FINAL REPORT: 2020 East Sand Island Avian Predation Rate Analysis

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Final Technical Report

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PROJECT SUMMARY

To address concerns of avian predation on Endangered Species Act (ESA) listed juvenile salmonids (*Oncorhynchus spp.*) in the Columbia River Estuary, the management plan "*Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary*" (hereafter "*Management Plan"* or "*Plan*") was developed and first implemented in 2008, with ongoing implementation through 2020. The primary goal of the *Management Plan* is to reduce the number of Caspian terns (*Hydroprogne caspia*) nesting on East Sand Island, the largest tern colony in the Columbia River Basin. The primary goal of this study was to provide the U.S. Army Corps of Engineers (USACE) and other regional stakeholders with information to evaluate the effectiveness of the *Plan* in reducing predation rates (percentage of available fish consumed) on ESA-listed juvenile salmonids by terns nesting on East Sand Island in 2020. More specifically, we generated population-specific (salmonid evolutionary significant units [ESU] or distinct population segments [DPS]) predation rates on passive integrated transponder (PIT) tagged 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, and temporal changes in fish availability to Caspian terns nesting on East Sand Island. We used previously published, standardized analytical methods to estimate predation rates on juvenile salmonids by Caspian terns on East Sand Island so that direct comparisons of predation rates in 2020 to those in years past were possible. To facilitate the review of results from 2020 relative to previous years, the organization and general content of this report is similar to that of past reports.

PIT tag recovery: Following the Caspian tern nesting season, a total of 4,595 PIT tags from 2020 migration year smolts (Chinook salmon [*O. tshawytscha*], coho salmon [*O. kisutch*], sockeye salmon [*O. nerka*], and steelhead trout [*O. mykiss*] tags combined) were recovered from both the prepared 1-acre (0.4 ha) main colony (n=3,705) and from a satellite colony located along the south beach (n=890) of East Sand Island where terns attempted to nest in 2020. Terns at both colony locations (main, south beach) failed to produce fledglings (young capable of flight) in 2020, but terns were present at both locations during the peak smolt out-migration period of April to June. Smolt PIT tags were detected by the USACE Fisheries Field Unit (FFU) by scanning the areas occupied by nesting terns on East Sand Island in 2020. Average annual PIT tag detection probabilities (proportion of deposited tags detected by researchers after the nesting season) were estimated at 0.67 (range during nesting season = 0.48–0.84) and 0.56 (0.11–0.94) on the main and south beach nesting sites, respectively. Average deposition probability (proportion of consumed tags deposited by terns during the nesting season) was assumed to be 0.71 (95% credible interval = 0.51–0.89) based on previously published studies of tern deposition on East Sand Island. All newly detected PIT tag codes recovered on the East Sand Island tern colony were uploaded to the PIT Tag Information System (PTAGIS) on 29 November 2020, thereby ensuring data was readily available to other researchers, managers, and the general public.

Predation rates: Predation rates on juvenile salmonids by Caspian terns nesting on East Sand Island in 2020 were the lowest recorded since terns began nesting on East Sand Island in 1999. Predation rate estimates by terns on the main colony ranged from 0.4% (95% credible interval = 0.2–0.8%) on Upper Columbia River spring Chinook to 3.6% (2.7–5.2) on Snake River steelhead. Predation rate estimates by terns that attempted to nest along the south beach of East Sand Island ranged from <0.1% on Upper Columbia River spring Chinook to 2.2% (1.3–3.7) on Snake River steelhead. Estimates of predation by all Caspian terns on East Sand Island, those from main and south beach nesting sites combined, ranged from 0.4% (0.2–0.9) on Upper Columbia River spring Chinook to 5.9% (4.5–8.1) on Snake River steelhead.

An investigation of Caspian tern predation rates based on the species of salmonid, the fish's rear-type (hatchery, wild), outmigration history (in-river, transported), and weekly abundance (density) indicated that multiple factors influenced smolt susceptibility to tern predation in 2020. Similar to results from years past, predation on steelhead DPSs were significantly higher than those of salmon ESUs, with estimates on steelhead DPSs that ranged from 4.5% (3.3–6.4) on Upper Columbia River steelhead to 5.9% (4.5–8.1) on Snake River steelhead, while the highest levels of predation on salmon ESUs were on Snake River sockeye at 1.1% (0.6–2.2). Also similar to years past, there was an inverse relationship between the weekly abundance of smolts and weekly predation rates, with predation rates being lower when smolt availability in the estuary was higher. Small sample size of tagged smolts, coupled with record low estimates of predation, prohibited meaningful comparisons of differences in predation rates by smolt rear-type and outmigration history in 2020. There was some evidence that hatchery Snake River steelhead were more susceptible to tern predation than their wild counterparts but results from years past indicate difference were minor and not statistically significantly when considered across multiple years (2006-2018). There was no evidence that fish with an in-river migration history were more susceptible to Caspian tern predation on East Sand Island than those that were transported in 2020, although in-river fish have been disproportionately consumed by East Sand Island terns in some but not all years past, depending on the ESU/DPS.

Management implications: An investigation of Caspian tern predation rates prior to (2000-2007) and following (2008-2020) implementation of management actions indicated that predation rates were significantly lower following management actions that reduced tern colony size on East Sand Island. A comparison of predation rates during 2017, 2018, and 2020, years with accurate and comparable estimates of predation and where tern colony size was at or near the target level of no more than 4,375 breeding pairs stipulated in the *Management Plan*, indicated that predation has been reduced by 65% to 76% on steelhead DPSs; reductions that meet or exceed those anticipated in the *Plan*. Reductions in Caspian tern predation rates by terns nesting on the main colony in 2020 were commensurate with reductions in tern colony size, with the lowest estimates of predation coincident with the lowest estimates of colony size. One unintended consequence of Caspian tern management actions on East Sand Island has been the large number of terns (several hundred to several thousand) that have attempted to nest outside of the prepared 1-acre nesting areas on East Sand Island, as well as nesting attempts by terns on Rice Island and other sites in the upper Columbia River estuary. In order to continue to meet and monitor the objectives of the *Management Plan,* we recommend: (1) continued use of Caspian tern nest dissuasion techniques to prevent tern nesting outside the designated colony area on East Sand Island, Rice Island, and other sites in the estuary; (2) continued monitoring of tern colonies throughout the estuary using previously established methods to ensure colony sizes do not exceed those stipulated in the *Plan*; (3) to continue to estimate predation rates on juvenile salmonids by terns using previously established methods at all active and incipient colony sites in the estuary to ensure impacts do not exceed acceptable levels.

BACKGROUND

Caspian tern (*Hydroprogne caspia*) predation has been identified as a factor that limits the survival of some Endangered Species Act (ESA) listed juvenile salmonid (*Oncorhynchus spp.*) populations in the Columbia River Basin (CRB; NMFS 2008, 2019). Previous research has demonstrated that Caspian terns nesting at the large breeding colony on East Sand Island near the mouth of the Columbia River were known to consume about 5 million juvenile salmonids per year and predation rates (percentage of available fish consumed) on ESA-listed salmonid populations were as high as 20% on Upper Columbia River and Snake River steelhead trout (*O. mykiss*) annually (Evans et al. 2016, 2019, Roby et al. 2021a). Predation losses by terns in the Columbia River Estuary also affect juvenile salmonids 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 Columbia River Power System (CRPS) and have a higher probability of survival to adulthood compared to those fish that have yet to complete outmigration (Roby et al. 2003, Payton et al. 2019).

While levels of tern predation on some ESA-listed ESUs/DPSs of juvenile salmonids have been high, there has also been substantial variability in predation rates. For instance, predation rates within and amongst ESUs/DPSs can vary significantly by year (Evans et al. 2012, Sebring et al. 2013) and by week within the same year (Evans et al. 2016). Past studies indicate that differences in colony size (number of breeding pairs) explain much of the variation in predation rates, with decreases in colony size associated with a decrease in predation rates. In addition to colony size, variation in predation rates have also been associated with a fish's rearing-type (hatchery, wild), outmigration history (e.g., transported vs. in-river migrants), abundance or density, and other factors, like river flows and ocean conditions, which affect the availability of alternative, non-salmonid prey in the estuary (Ryan et al. 2003, Lyon et al. 2014, Hostetter et al. 2012, Evans et al. 2016, Hostetter et al. 2021a). Collectively, results from these studies indicate that predation by Caspian terns is not only a substantial source of smolt mortality for some ESUs/DPSs, but also that predator-prey interactions are dynamic and may vary based on different biotic and abiotic conditions experience by smolts during outmigration through the Columbia River Estuary.

