outmigration period (see Results)

Table 7. Average annual predation rates (95% credible intervals) by double-crested cormorants nesting on East Sand Island prior to and following management. Salmonid populations (ESU/DPS) with runs of spring (Sp), summer (Su), and fall (Fall) fish were evaluated, where applicable. Average predation rate estimates following management in 2016 and 2017 were not available (NA) because cormorants dispersed from East Sand Island during the peak smolt outmigration period and consume an unknown percentage of tagged fish (see Results).

	Pre-management Period	Management Period
Salmonid ESU/DPS	2003-2015	2016-2017
Snake River Sockeye [1]	3.6% (2.7-4.5)	NA
Snake River Spr/Sum Chinook	5.2% (4.4-6.1)	NA
Upper Columbia River Spr Chinook	3.1% (2.4-3.9)	NA
Snake River Fall Chinook	3.0% (2.6-3.6)	NA
Upper Willamette River Spr Chinook [2]	1.3% (0.5-1.8)	NA
Snake River Steelhead	9.3% (8.0-11.0)	NA
Upper Columbia River Steelhead [3]	5.1% (4.1-6.1)	NA
Middle Columbia River Steelhead [4]	8.3% (6.8-10.1)	NA

[1] Predation rate estimates were not available in 2000-2008 and in 2016-2017 due to insufficient sample sizes

[2] Predation rate estimates were not available in 2000-2006 and in 2017 due to insufficient sample sizes

[3] Predation rate estimates were not available in 2000-2002 due to insufficient sample sizes

[4] Predation rate estimates were not available in 2000-2006 due to insufficient sample sizes

APPENDIX A: HISTORICAL PREDATION RATES

This appendix provides annual PIT tag predation rate estimates for Caspian terns and double-crested cormorants nesting on East Sand Island during 2006-2016. Predation rate estimates were based on the number (N) of PIT-tagged fish interrogated passing Bonneville Dam or Sullivan Dam (in-river migrants; Table A1 and A2) or the number released from barges downstream of Bonneville Dam (transported migrants; Table A3). Predation rates were corrected for PIT detection and deposition probabilities unique to each colony and year. Salmonid populations originating from the Snake River (SR), Upper Columbia River (UCR), Middle Columbia River (MCR) and Upper Willamette River (UWR) were evaluated, with runs of spring (Sp), summer (Su), and fall (Fall) fish included, where applicable.

Predation rate estimates for Caspian terns and double-crested cormorants during 2006-2015 are those of Evans et al. (2016). Estimates for East Sand Island Caspian terns in 2016 are those of Roby et al. (2017). Predation rate estimates dating back to 2000 are also available for some ESUs/DPSs and years, depending sample sizes, and can be found in Evans et al. (2016).

Table A1. Annual predation rates (95% credible interval) of PIT-tagged juvenile salmonid last detected (N) passing Bonneville or Sullivan dams by Caspian terns nesting on East Sand Island during 2006-2016. Dashes denote insufficient sample sizes (< 500 PIT-tagged fish were available) for generating predation rates.

