Recovery of coded wire tags on a Caspian tern colony in San Francisco Bay: A technique to evaluate impacts of avian predation on juvenile salmonids

by

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Abstract

We recovered coded wire tags (CWTs) from a Caspian tern (Hydroprogne caspia) colony on Brooks Island in San Francisco Bay, California to evaluate predation on juvenile salmonids (Oncorhynchus spp.) originating from the Sacramento and San Joaquin rivers. Subsamples of colony substrate representing 11.7% of the nesting habitat used by terns yielded 2,079 salmonid CWTs from fish released and subsequently consumed by terns in 2008. The estimated number of CWTs deposited on the entire tern colony was 40,143 (ranging from 26,763 to 80,288), once adjustments are made to account for tag loss and the total amount of nesting habitat used by terns. Tags ingested by terns and then egested on the colony were undamaged, with the tags' complete numeric code still identifiable. The CWTs found on the tern colony indicated that hatchery Chinook salmon (O. tshawytscha) trucked to and released in San Pablo Bay, located roughly 25 km from Brooks Island, were 313 times more likely to be consumed by Brooks Island Caspian terns than Chinook salmon that migrated in-river to the Bay. Of the CWT recovered on the tern colony, 98% were fall-run Chinook salmon, indicating a high susceptibility to tern predation relative to spring, winter, and late-fall run-types. None of the approximately 518,000 wild Chinook salmon that were coded wire tagged and released in the basin were recovered on the tern colony, suggesting impacts to wild, ESA-listed Chinook salmon populations were minimal in 2008. Overall, we estimate that ca. 0.3% of the approximately 12.3 million coded wire tagged Chinook salmon released in the basin in 2008 were subsequently consumed by Caspian terns and the tags deposited on the Brooks Island colony. Results indicate that CWTs implanted in juvenile salmon can be recovered from a piscivorous waterbird colony and used to evaluate smolt losses for those runs that are tagged.

Introduction

Each year millions of anadromous juvenile salmonids (*Oncorhynchus* spp.) are implanted with coded wire tags (CWT) in the Pacific Region of North America (RMISD 1977). Since its inception in the 1960s, coded wire tagging of juvenile salmonids in North America has been considered one of the largest fish marking programs in the world (Johnson 2005). Salmonid stocks from Alaska to California are coded wire tagged to evaluate migration histories, harvest rates, adult return rates, as well as stock-specific survival and mortality (Johnson 2005). A coded wire tag (CWT) is a small (ranging from 0.5 to 2.1 mm in length, 0.25 mm in diameter) piece of stainless steel wire emblazoned with a numeric code. Coded wire tags are implanted in the nasal cartilage of fish and provide a variety of information on each fish, including (but not limited to) species, stock, run, rearing-type (hatchery or wild), release date, and release location. The Regional Mark Processing Center, which is operated by the Pacific States Marine Fisheries Commission, provides coordination and maintains a centralized database for information on all salmonids marked with CWTs in the Pacific Region of North America (RMISD 1977).

Despite the large scale and geographic scope of salmonid CWT releases in North America, very few studies have focused on how the subsequent recovery of CWTs can be used to evaluate impacts of specific mortality factors, such as avian predation, on smolt survival. Numerous studies have documented the negative impact of avian predators on the survival of salmonids in the Pacific Region of North America using observational studies at foraging locations (Ruggerone 1986), analysis of stomach contents to determine food habits (York et al. 2000; Collis et al. 2002), bioenergetics modeling to estimate fish consumption (Roby et al. 2003; Antolos et al. 2005), and the recovery of fish tags on piscivorous waterbird colonies to document fish losses to avian predators (Collis et al. 2001; Ryan et al. 2001; Ryan et al. 2003; Antolos et al. 2005; Schreck et al. 2006). Studies of avian predation that utilized fish tag recoveries to estimate predation rates on juvenile salmonids have relied primarily on Passive Integrated Transponder (PIT) tags, radio telemetry tags, or hydro-acoustic telemetry tags; all types of tags that transmit or receive a signal. Although these electronic tags have numerous advantages in fish marking and tracking studies, they tend to be expensive, require costly equipment for their detection, and require invasive procedures for implantation. In the case of radio and hydro-acoustic tags, the fish must be of sufficient size for tagging, the tags have a limited life span, and tagging may have an effect on the survival and behavior of the tagged fish (Adams et al. 1998; Hockersmith et al. 2003; Hall et al. 2009). Furthermore, the extent of tagging programs that utilize electronic tags are often smaller in scale and geographic scope than that of research and monitoring programs that use CWTs.