In response to Reasonable and Prudent Alternatives (RPAs) specified in Biological Opinions on the operation of the CRPS issued by the National Marine Fisheries Service (NMFS 2008, 2019), a management plan entitled "*Caspian Tern Management to Reduce Predation on Juvenile Salmonids in the Columbia River Estuary"* (hereafter "*Management Plan"* or *"Plan"*; USFWS 2005, USACE 2015) was developed to reduce the predation impacts of terns on smolts in the estuary, a plan that has been implemented in each year from 2008 to the present. The *Management Plan* aims to reduce the number of Caspian terns nesting on East Sand Island to 3,125–4,375 breeding pairs by reducing the area of suitable nesting habitat on East Sand Island to 1.0 acre (0.4 ha) and preventing terns from nesting elsewhere on the island. Reductions in colony size were then assumed to be commensurate with reductions in predation rates and, ultimately, increases in the survival of juvenile salmonids migrating through the estuary (USFWS 2005). Efforts to reduce colony sizes have been through non-lethal (i.e. passive and active nest dissuasion) strategies for Caspian terns on East Sand Island. The *Management Plan* also specifies that annual changes in predation rates be used to evaluate the efficacy of the *Plan* to reduce predation by terns on juvenile salmonids in the Columbia River Estuary (USFWS 2005, USACE 2015).

As part of the work presented here, we estimated predation rates by Caspian tern on East Sand Island on ESA-listed salmonid populations in 2020. Predation rates from 2020 were then compared with predation rate estimates from years past to evaluate the effectiveness of management actions in reducing predation rates through reductions in the size of East Sand Island Caspian tern colony. Since the reporting requirements associated with this study were the same as those of years past, and to facilitate review of results from 2020 to those of years past, the organization and general content of this report is similar to past reports (Evans et al. 2016, 2018, 2019).

METHODS

The hierarchical Bayesian model of Hostetter et al. (2015) was used to estimate predation rates based on recoveries of smolt PIT tags from the East Sand Island Caspian tern colony following the 2020 nesting season. Predation rate estimates or probabilities (percentage or proportion of available tagged fish consumed) were calculated using the proportion of smolt PIT tags found on-colony from the available population of PIT-tagged fish found in-river (i.e., smolt availability), and then adjusting that rate by the probability that a consumed PIT tag was subsequently deposited on that colony (referred to as “deposition” probability) and then detected by researchers following the nesting season (referred to as “detection” probability; see also Hostetter et al. 2015).

PIT-Tag Recovery

The USACE Fisheries Field Unit (FFU) recovered smolt PIT tags on the East Sand Island Caspian tern colony following the 2020 nesting season in October and November. Methods to recovery tags in 2020 were the same as those used in years past (see Evans et al. 2012). In brief, PIT tag antennas were used to systematically scan (referred to as a “pass”) the prepared 1-acre colony area on East Sand Island. Multiple passes (n = 7) were conducted until fewer than 5% unique (newly detected) tags were recovered during a pass. In addition to electronic detection, PIT tags were also physically removed using a tow behind sweeper magnet. The physical removal of PIT tags reduces tag collision, a phenomenon that renders PIT tags near each other undetectable using electronics. The physical removal of PIT tags (and subsequent hand scanning of each tag to acquire its unique code) increases PIT tag detections at sites where tag densities are high, like on the East Sand Caspian tern colony (Evans et al. 2016). In addition to scanning for PIT tags on the 1-acre main colony (hereafter “main” colony), Caspian terns also attempted to nest along the south beach of East Sand Island (hereafter “south beach”), where large numbers Caspian terns (hundreds to thousands, depending on the date of the survey during the breeding season) were counted in 2020 (Tidwell 2020). Handheld scanners were used by USACE FFU to detect PIT tag along the south beach following the breeding season in October. Scanning efforts at this incipient nesting site were haphazard, with at least one full pass of the south beach conducted (K. Tidwell, USACE, personal communication). All tag codes were uploaded to a central storage drive at the completion of each scanning session, along with metadata regarding the recovery date and pass number. Following validation and removal of duplicate records, all newly detected tag codes were reported to the PIT Tag Information System (PTAGIS) on 29 November 2020 using guidelines and protocols established by the PIT-tag Steering Committee (PSFMC 2020).

Smolt Availability

Smolt availability to Caspian terns nesting on East Sand Island were limited to those fish last interrogated alive passing Bonneville Dam (river kilometer [Rkm] 234) on the Lower Columbia River or fish captured at Lower Granite Dam (Rkm 695), Little Goose Dam (Rkm 635), or Lower Monumental Dam (Rkm 589) on lower Snake River that were transported and release below Bonneville Dam (*Figure 1*; see also Roby et al. 2021b). PIT-tagged smolts originating upstream of Sullivan Dam (Rkm 205) on the Willamette River were not included in predation rate analyses in 2020, however, due to inadequate sample sizes of available smolt (less than 500 tagged smolts; see *below*). Adequate numbers of PIT-tagged smolts passing Sullivan Dam, however, were available in some, but not all, years past (see *Appendix A, Table A.1*).

Figure 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 migrants) and Skamania landing (release site for transported fish). Interrogation and release sites were used to determine the availability of PIT-tagged fish to terns nesting on East Sand Island in the Columbia River Estuary. Figure from Evans et al. 2016.

Smolt availability was based on PIT-tagged smolts detected from 1 March to 31 August, which reflects the period of overlap between active smolt out-migration and the breeding season for Caspian terns on East Sand Island in most years (Evans et al. 2012). PIT-tagged fish were grouped by ESA-listed ESU/DPS, representing a unique combination of the species (steelhead trout, Chinook salmon [*O. tshawytscha*], sockeye salmon [*O. nerka*], coho salmon [O. kisutch]), run-type (spring, summer, fall, or winter), and river-of-origin (Snake River, Upper Columbia River, Middle Columbia River, or Willamette River). The classification of fish from each ESU/DPS followed that of NOAA Fisheries (2014) and was based on the release location and rear-type (hatchery, wild) of tagged fish relative to the geographic boundary of each ESU/DPS. Fish within each ESU/DPS were further grouped by week. Tagging and in-river detection (recapture) histories for each PIT-tagged fish were retrieved from PTAGIS (PSFMC 2020).

In addition to fish volitionally interrogated passing PIT tag arrays at Bonneville Dam (collectively referred to as "in-river migrants"), PIT-tagged smolts that were loaded into barges at dams on the lower Snake River and transported and release below Bonneville Dam near Skamania Landing (Rkm 225) were also included in predation rate analyses (referred to as "transported fish"). Availability of transported fish was based on fish collected at the Lower Granite Dam, Little Goose Dam, or Lower Monumental Dam 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 antenna site detections (e.g., detected entering a raceway) and date at each JBS. Downstream interrogation histories, JBS facility collection reports, and other sources (e.g., NOAA Fisheries, USACE, and Fish Passage Center 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 were not included in predation rate analyses (see also Evans et al. 2016).

Not all ESA-listed salmonid ESUs/DPSs in the CRB were included in predation rate analyses evaluated herein. More specifically, those ESA-listed populations that originate wholly or partially below Bonneville and Sullivan dams were excluded and some populations that originate upstream of Bonneville or Sullivan dams were not adequately PIT-tagged in 2020 (see also *Predation Rate Estimates below*). In 2020, these ESUs/DPSs included: (1) Lower Columbia River steelhead, (2) Lower Columbia River Chinook, (3) Lower Columbia River coho, (4) Columbia River chum [*O. keta*], (5) Upper Willamette River Spring Chinook, and (6) Willamette River winter-run steelhead. In addition, unlisted salmonid stocks and non-salmonid fishes of conservation concern (e.g., Pacific lamprey [*Lampetra tridentate*], Eulachon [*Thaleichthys pacificus*], white sturgeon [*Acipenser transmontanus*], coastal cutthroat trout [*O. clarki clarki*]) were also available as prey to Caspian terns on East Sand Island (Lyons et al. 2014). Small numbers of these other fish species/populations were PIT-tagged, depending on the species, but predation rate analysis of these groups of fish were beyond the scope of this study.