Year	SR Sp/Su Chinook	SR Fall Chinook	UCR Sp Chinook	UWR Sp Chinook	SR Sockeye	MCR Steelhead	SR Steelhead	UCR Steelhead
2006	3.3% (2.4-5.0)	2.5% (1.7-3.9)	3.6% (1.8-6.6)	-	-	-	27.5% (21.0-39.1)	23.4% (18.1-34.1)
N	*5,570*	*4,057*	*731*				*1,100*	*2,064*
2007	3.1% (2.5-4.4)	3.4% (2.3-5.3)	1.9% (1.2-3.2)	1.4% (0.8-2.5)	-	18.7% (14.6-26.8)	22.6% (18.2-32.4)	15.7% (12.4-22.6)
N	*23,830*	*2,005*	*2,268*	*1,505*		*2,234*	*6,391*	*3,042*
2008	2.5% (1.9-3.6)	1.9% (1.5-2.7)	1.7% (1.0-2.9)	4.4% (3.2-6.7)	-	13.5% (10.6-19.2)	14.2% (11.5-19.9)	16.7% (13.1-24.2)
N	*11,425*	*24,136*	*1,662*	*2,509*		*2,291*	*19,572*	*2,513*
2009	4.7% (3.7-6.9)	2.0% (1.5-2.9)	3.7% (2.5-5.6)	1.7% (1.2-2.7)	1.3% (0.7-2.2)	14.1% (11.1-20.0)	14.5% (11.9-20.1)	20.0% (15.6-29.3)
N	*17,396*	*16,314*	*2,064*	*5,573*	*1,845*	*2,700*	*23,311*	*2,265*
2010	3.4% (2.7-4.8)	0.7% (0.5-1.1)	2.9% (2.2-4.3)	1.8% (0.6-4.4)	1.6% (0.8-2.9)	11.9% (9.4-17.4)	14.3% (11.3-20.4)	13.7% (11.0-19.3)
N	*38,441*	*17,974*	*5,972*	*510*	*1,382*	*8,515*	*40,024*	*12,284*
2011	2.5% (1.8-3.6)	0.7% (0.5-1.1)	2.9% (1.4-5.3)	0.9% (0.3-2.0)	0.4% (0.1-1.3)	9.6% (6.6-14.7)	12.0% (9.4-17.3)	9.1% (6.9-13.4)
N	*6,557*	*12,327*	*704*	*1,119*	*826*	*865*	*7,028*	*2,419*
2012	2.2% (1.7-3.3)	0.7% (0.5-1.1)	1.2% (0.7-2.1)	0.7% (0.4-1.3)	2.1% (1.2-3.7)	9.4% (6.5-14.4)	10.2% (7.7-14.9)	7.5% (5.6-11.3)
N	*17,929*	*10,742*	*3,227*	*3,731*	*1,457*	*1,084*	*4,768*	*3,357*
2013	1.2% (0.8-1.8)	0.9% (0.5-1.6)	0.7% (0.3-1.4)	1.0% (0.5-1.8)	0.8% (0.3-2.0)	9.9% (7.0-15.3)	12.7% (9.6-18.5)	8.9% (6.6-13.4)
N	*16,167*	*4,465*	*3,112*	*2,629*	*1,454*	*1,865*	*8,516*	*4,473*
2014	1.1% (0.8-1.7)	1.0% (0.5-1.9)	1.4% (0.7-2.5)	1.2% (0.5-2.5)	1.6% (0.8-3.0)	9.5% (6.5-14.5)	8.6% (6.7-12.5)	11.4% (8.5-16.8)
N	*14,828*	*2,800*	*2,297*	*1,587*	*1,739*	*1,119*	*8,812*	*3,841*
2015	2.0% (1.5-2.9)	0.8% (0.4-1.5)	1.9% (1.3-2.9	0.4% (0.1-1.5)	1.6% (1-2.6)	7.8% (5.9-11.4)	10.2% (8.2-14.6)	10.5% (8.2-15.0)
N	*20,245*	*2,629*	*5,943*	*768*	*3,311*	*3,927*	*16,451*	*6,004*
2016	*0.8% (0.6-1.2)*	*0.7% (0.3-1.3)*	*1.4% (0.9-2.1)*	*1.2% (0.4-3.2)*	-	*8.8% (6.4-13.0)*	*6.1% (4.8-8.8)*	*7.5% (5.8-10.7)*
N	*21,874*	*2,887*	*5,939*	*604*		*2,086*	*14,473*	*8,123*

Table A2. Annual predation rates (95% credible interval) of PIT-tagged juvenile salmonid last detected (N) passing Bonneville or Sullivan dams by double-crested cormorants nesting on East Sand Island during 2006-2016. Dashes denote insufficient sample sizes (< 500 PIT-tagged fish) for generating predation rates. NA denotes that comparable rates of predation were not available that year (see Methods).