Deposition & Detection Probabilities

Not all PIT tags that are ingested by colonial waterbirds are subsequently deposited on their nesting colony (Hostetter et al. 2015). For instance, a portion of PIT tags consumed by birds are damaged and rendered unreadable following digestion or are regurgitated off-colony at loafing, staging, or other areas used by birds during the breeding season. Deposition probability (i.e. probability that a tag consumed by a nesting bird is deposited on its breeding colony) was previously estimated by intentionally feeding PIT-tagged fish to nesting Caspian terns on East Sand Island with the proportion of known ingested tags subsequently recovered follow the nesting season used to estimate deposition probabilities (see also Hostetter et al. 2015). The distribution of the median deposition probability derived from those studies was 0.71 (95% credible interval {CRI}= 0.51–0.89). Results from Caspian tern deposition studies indicated that deposition probabilities did not vary significantly within or between years, so deposition probabilities from past studies were used in 2020.

Not all PIT tags deposited by Caspian terns on their nesting colony are subsequently detected by researchers after the nesting season (Ryan et al. 2003, Evans et al. 2012, Hostetter et al. 2015). For example, tags can be blown off the colony during windstorms, 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 is detected by researchers after the nesting season) often vary significantly within and between nesting seasons, variation that necessitates a direct measure of detection probabilities for each colony, in each study year (Evans et al. 2012, Hostetter et al. 2015, Payton et al. 2019). To address this, PIT tags with known tag codes were intentionally sown (hereafter referred to as "control tags") by the USACE FFU on the East Sand Island Caspian tern colony prior to and following the nesting season to quantify PIT tag detection probability during the nesting season. Control tags were the same size and type as those used to mark most juvenile salmonids from the Columbia River basin (12-mm [length] × 2-mm [width], full duplex). During each discrete sowing period, control tags were haphazardly sown throughout the area occupied by nesting terns. Detections (i.e. recoveries) of control tags during scanning efforts after the breeding season were then used to model the probability of detecting tags that are deposited at different times during the breeding season via logistic regression. Equal numbers of control tags were sown during each discrete time period and sample sizes were selected by considering historic sample sizes. This approach allows direct comparisons of independent detection probabilities, with similar precision between years (see also Evans et al. 2016 and Payton et al. 2019). In 2020, pre-season control tags were sown on both the main (n=200) and south beach (n=200) nesting sites, but only post-season tags were sown on the main colony (n=200). Post-season detection probability estimates at satellite colonies on East Sand Island in years past were limited to a single year (in 2016) where 0.94 or 94% of sown tags were recovered. Given the lack of historic estimates and to ensure calculated predation rates do not overestimate the proportion of consumed fish, post-season detection on the south beach colony was assumed to be near 100% (i.e. we assume 50 tags recovered out of 51 tags sown) in 2020.

Predation Rate Estimates

Following the methodology of Hostetter et al. (2015), predation rates were modeled independently for each salmonid ESU/DPS and year. The probability of recovering a PIT tag from a smolt 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):

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

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

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

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. 2016, Payton et al. 2019). 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:

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

and $\varepsilon_w \sim normal(0,\ \sigma_\theta^2)\ \forall\ w$. We placed non-informative priors on these two hyperparameters: logit^{-1} $(\mu_\theta) \sim uniform(0,1)$ 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 to improve precision of the estimates.

Informative Beta priors were used to model deposition probability(ϕ). The shape parameters (α, β) are dependent on the predator species and for Caspian terns we assumed α = 16.20 and β = 6.55 (see also Hostetter et al. 2015).

Weekly predation estimates were defined as the estimated number of PIT-tagged smolts consumed divided by the total number available 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 available:

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

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 (Payton et al. 2019).

Abundance and run-timing: To investigate if changes in the relative abundance and run-timing of PIT-tagged smolts in 2020 were associated with differences in predation rates, weekly estimates of predation were plotted relative to the run-timing and abundance (number) of smolts to investigate intra-annual trends in predation within and across each ESU/DPS.

Rear-type and outmigration history comparisons: To investigate potential differences in predation probabilities based on fish's rear-type (hatchery vs. wild) and outmigration history (in-river migrants vs. transported migrants) in 2020, we used a previously developed Bayesian approach that acknowledges the autocorrelative nature of predation rates (as outlined *above*) while additionally allowing for the common estimate of deposition and detection across cohorts or unique groups of fish. Predation rates specific to each cohort (hatchery, wild, in-river, transported) were developed by partitioning the release and recovery of tags 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*. Annual and weekly predation probabilities for each cohort were then calculated simultaneously, with shared estimates of deposition and detection, using the autoregressive methods described *above*. To evaluate differences in predation rates more thoroughly among cohorts we accessed the prevalence of differences by category (rear-type, outmigration history) across multiple years of data. We defined v_0 to be the cohorts of wild fish and transported fish for the rearing and migration history analysis, respectively. Thus v_1 respectively represented hatchery and in-river fish. We defined ρ to be the average proportional difference in the log-odds of predation among cohorts over the entire study period. 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. A random error term was included to account for extraneous variation of the proportional difference in log-odds among weeks. Therefore, we assumed:

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

and

$$k_{iv_1} \sim Binomial\left(n_{iv_1}, logit^{-1}\left((\rho + \eta_i) * \ logit(\theta_i)\right) * \phi * \psi_i\right)$$

where $\eta_i \sim normal(0, \sigma_\rho)$. Credible intervals for ρ which overlapped 1 were defined as not statistically significant. This test was applied to all appropriate ESUs/DPSs for each comparison.

Models were analyzed using the software STAN (Stan Development Team), accessed through R version 3.6.2 (R Development Core Team 2015), and using the rstan package (version 2.19.3). To simulate random draws from the joint posterior distribution, we ran four Hamiltonian Monte Carlo (HMC) Markov Chain processes. Each chain contained 4,000 warm-up iterations followed by 4,000 posterior iterations thinned by a factor of 4. Chain convergence was visually evaluated and verified using the Gelman-Rubin statistic (Gelman et al. 2013); only chains with zero reported divergent transitions were accepted. Posterior predictive checks compared simulated and observed annual aggregate raw recapture and recovery numbers to ensure model estimates reflected the observed data. Reported estimates represent simulated posterior medians along with 95% highest (posterior) density intervals (95% CRI) calculated using the HDInterval package (version 0.2.0). 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 (Evans et al. 2012).

Predation impacts prior to and following management actions: It is expected that the management of Caspian terns on East Sand Island will have a measurable effect on the level of predation, whereby reductions in colony size will lead to reductions in predation rates. The goal of management is to reduce the size of East Sand Island Caspian tern colony to 3,125–4,375 breeding pairs (USACE 2015), a reduction of approximately 60% from the pre-management average colony size of 9,080 breeding pairs (Roby et al.2021a). Reductions in colony size were then assumed to be commensurate with reductions in predation rate on juvenile salmonids in the Columbia River Estuary (i.e. an approximately 60% reduction in predation rates). To evaluate this, we compared ESU/DPS-specific predation rates prior to and during management periods on East Sand Island. Management periods were defined as those during 2000-2007 (pre-management), those during 2008-2018, 2020 (management), and those during 2017-18, 2020 (recent management). The management time period was considered to have started in 2008, the first year habitat was reduced on East Sand Island to reduce colony size (USACE 2015). Recent management is defined as the three most recent years where the target colony size goal was met or nearly so and years where accurate and comparable estimates of predation rates were available.

To further monitor the effectiveness of the *Management Plan* to reduce predation rates by reducing the size of East Sand Island Caspian tern colony, the methods of Evans et al. (2016) were used to estimate per capita (per bird) predation rates. Per capita predation rates were calculated by dividing the annual ESU/DPS-specific predation rate by the peak measure of colony size (i.e. number of breeding pairs):

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

where C_y is the peak colony size in year, *y.* The relationship between colony size and predation rates across years was estimated from a post-hoc evaluation of predation rate estimates. That is, we repeatedly simulated random samples from the posterior distribution of each year's predation rate and calculated least squares regression lines. The relationship was then be inferred from the median value of the collection of simulated posterior distribution samples with the slope of the resulting distribution and the 95% CRI defined as the 2.5th and 97.5th quantiles. Statistical significance was identified by the credibility interval of the slope parameter not overlapping with zero.

Estimates of the peak colony size (2,487 breeding pairs) on the main East Sand Island Caspian tern colony in 2020 were provided by USACE FFU based on a count that occurred on June 19, the highest of three counts conducted between June 19 and July 8, 2020 (K. Tidwell, USACE, personal communication). Due to travel restrictions imposed to control the outbreak of the coronavirus during the spring of 2020, the number of surveys conducted by the USACE FFU on East Sand Island was reduced and delayed (right shifted) relative to years past. There were no estimates of the number of breeding pairs on the south beach, although of the total number of adult terns counted on areas outside of the main colony ranged from 213 to 2,600 per survey during 7 May to 6 August (Tidwell 2020).

RESULT & DISCUSSION

PIT-Tag Recovery

In total, 4,595 PIT tags from 2020 migration years smolt (Chinook, coho, sockeye, and steelhead tags combined) were recovered by the USACE FFU on nesting sites used by Caspian terns on East Sand Island. Of these, 3,705 and 890 tags were recovered from the main and south beach nesting sites, respectively (*Table 1*). The total number of smolt tags recovered from the East Sand Island tern colony in 2020 was the lowest number recorded since the colony was first scanned in 1999. The number of smolt tags recovered in 2020 was only slightly lower than the number recovered during 2019 (n=4,831), and substantially lower than the number of tags recovered in all other years (annual range during 2000-2018 = 8,407 to 44,947 tagged smolts; Evans et al. 2019).

Satellite Caspian tern colonies on East Sand Island have been observed in most years since 2012, when the amount of tern nesting habitat provided for terns on East Sand was reduced to a point where it no longer accommodated all individual's intent on nesting there (Roby et al. 2021a). In years where large numbers of terns have attempted to nest at satellite colonies during the peak smolt outmigration period (April to June), smolt PIT tags have been recovered and were included in predation rate estimates (e.g., in 2015 and 2016). The number of tags recovered on satellite colonies in years past (annual range = 201–420) were smaller than those in 2020 (n=890; *Table 1*). Estimates of predation rates by terns that attempted to nest at satellite colonies should be interpreted cautiously, however, because terns were actively dissuaded from nesting in these sites and because not all terns were known to be breeding adults. Due to these and other uncertainties regarding detection and deposition probabilities at the south beach nesting site (see *below*), we report estimates of predation for the main and south beach nesting sites separately and as a combined (cumulative) estimate for all Caspian terns on East Sand Island (see *Predation Rate Estimates below*).

Table 1. Numbers of 2020 migration year PIT-tagged smolts (Chinook salmon, coho salmon, sockeye salmon, and steelhead trout) recovered on the East Sand Island Caspian tern colony following the 2020 nesting season. Tags are provided separately for those recovered on the main and south beach nesting sites. Data collected by the USACE FFU (see Methods).

	Number of PIT Tags Recovered				
Location	Steelhead	Chinook	Coho	Sockeye	TOTAL
Main	2,477	1,033	142	53	3,705
South Beach	576	276	28	10	890
TOTAL	3,053	1,309	170	63	4,595

Detection & Deposition Probabilities

Recoveries of control PIT tags sown on the main East Sand Island Caspian tern nesting site (n = 400) resulted in an average detection probability estimate of 0.67 (seasonal range = 0.48–0.84) during the 2020 breeding season (*Table 2*). The estimated average annual detection probability in 2020 was lower than those in recent years (range of annual averages = 0.73–0.87 during 2016-2018) but within the range observed in several other years (range of annual averages = 0.64–0.77 during 2011-2015). In 2020, tags were not recovered during a continuous period following the breeding season, but rather during two discrete periods (15 October and 18-19 November), which contributed to the lower average annual detection probabilities observed because the longer tags remain on-colony the lower the probability of detection (Evans et al. 2012, Payton et al. 2019). Estimated average annual detection probability on the south beach nesting site was lower than that on main nesting site, with an average annual estimate of 0.56 (seasonal range = 0.11–0.94; *Table 2*). Due to the low early-nesting season detection probability estimate of 0.11, the inferred late-season estimate of 0.94 had little influence on predation probabilities because most PIT-tagged smolt were consumed by terns earlier in the nesting season. Lower average annual detection probabilities on the south beach nesting site are not surprising given tags were deposited near the wrack line, a location where tags are presumably more likely to be removed (lost) by high tides and erosion, and due to reduced scanning effort on the south beach nesting site relative to the main nesting colony.

Table 2. Average annual PIT tag deposition (95% credible interval) and detection (range; first-to-last week of nesting season) probability estimates for Caspian tern nesting sites on East Sand Island in 2020. Deposition estimates are those reported by Hostetter et al. (2015).

Location	Deposition Probability	Detection Probability
Main	0.71 (0.51-0.89)	0.67 (0.48-0.84)
South Beach	0.71 (0.51-0.89)	0.56 (0.11-0.94) [1]

[1] Post-season detection probability inferred (see Methods).

Based on previous studies that empirically measured deposition probabilities for Caspian terns nesting on East Sand Island, deposition probabilities were assumed to be 0.71 (95% CRI = 0.51–0.89; see Hostetter et al. 2015) in 2020 (*Table 2 above*). This estimate of deposition probability was applied to tags recovered from both the main and south beach nesting sites in predation rate estimates. Some proportion of tags deposited by terns on the south beach, however, were potentially from non-breeding or failed breeding adults on the main colony. As such, the actual deposition probability of PIT tags by terns on the south beach may differ from the assumed deposition probability to an unknown degree. Since each PIT tag represents a unique fish and since terns were attending nests and laying eggs on the south beach (Tidwell 2020), however, it is likely that the vast majority of tags recovered on the south beach were those deposited by breeding Caspian terns in 2020.

Predation Rate Estimates

Predation rate estimates by Caspian terns that attempted to nest on the 1-acre main colony area on East Sand Island in 2020 ranged from 0.4% (95% CRI= 0.2–0.8%) on Upper Columbia River spring Chinook to 3.6% (2.7–5.2) on Snake River steelhead (*Table 3*). Predation rate estimates by Caspian terns that attempted to nest along the south beach of East Sand Island ranged from <0.1% on Upper Columbia River spring Chinook to 2.2% (1.3–3.7) on Snake River steelhead (*Table 3*). Trends in predation by terns nesting on the main and south beach sites were very similar across salmonid species and ESUs/DPSs (*Table 3*). Estimates of predation by all Caspian terns nesting on East Sand Island, those from both main and south beach nesting sites combined, ranged from 0.4% (0.2–0.9) on Upper Columbia River spring Chinook to 5.9% (4.5–8.1) on Snake River steelhead (*Table 3*). Estimates of predation by all Caspian terns on East Sand Island in 2020 were the lowest recorded since the colony formed on East Sand Island in 1999 (see *Appendix* for historical estimates of tern predation).

Similar to results from years past, Caspian tern predation rate estimates varied considerably by salmonid ESU/DPS in 2020, with predation rate estimates significantly higher on steelhead DPSs compared with salmon ESUs. For instance, the highest predation rate on a salmon ESU in 2020 was on Snake River sockeye at 1.1% (0.6–2.2), while predation rates on steelhead DPSs ranged from 4.5% (3.3–6.4) on Upper Columbia River steelhead to 5.9% (4.5–8.1) on Snake River steelhead (*Table 3*). The greater susceptibility of juvenile steelhead to Caspian tern predation relative to salmon is likely due to the greater size and nutritional value of steelhead smolts (Lyons 2010), plus the greater surface-orientation of steelhead during out-migration compared to other species of salmonid (Beeman and Maul 2004), factors that increase their risk of predation by plunge-diving predators like terns (see also Hostetter et al. 2021a).

Table 3. Estimated predation rates (95% credible interval) of PIT-tagged salmonid smolts last detected at Bonneville Dam (number available) on the Columbia River (In-river) or released from transportation barges (Transported) below Bonneville Dam by Caspian terns on the main and south beach nesting sites on East Sand Island in 2020. Predation rates were adjusted to account for tag loss due to on-colony PIT tag detection and deposition probabilities (see Table 2 above). 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.