Year	SR Sp/Su Chinook	SR Fall Chinook	UCR Sp Chinook	UWR Sp Chinook	SR Sockeye	MCR Steelhead	SR Steelhead	UCR Steelhead
2006	5.2% (3.5-8.5)	2.7% (1.6-4.6)	4.7% (2.2-9.5)	-	-	-	13.1% (8.2-22.7)	4.7% (2.8-8.2)
N	*5,570*	*4,057*	*731*				*1,100*	*2,064*
2007	1.7% (1.1-2.7)	1.6% (0.7-3.3)	2.7% (1.5-5.1)	1.0% (0.3-2.6)	-	2.8% (1.5-5.2)	3.5% (2.3-5.8)	3.4% (2.1-6.1)
N	*23,830*	*2,005*	*2,268*	*1,505*		*2,234*	*6,391*	*3,042*
2008	3.5% (2.4-5.5)	2.6% (1.9-4.2)	3.6% (2.0-6.6)	3.3% (1.9-5.8)	-	14.0% (9.5-23.2)	14.7% (10.6-23.2)	6.2% (4.0-10.4)
N	*11,425*	*24,136*	*1,662*	*2,509*		*2,291*	*19,572*	*2,513*
2009	6.8% (4.9-10.7)	4.5% (3.2-7.1)	2.7% (1.5-4.9)	1.4% (0.8-2.4)	5.7% (3.5-9.8)	14.9% (10.3-23.8)	16.6% (12.0-25.7)	7.2% (4.7-12.0)
N	*17,396*	*16,314*	*2,064*	*5,573*	*1,845*	*2,700*	*23,311*	*2,265*
2010	5.3% (3.9-8.4)	3.9% (2.7-6.1)	3.3% (2.3-5.4)	4.2% (1.6-9.2)	2.6% (1.3-4.9)	8.2% (5.8-13.1)	7.5% (5.5-12.0)	6.8% (4.9-10.6)
N	*38,441*	*17,974*	*5,972*	*510*	*1,382*	*8,515*	*40,024*	*12,284*
2011	4.3% (2.9-6.9)	1.9% (1.3-3.1)	5.6% (2.9-10.8)	0.4% (0.1-1.5)	4.8% (2.4-9.1)	7.8% (4.6-14.0)	5.3% (3.7-8.5)	11.4% (7.8-18.6)
N	*6,557*	*12,327*	*704*	*1,119*	*826*	*865*	*7,028*	*2,419*
2012	3.7% (2.6-6.0)	2.6% (1.8-4.2)	2.1% (1.2-3.7)	0.6% (0.3-1.3)	3.7% (2.0-6.9)	3.3% (1.7-6.4)	4.9% (3.2-8.1)	6.5% (4.3-10.8)
N	*17,929*	*10,742*	*3,227*	*3,731*	*1,457*	*1,084*	*4,768*	*3,357*
2013	3.6% (2.5-5.7)	2.2% (1.3-3.7)	3.0% (1.8-5.3)	1.0% (0.4-2.0)	3.3% (1.8-6.2)	2.1% (1.0-4.1)	2.5% (1.7-4.0)	3.4% (2.2-5.7)
N	*16,167*	*4,465*	*3,112*	*2,629*	*1,454*	*1,865*	*8,516*	*4,473*
2014	8.5% (6.1-13.2)	2.4% (1.5-4.2)	6.1% (3.9-10.1)	1.8% (0.9-3.6)	4.5% (2.7-7.7)	6.4% (3.7-10.7)	7.8% (5.6-12.0)	10.4% (7.3-16.3)
N	*14,828*	*2,800*	*2,297*	*1,587*	*1,739*	*1,119*	*8,812*	*3,841*
2015	14.5% (10.5-22.4)	8.7% (6.0-14.0)	8.3% (5.9-12.9)	2.4% (0.9-5.2)	2.4% (1.5-4.1)	12.4% (8.8-19.2)	12.8% (9.3-19.6)	10.5% (7.6-16.2)
N	*20,245*	*2,629*	*5,943*	*768*	*3,311*	*3,927*	*16,451*	*6,004*
2016	*NA*	*NA*	*NA*	*NA*	-	*NA*	*NA*	*NA*
N	*21,874*	*2,887*	*5,939*	*604*		*2,086*	*14,473*	*8,123*

Table A3. Annual predation rates (95% credible interval) of PIT-tagged juvenile salmonid collected at Lower Granite Dam, Little Goose Dam, and Lower Monumental Dam on the Snake River and released from barges downstream of Bonneville Dam by double-crested cormorants and Caspian terns nesting on East Sand Island during 2006-2016. Dashes denote insufficient sample sizes (< 500 PIT-tagged fish) for generating predation rates. NA denotes that comparable rates of predation were not available that year (see Methods).