				Predation Rates					
		Number Available		Main		South Beach		ALL	
ESU/DPS [1]	ESA [2]	In-river	Transported	In-river	Transported	In-river	Transported	In-river	Transported
SR Sockeye	E	2,122	1,065	0.9% (0.4-1.7)	0.3% (0.1-1.1)	0.2% (0.1-0.9)	0.1% (<0.1-1.0)	1.1% (0.6-2.2)	0.4% (0.1-1.6)
SR Spr/Sum Chinook	T	20,246	19,125	0.5% (0.3-0.8)	0.4% (0.3-0.7)	0.1% (<0.1-0.3)	0.7% (0.4-1.2)	0.7% (0.5-1.1)	1.1% (0.9-1.7)
UCR Spr Chinook	E	4,895		0.4% (0.2-0.8)		<0.1%		0.4% (0.2-0.9)	
SR Fall Chinook	T	3,389	3,354	0.5% (0.2-1.0)	0.2% (0.1-0.6)	0.2% (<0.1-0.7)	0.1% (<0.1-0.3)	0.7% (0.3-1.4)	0.3% (0.1-0.7)
SR Steelhead	T	11,868	5,730	3.6% (2.7-5.2)	3.3% (2.4-5.0)	2.2% (1.3-3.7)	1.9% (1.0-3.5)	5.9% (4.5-8.1)	5.3% (3.9-7.5)
UCR Steelhead	T	5,894		3.2% (2.3-4.8)		1.2% (0.6-2.3)		4.5% (3.3-6.4)	
MCR Steelhead	T	3,157		3.8% (2.6-6.0)		1.4% (0.6-3.1)		5.4% (3.8-7.9)	

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

Run-timing and abundance: An investigation of smolt run-timing, based on the passage date of PIT-tagged fish at Bonneville Dam, indicated that most tagged smolts were available as prey to Caspian terns nesting on East Sand Island in 2020 (*Figure 2*). Due to travel restrictions and safety concerns associated with the coronavirus outbreak, visits to East Sand Island to dissuade terns from nesting outside of the main colony started on 7 May 2020 (later than originally planned) and estimates of the number of breeding pairs on the main colony did not commence until 19 June (later than original planned; see also Tidwell 2020). Due to a later than anticipated start date, comparisons of weekly predation rates to weekly estimates of colony size were not available in 2020, but weekly predation rate estimates indicate that East Sand Island Caspian terns were consuming smolts as early as the week beginning 16 April and as late at week ending July 8, 2020 (*Figure 2*). East Sand Island Caspian terns on both the main and south beach nesting sites also apparently failed to produce fledglings in 2020 (K. Tidell, USACE, personal communication), so the length of the breeding season was, on average, shorter than in years when adults remained on-colony to rear young capable of flight. It is unknown to what degree colony failure in 2020 influenced predation impacts on smolts, but the vast majority of the PIT-tagged smolts from the ESUs/DPSs evaluated in this study, which were predominately yearlings, were available as prey to terns nesting on East Sand Island during April to June (*Figure 2*), prior to the traditional late chick rearing and fledging period of July and August (Roby e al. 2021a). Impacts to Lower Columbia River Chinook (LCR), which are predominately sub-yearlings that migrate in July and August, were not evaluated as part of this study (see Methods) but impacts on LCR Chinook might have been lower in 2020 relative to years when the colony successfully fledged young.

An investigation of weekly predation impacts also indicated that estimated predation rates were generally lower when the largest number or greatest density of PIT-tagged smolts were available as prey to terns in the estuary (*Figure 2*). For instance, estimated East Sand Island Caspian tern predation rates on steelhead DPSs and salmon ESUs were the lowest during the peak of the run in May and slightly higher before (April) and especially after (June) the peak passage period. Results are consistent with those of years past and indicate an inverse relationship between prey density and Caspian tern predation rates. In a multiyear analysis of per capita predation rates by East Sand Island Caspian terns on steelhead smolts, Hostetter et al. (2021b) also observed an inverse relationship between prey abundance and tern predation rates that was consistent with a Type II functional response (also referred to as prey swamping; Ims 1990), whereby the probability of an individual fish being consumed decreases as the number of available prey increases. Results suggest that Caspian tern predation rates are highest when juvenile salmonids are relatively scarce, which has been attributed to the selective foraging strategy of terns and their reliance of juvenile salmonids as a food source (see Hostetter et al. 2021b for a more detailed discussion).

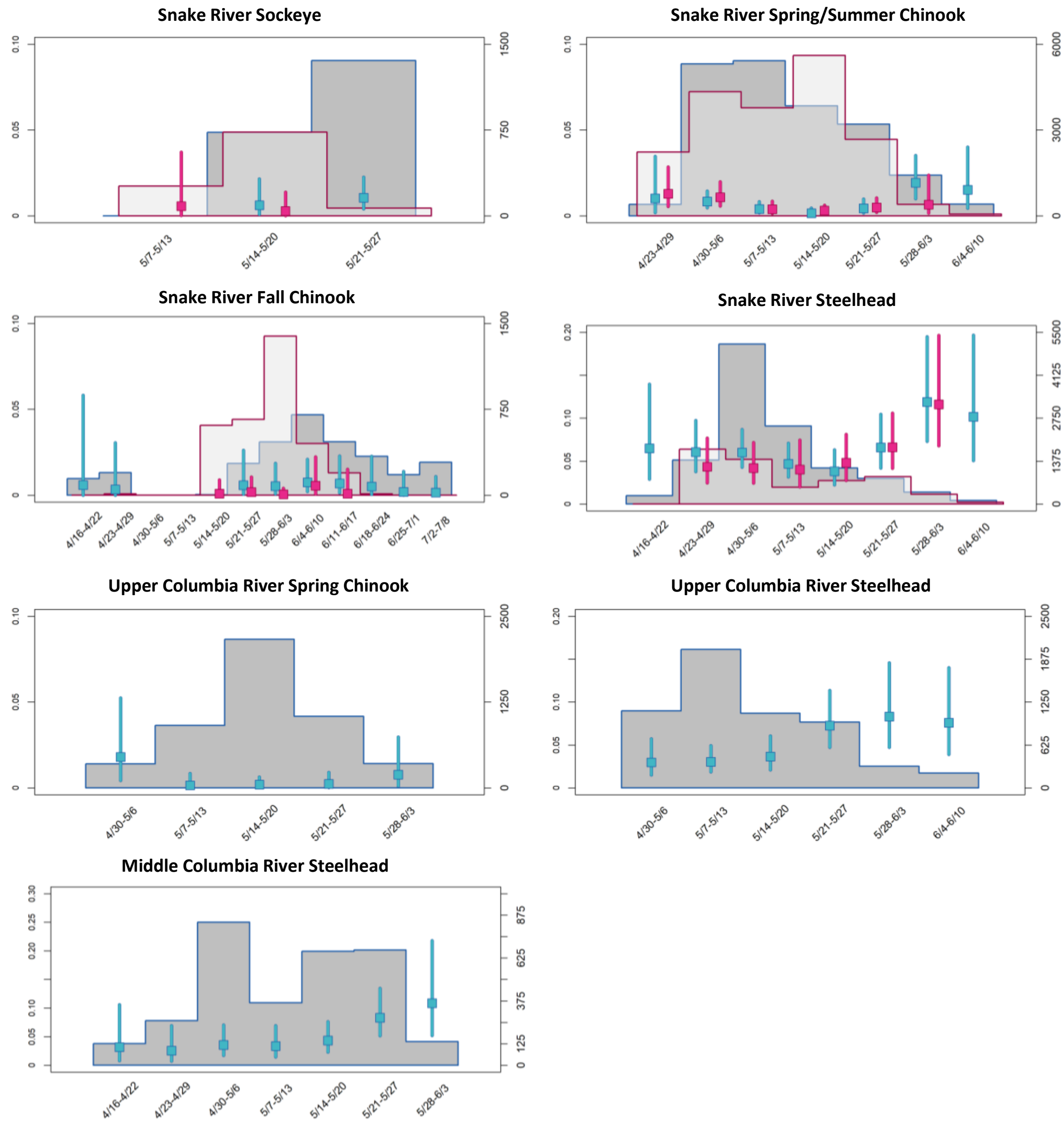

Figure 2. Estimated weekly predation rates (y_1; proportion of fish consumed) by Caspian nesting on East Sand Island on in-river (blue squares) and transported (red squares) PIT-tagged juvenile salmonids last detected passing Bonneville Dam (y_2; number available, dark gray bars) or transported from the lower Snake River (y^2; number available; light gray bars) during 2020. Error bars represent 95% credible intervals for predation rates.

Rear-type and outmigration history comparisons: Estimates of the relative susceptibility of smolts based their rearing-type (hatchery, wild) and outmigration history (in-river, transported) were constrained by small samples of PIT-tagged smolts and low estimates of predation in 2020. For those groups with adequate sample sizes, there was some evidence that hatchery Snake River steelhead were more susceptible to predation by East Sand Island Caspian terns compared with their wild counterparts in

2020 (*Table 5*). No difference in relative susceptibility, however, was observed between hatchery and wild Snake River steelhead based on a multiyear (2006-2018) analysis of odds ratios (*Table 5*). An investigation of weekly and annual trends over the course of the last 13 years (2006-2018), however, indicated that hatchery Snake River spring/summer Chinook and hatchery Upper Columbia River spring Chinook were, on average, more susceptible to East Sand Island tern predation compared to their wild counterparts (*Table 5*; see Roby et al. 2021a). Data from other studies indicates that both behavior and physical traits associated with hatchery-rearing may enhance susceptibility of juvenile salmonids to predation (Olla and Davis 1989, Fritts et al. 2007, Hostetter et al. 2012, Hostetter et al. 2021a). Evans et al. (2016) attributed difference in the vulnerability of hatchery spring/summer Chinook salmon to East Sand Island 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 associations between predation rates and 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 an estimated 12% (95% CRI = 11.9–12.6%) for every 10-mm increase in fork-length (Evans et al. 2016). Hostetter et al. (2012) also found evidence of size-selectivity in Caspian terns nesting at Crescent Island in McNary Reservoir (lower Columbia River), with larger fish more likely to be preyed upon than smaller fish up to about 175 mm, at which point susceptibility to tern predation was estimated to be similar for fish up to about 225 mm. Tern predation rates on fish > 225 mm, however, was estimated to rapidly decrease as fish reached or exceeded the maximum prey size for Caspian terns (about 275 mm: Cuthbert and Wires 1999; Lyons 2010, Hostetter et al. 2021a).

Table 5. Relative susceptibility of PIT-tagged smolts by rear-type and outmigration history to predation by Caspian terns nesting on East Sand Island during 2006-2018 (average across all years) and in 2020. 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 low rates of predation rates (< 1.0% of each category) prevented comparisons in 2020. Asterisk denotes a statistical significance difference. See Roby et al. (2021a) for weekly and year-specific results during 2006-2018.

Rear-type Comparisons	2006-2018 [1]	2020
Snake River Spr/Sum Chinook	0.38 (0.31-0.46)*	-
Upper Columbia River Spring Chinook	0.24 (0.07-0.38)*	-
Snake River Steelhead	1.02 (0.94-1.11)	0.38 (0-0.79)*
Upper Columbia River Steelhead	0.89 (0.75-1.04)	-
Outmigration History Comparisons	2006-2018 [1]	2020
Snake River Spr/Sum Chinook	0.85 (0.78-0.91)*	0.97 (0.45-1.53)
Snake River Fall Chinook	0.92 (0.81-1.04)	-
Snake River Sockeye	0.65 (0.43-0.85)*	-
Snake River Steelhead	0.88 (0.82-0.94)*	0.86 (0.60-1.19)

[1] *Comparable estimates of predation rates in 2019 were not available.*

For those ESUs/DPSs with adequate sample sizes and sufficient levels of predation, there was no evidence that Caspian terns disproportionately consumed in-river migrating fish from the Snake River relative to transported migrants from the Snake River in 2020 (*Table 5* and *Figure 5 above*). An investigation of the transported versus in-river migrant data over the course of the last thirteen years (2006-2018) indicated that in-river Snake River spring/summer Chinook, sockeye, and steelhead were, on average, more likely to be consumed then their transported counterparts (*Table 5* above; see also *Appendix, Table A.2* for annual estimates in years past). Odds-ratios were close to 1.0 (no preference), however, with no consistent trend identified across all weeks and years (see Roby et al. 2021a for weekly and year-specific estimates during 2006-2018). Collectively, results indicate that in-river fish were more likely to be consumed than transported fish in most weeks and years, but those differences in susceptibly were relatively small and inconsistent. Roby et al. (2021a) 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.

Predation impacts prior to and following management actions: An investigation of Caspian tern predation rates prior to (2000-2007) and during (2008-2020) management actions indicated that predation rates were significantly lower during implementation of management actions that reduced colony size on East Sand Island (*Table 4*). For instance, average annual predation rates on Snake River steelhead during 2000-2007 were estimated to be 25.3% (95% CRI = 22.7–28.3%) compared with 10.3% (9.4–11.4) during implementation of management actions that reduced the number of terns nesting on East Sand Island. Significant reductions in predation rates were observed in nearly all ESA-listed ESUs/DPSs evaluated (*Table 4*), with the exception of Upper Willamette River spring Chinook, where no statistically significant difference by management period was observed. Insufficient samples sizes of Upper Willamette River spring Chinook, Snake River sockeye, and some other ESUs/DPSs (depending on year), however, limited comparisons across all years within each management period (*Table 4*; see also *Appendix, Table A.1* for annual estimates in years past).

Table 4. Average annual predation rates (95% credible intervals) by Caspian terns nesting on East Sand Island prior to and during 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 the pre-management and management periods. Dash line indicates inadequate sample sized during that time period.

	Pre-management	**Management**	**Recent-Management**
Salmonid ESU/DPS	2000-2007	2008-2018 [1], 2020	2017-2018 [1], 2020
Snake River Sockeye [2]	-	1.8% (1.4-2.2)	1.6% (1.3-2.0)
Snake River Spr/Sum Chinook	5.2% (4.6-6.0)	2.0% (1.8-2.2)*	0.9% (0.7-1.2)*
Upper Columbia River Spr Chinook	4.3% (3.7-5.1)	1.8% (1.5-2.1)*	1.1% (0.7-1.4)*
Snake River Fall Chinook	2.9% (2.4-3.4)	1.0% (0.8-1.1)*	0.5% (0.3-0.8)*
Upper Willamette River Spr Chinook [3]	1.4% (0.7-2.4)	1.7% (1.3-2.1)	-
Snake River Steelhead	25.3% (22.7-28.3)	10.3% (9.4-11.4)*	6.1% (5.1-7.4)*
Upper Columbia River Steelhead [4]	17.2% (15.2-19.5)	10.5% (9.5-11.6)*	5.9% (4.8-7.3)*
Middle Columbia River Steelhead [5]	17.1% (14.0-22.0)	9.7% (8.7-10.9)*	6.5% (5.0-8.1)*

[1] Comparable estimates of predation rates were not available in 2019.
[2] Predation rate estimates were not available in 2000-2008 and in 2016-2017 due to insufficient sample sizes.
[3] Predation rate estimates were not available in 2000-2006 and in 2017-2018, 2020 due to insufficient sample sizes.
[4] Predation rate estimates were not available in 2000-2002 due to insufficient sample sizes.
[5] Predation rate estimates were not available in 2000-2006 due to insufficient sample sizes.

A comparisons of predation rates during 2017, 2018, and 2020, years with accurate and comparable estimates of predation and where the size of the East Sand Island tern colony was at or near the target specified in the *Management Plan* (4,375 breeding pairs; *Figure 2*), indicated that predation rates on steelhead DPSs have been reduced by 65% to 76%, depending on the DPS. For instance, average annual predation rates by East Sand Island Caspian terns declined from 17.2% on Upper Columbia River steelhead and 25.3% on Snake River steelhead prior to management to 5.9% and 6.1% during recent management, respectively (see *Table 4 above*). Results indicate that the *Management Plan* has achieved the targeted reductions of approximately 60% in predation rates on steelhead populations. Similar proportionate reductions in predation were also observed in salmon ESUs (*Table 4*), indicating that East Sand Island tern predation on both steelhead and salmon have been substantially reduced in recent years.