Year	Predation by Caspian terns				Predation by Double-crested cormorants			
	SR Sp/Su Chinook	SR Fall Chinook	SR Sockeye	SR Steelhead	SR Sp/Su Chinook	SR Fall Chinook	SR Sockeye	SR Steelhead
2006	4.0% (3.2-5.6)	1.8% (1.4-2.6)	-	22.7% (18.2-31.1)	4.9% (3.5-7.7)	1.7% (1.2-2.6)	-	8.1% (5.9-12.8)
N	78,532	48,661		70,988	78,532	48,661		70,988
2007	2.3% (1.8-3.4)	3.0% (1.6-5.5)	-	16.7% (13.4-24.5)	2.1% (1.4-3.3)	0.9% (0.1-3.4)	-	3.9% (2.7-6.1)
N	*32,184*	*607*		*45,276*	*32,184*	*607*		*45,276*
2008	4.2% (3.4-5.9)	1.6% (1.2-2.2)	-	18.7% (15.2-26.1)	3.9% (2.8-6.1)	5.3% (3.9-8.2)	-	6.0% (4.3-9.1)
N	*95,267*	*48,039*		*65,097*	*95,267*	*48,039*		*65,097*
2009	4.3% (3.5-6.3)	1.8% (1.4-2.6)	1.1% (0.8-1.6)	16.1% (13.1-23.1)	6.8% (4.9-10.3)	5.8% (4.2-8.9)	8.9% (6.4-13.8)	10.7% (7.8-16.8)
N	*51,805*	*34,407*	*10,167*	*22,627*	*51,805*	*34,407*	*10,167*	*22,627*
2010	3.6% (2.9-5.1)	0.9% (0.7-1.3)	-	14.9% (12.0-21.2)	4.7% (3.4-7.2)	5.3% (3.8-8.1)	-	9.4% (6.8-14.3)
N	*40,996*	*46,843*		*32,904*	*40,996*	*46,843*		*32,904*
2011	1.9% (1.5-2.7)	0.5% (0.4-0.8)	0.4% (0.2-0.7)	9.2% (7.3-13.0)	3.6% (2.6-5.6)	4.0% (2.9-6.2)	8.6% (6.2-13.5)	6.5% (4.8-10.1)
N	*64,858*	*53,093*	*7,038*	*26,862*	*64,858*	*53,093*	*7,038*	*26,862*
2012	2.4% (1.8-3.4)	1.0% (0.8-1.5)	1.0% (0.7-1.5)	8.2% (6.5-12.0)	2.7% (1.9-4.2)	6.6% (4.8-10.3)	6.2% (4.4-9.7)	4.4% (3.1-6.9)
N	*38,963*	*41,537*	*14,013*	*30,542*	*38,963*	*41,537*	*14,013*	*30,542*
2013	1.1% (0.8-1.6)	1.3% (0.6-2.5)	0.5% (0.3-0.9)	8.9% (6.8-13.3)	4.0% (2.9-6.3)	9.7% (6.6-15.5)	1.3% (0.8-2.1)	4.4% (3.2-6.8)
N	*49,592*	*2,106*	*9,280*	*32,490*	*49,592*	*2,106*	*9,280*	*32,490*
2014	1.1% (0.8-1.6)	0.9% (0.4-2.0)	0.8% (0.4-1.3)	9.5% (7.4-13.4)	8.4% (6.2-13.2)	4.4% (2.6-7.6)	7.6% (5.4-12.0)	8.5% (6.2-13.1)
N	*66,759*	*1,539*	*5,839*	*33,327*	*66,759*	*1,539*	*5,839*	*33,327*
2015	1.3% (1.0-2.0)	2.1% (1.6-3.1)	2.4% (1.7-3.6)	8.9% (7.0-12.8)	16.1% (11.7-24.8)	5.3% (3.8-8.3)	7.8% (5.4-12.3)	9.3% (6.7-14.5)
N	*20,575*	*8,347*	*4,357*	*10,461*	*20,575*	*8,347*	*4,357*	*10,461*
2016	0.8% (0.6-1.1)	1.1% (0.8-1.6)	5.9% (4.2-8.7)	11.3% (8.9-16.2)	*NA*	*NA*	*NA*	*NA*
N	43,068	10,948	2,829	13,608	43,068	10,948	2,829	13,608