In 2019, the management goal for Caspian tern colony size on East Sand Island (3,125–4,375 breeding pairs) was achieved, with an estimated 3,860 breeding pairs observed during the peak nesting period (Roby et al. 2021a). Comparable estimates of predation rates in 2019, however, were not available for use in this study because standardized methods were not used in that year. More specifically, previously developed methods to classify PIT-tagged smolts by salmonid ESU/DPS were not followed resulting in smaller sample sizes of available smolts and predation rate calculations did not follow the stated methods, with estimates consistently biased upward relative to estimates calculated using the stated methods. For example, Stachura et al. (2020) estimated that East Sand Island Caspian tern predation rates on in-river migrating Snake River steelhead in 2019 were 7.6% (4.9–12.0) compared to an estimated 5.1% (3.9–7.5) generated using the stated methods (authors, unpublished data). Similar levels of discrepancy (ca. 40%) were noted in all other ESUs/DPSs that were analyzed using the two different approaches (authors, unpublished data). If comparable estimates of predation from 2019 were available for use in this study, average annual reductions in Caspian tern predation rates during the entire management period (2008-2020) would be greater than those reported herein (which excludes 2019). To ensure predation rate estimates within and across salmonid ESUs/DPSs and years are directly comparable to one another, standardized methods should be used (see also Roby et al. 2021b).

Addressing high rates of steelhead predation by Caspian terns was the primary impetus of the *Management Plan* in the Columbia River Estuary (USFWS 2005). The over-riding assumption behind management actions described in the *Management Plan* was that the number of tern breeding pairs on East Sand Island was directly related to tern predation rates on juvenile salmonids, whereby reductions in colony size were proportional to reductions in predation rates (USFWS 2005, NMFS 2008). An investigation of the relationship between estimates of peak colony size and estimates of annual predation rates on steelhead DPSs supports this assumption, with reductions in colony size generally commensurate with reductions in predation rates (*Figure 2*). Trends were particularly evident when large changes in colony size occurred (i.e. several thousand breeding pairs) like those observed prior to implementation of management actions and those during the last three years of management actions where comparable estimates of predation were available (*Figure 2*). Plots of predation rates as a function of colony size indicate a linear relationship between peak colony size and annual predation rates for all steelhead DPSs evaluated ($p < 0.01$ in all comparisons; *Figure 2*). Collectively, these results support the conclusion that, if given sufficient time and a large enough reduction in the size of Caspian tern colony on East Sand Island, significant reductions in tern predation rates on steelhead smolts will, and have, occurred (see also Roby et al. 2021a).

Although these results provide evidence that predation rates, on average, can be reduced by reducing the number of Caspian terns nesting on East Sand Island, there was still considerable residual variation in predation rates. Significantly different predation rates on steelhead DPSs were observed at similar tern colony sizes (*Figure 2*), suggesting that colony size alone was not the only factor causing variation in predation rates (Lyons 2014, Evans et al. 2016). For example, Roby et al. (2021a) determined that estimates of peak colony size explained 52.0% (95% CRI = 25.1–72.0%) and 70.6% (38.4–94.4%) of variation in annual predation rates on Snake River and Upper Columbia River steelhead DPSs, respectively. In addition to colony size, the productivity of the colony (number of fledglings), the run-timing and abundance of smolts in the estuary, river flows and spill at hydroelectric dams, and ocean conditions (e.g., North Pacific Gyre Oscillation and upwelling) have all be linked to variation in East Sand Island Caspian tern predation rates (Roby et al. 2021b; Hostetter et al. 2021a). Collectively, results indicate that a complex and dynamic suite of factors are associate with smolt susceptibility to Caspian tern predation in the Columbia River Estuary (see also Hostetter et al. 2021a for a detailed discussion of these and other factors).

Finally, in the context of over-all smolt mortality due to Caspian tern predation in the estuary, it is important to note that predation rate results presented herein are specific to terns that attempted to nest on East Sand Island and does not account for large numbers (hundreds to thousands of pairs annually) of Caspian terns that have attempted to nest on Rice Island (Rkm 34) in the upper Columbia River estuary during the management period (Roby et al. 2021a). For instance, in 2017, upwards of 3,000 Caspian terns were observed digging nest scrapes, laying eggs, and incubating eggs on Rice Island and smolt PIT tag recoveries during that year resulted in predation rate estimates as high at 3.0% (2.3–4.4) on Snake River steelhead (Roby et al. 2021a). In 2020, there was no established tern colony on Rice Island, but 293 smolt tags were recovered from areas that were temporarily occupied by terns during the breeding season (authors, unpublished data). Results indicate that the overall impact of Caspian tern predation on survival of smolts in the estuary is often greater than that of Caspian terns nesting on East Sand Island alone. As such, continued efforts to prevent satellite tern colonies from forming on East Sand Island, Rice Island, or other islands in the estuary, especially those in the upper estuary where salmonids compromise a greater proportion of tern diets (Roby et al. 2003; Cramer et al. 2021), will likely be important in achieving the over-all goal of reducing predation by terns throughout the Columbia River Estuary (see also Roby et al. 2021a).

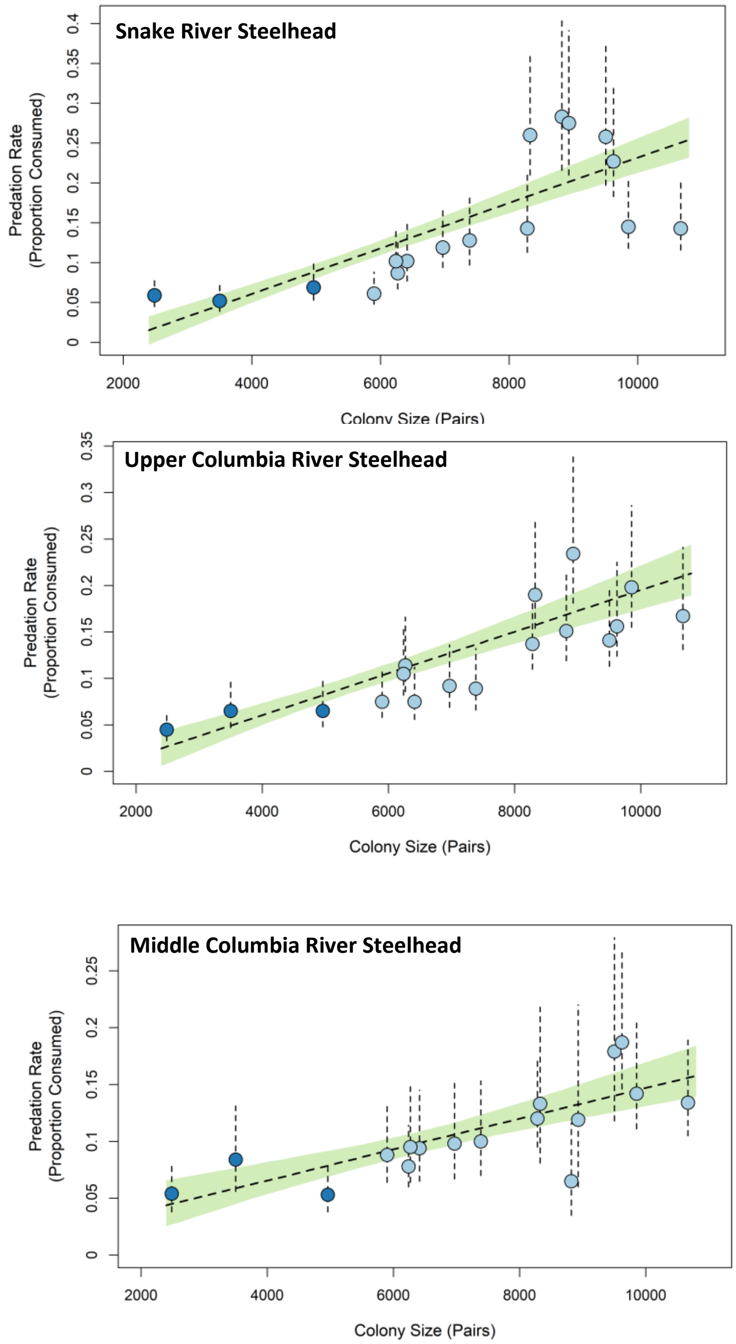

Figure 2. Estimated annual predation rates on PIT-tagged Snake River, Upper Columbia River, and Middle Columbia River steelhead smolts by East Sand Island Caspian terns as a function of colony size during 2003–2018, 2020 (years with adequate samples sizes and/or comparable estimates of predation). Estimates from 2020 are those from the main colony, where a measure of colony size was available (see Methods). Estimates from 2017, 2018, and 2020 are highlight in dark-blue. Error bars about predation rates represented 95% credible intervals. The dashed lines represent the best fit least squares linear regression between predation rates and colony sizes.

Conclusions & Recommendations

A synopsis of study conclusions, as well as recommendations for future predation rate monitoring and evaluation studies on the East Sand Island Caspian tern colony are provided below. Many of these recommendations were also provided as part of the recently completed Avian Predation Synthesis Report (see Roby et al. 2021a).

1. Estimates of predation rates on ESA-listed juvenile salmonids by Caspian terns nesting on East Sand Island in 2020 were the lowest ever recorded.

2. Comparisons of predation rates prior to (2000-2007) and during (2008-2018, 2020) implementation of management actions on East Sand Island indicated that predation rates were significantly lower following management actions to reduce colony size.

3. A comparisons of predation rates from the three most recent years of management, those with accurate and comparable estimates of predation (2017-2018, 2020) and where tern colony size was at or near the target level of no more than 4,375 breeding pairs stipulated in the *Management Plan*, indicated that predation rates have been reduced by 65% to 76% on steelhead DPSs; reductions that meet or exceed those anticipated in the *Plan*.

4. Caspian terns attempted to nest outside the designated colony area on East Sand Island during the peak smolt outmigration period of April to June 2020 and consumed upwards of 2.2% of available Snake River steelhead.

5. In order to continue to meet and monitor the objectives of the *Management Plan,* we recommend (1) continued use of Caspian tern nest dissuasion techniques to prevent tern nesting outside the designated colony area on East Sand Island, Rice Island, and other sites in the estuary; (2) continued monitoring of tern colonies throughout the estuary using previously established methods to ensure colony sizes do not exceed those stipulated in the *Plan*; (3) to continue to estimate predation rates on juvenile salmonids by terns using previously established methods at all active and incipient colony sites in the estuary to ensure impacts do not exceed acceptable levels.

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APPENDIX: HISTORICAL PREDATION RATES

This appendix provides annual PIT tag predation rate estimates for Caspian terns nesting on East Sand Island during 2000-2020. 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*) or the number released from barges downstream of Bonneville Dam (transported migrants; *Table A2*). Predation rates were corrected for PIT detection and deposition probabilities (see Methods). Estimates during 2000-2018 are those of Evans et al. (2016, 2018, 2019). Estimates from 2019 are those of Stachura et al. (2020), while estimates from 2020 are those of the current study (i.e. Evans et al. 2021).

Table A.1. Number of available PIT-tagged smolts (N) and annual predation rates (95% credibility intervals) by Caspian terns nesting on East Sand Island on ESA-listed salmonid populations originating from the Snake River (SR; based on detection at Bonneville Dam), Upper Columbia River (UCR; based on detections at Bonneville Dam), middle Columbia River (MCR; based on detection at Bonneville Dam), and Upper Willamette River (WR; based on detections at Sullivan Dam) during 1999-2020. A dashed line indicates that sample sizes of PIT-tagged smolts interrogated passing dams were too small (< 500) to generate reliable predation rates.

	East Sand Island, Columbia River Estuary							
Year	SR Sp/Su Chinook	SR Fall Chinook	UCR Sp Chinook	UWR Sp Chinook	SR Sockeye	MCR Steelhead	SR Steelhead	UCR Steelhead
2000	4.6% (3.6-6.6)	3.3% (2.1-5.3)	2.2% (1.2-3.8)	-	-	-	10.5% (8.4-15.0)	16.3% (12.8-22.9)
N	11,810	1,323	1,123				10,356	3,100
2001	14.0% (11.1-20.0)	6.4% (4.2-10.0)	13.2% (9.9-19.5)	-	-	15.0% (11.1-21.9)	33.9% (26.3-49.1)	-
N	8,845	807	1,230			872	774	
2002	2.9% (2.3-4.1)	1.7% (1.2-2.6)	2.5% (1.9-3.5)	-	-	-	21.9% (17.6-31.0)	14.2% (10.1-21.3)
N	30,617	4,899	20,493				7,331	561
2003	4.7% (3.7-6.9)	2.7% (2.0-4.0)	3.7% (2.9-5.3)	-	-	-	26.0% (21.0-36.2)	19.0% (15.4-26.9)
N	28,150	6,234	30,723				8,553	27,918
2004	4.8% (3.6-7.0)	1.3% (0.6-2.6)	3.7% (2.9-5.4)	-	-	-	25.8% (19.7-37.3)	14.1% (11.3-19.8)
N	4,816	929	9,533				803	6,040
2005	3.0% (2.2-4.4)	1.3% (0.6-2.6)	2.4% (1.6-3.8)	-	-	-	28.3% (21.6-40.6)	15.1% (11.9-21.6)
N	5,935	1,121	2,518				753	5,610
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

Table A1 Continued								
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% (1.0-2.6)	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
2017	0.8% (0.5-1.2)	0.2% (0.1-0.5)	1.4% (0.9-2.3)	-	-	8.4% (5.6-13.1)	5.3% (3.9-7.7)	6.5% (4.7-9.6)
N	13,151	4,635	4,622			1,069	6,497	3,275
2018	1.4% (1.0-2.1)	1.3% (0.7-2.1)	1.4% (0.9-2.3)	-	4.2% (2.9-6.4)	5.3% (3.8-8.0)	6.9% (5.3-10.2)	6.5% (4.8-9.7)
N	11,174	5,981	3,370		2,546	3,209	9,572	5,322
2019 [1]	1.3% (0.6-2.2)	0.5% (0.1-1.1)	1.6% (0.8-2.9)	-	1.5% (0.7-2.5)	7.1% (4.2-11.4)	7.6% (4.9-12.0)	6.0% (3.8-9.4)
N	6,045	3,727	3,987		4,140	2,843	8,855	5,677
2020	0.7% (0.5-1.1)	0.3% (0.1-0.7)	0.4% (0.2-0.9)	-	1.1% (0.6-2.2)	5.4% (3.8-7.9)	5.9% (4.5-8.1)	4.5% (3.3-6.4)
N	20,246	3,389	4,895		2,122	3,157	11,868	5,894

[1] Estimates based on different methodology, resulting in estimates that were higher than those generated using previously published methods (see Results).

Table A.2. Annual predation rates (95% credible interval) of ESA-listed PIT-tagged salmonids collected at Lower Granite, Little Goose, and Lower Monumental dams on the Snake River (SR) and released from barges downstream of Bonneville Dam by Caspian terns nesting on East Sand Island in the Columbia River estuary during 2006-2020. A dashed line denotes insufficient sample sizes (< 500 PIT-tagged fish) for generating reliable estimates of predation rates.

	East Sand Island, Columbia River Estuary			
Year	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)
N	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)
N	32,184	607		45,276
2008	4.2% (3.4-5.9)	1.6% (1.2-2.2)	-	18.7% (15.2-26.1)
N	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)
N	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)
N	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)
N	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)
N	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)
N	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)
N	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)
N	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)
N	43,068	10,948	2,829	13,608
2017	0.8% (0.6-1.3)	0.3% (0.2-0.5)	2.3% (1.3-4.0)	6.4% (5.0-9.2)
N	32,395	13,205	1,589	28,964
2018	1.1% (0.9-1.7)	0.4% (0.3-0.7)	1.5% (1.1-2.4)	6.1% (4.8-8.8)
N	66,723	17,402	10,087	44,241
2019 [1]	1.1% (0.7-1.8)	0.8% (0.4-1.3)	0.7% (0.2-1.4)	3.7% (2.4-5.7)
N	21,696	13,237	3,418	15,600
2020	1.1% (0.9-1.7)	0.3% (0.1-0.7)	0.4% (0.1-1.6)	5.3% (3.9-7.5)
N	19,125	3,354	1,065	5,730

[1] Estimates based on different methodology, resulting in estimates that were higher than those generated using previously published methods (see Results).