Although previous studies have been successful in recovering CWTs consumed by piscivorous waterbirds, efforts to quantify the impacts of avian predation using CWT recoveries have been limited. Bostrom et al. (2009) attempted to recover CWTs from great cormorant (*Phalacrocorax carbo*) castings collected on a colony, but recovered only a single CWT. Lovvorn et al. (1999) managed to recover several hundred CWTs from stomach contents of double-crested cormorants (N = 30 birds) and from a limited number of castings (N = 15) to evaluate impacts of avian predation on trout fingerlings. An effort to recover CWTs from a Caspian tern (*Hydroprogne caspia*) breeding colony in Puget Sound was marginally successfully, with several hundred CWTs from juvenile salmonids recovered (G. Shugart, University of Puget Sound, personal communication). No attempt, however, was made to associate these tag recoveries with fish availability and mortality rates.

The management of piscivorous bird colonies in the Pacific Northwest is a component of regional plans to recover salmonid populations that are listed under the U.S. Endangered Species Act (ESA; NOAA Fisheries 2008). Caspian terns that nest in the Columbia River estuary on East Sand Island have been found to consume millions of juvenile salmonids annually (USFWS 2005; USFWS 2006; Collis et al. 2007). As a result, a plan entitled *Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary* was developed to reduce impacts on salmonids from Caspian terns nesting in the Columbia River estuary by redistributing a portion of the East Sand Island tern colony – the largest of its kind in the world at ca. 10,700 breeding pairs in 2008 – to newly created or enhanced alternative colony sites in Oregon and California, where far fewer, if any, salmonids have been found in the diet of Caspian terns (USFWS 2005, 2006). One of the potential alternative colony sites in California is on Brooks Island in San Francisco Bay. Caspian terns have been nesting on Brooks Island for over 20 years (Strong et al. 2004) and Brooks Island is currently the location of the largest Caspian tern colony in the San Francisco Bay area (ca. 1,025 breeding pairs in 2008; Collis et al. in review). The above mentioned Caspian Tern Management Plan seeks to expand the available nesting habitat for terns on Brooks Island to accommodate terns displaced from East Sand Island. The potential expansion of the Brooks Island Caspian tern colony may be controversial, however, due to the rapidly declining status of Chinook salmon (*O. tshawytscha*) and steelhead trout (*O. mykiss*) populations from the Central Valley of California, including those that are listed under the ESA (Yoshiyama et al. 1998; Good et al. 2005).

The purpose of this study was to (1) develop a method to recover CWTs from piscivorous waterbird colonies and to (2) evaluate the impact of Caspian terns nesting at the Brooks Island colony on survival of juvenile salmonids that migrate through San Francisco Bay. If successful, techniques to recover CWTs on bird colonies could be used to provide a wealth of information to fisheries managers throughout North America and elsewhere, including, but not limited to, stock-specific predation rates on ESA-listed or otherwise imperiled salmonid populations. Techniques that maximize the efficiency and efficacy of CWT recovery, while minimizing impacts to nesting birds, were evaluated here. Finally, if Caspian terns that are currently nesting on Brooks Island are shown to negatively impact the survival of ESA-listed salmonid populations in central California, plans to increase the size of the Brooks Island tern colony may warrant further consideration.

Study Site

Brooks Island (Figure 1) is a natural island in central San Francisco Bay, approximately half-way between San Pablo Bay and the Pacific Ocean and is owned by the City of Richmond and managed under a long-term lease with the East Bay Regional Parks District. Caspian terns first nested on Brooks Island in 1985 and their colony is located on a sandy spit, built from deposited dredge spoils, extending northwest from the historical island center (Strong et al. 2004). This colony has been the site of the largest nesting colony of Caspian terns in the San Francisco Bay area for at least the last decade (Strong et al. 2004; Collis et al. in review). Juvenile, anadromous salmonids originating from the Sacramento and San Joaquin rivers must migrate past Brooks Island to reach the Pacific Ocean.

Methods

Colony Size, Nesting Density, and Chronology

The number of Caspian terns nesting on Brooks Island was determined from aerial photographs taken during the peak of egg incubation in May 2008 (see Roby et al. 2003 and Collis et al. in review for further details on the methods used to estimate colony size). Digital photos of the Brooks Island Caspian tern colony were analyzed using Arc Geographic Information System (ESRI, Redlands, CA) software to estimate the number of breeding pairs, the colony area (m^2) used by nesting terns, and nesting density (number of breeding pairs per m^2). Periodic counts of Caspian terns were also conducted from an observation blind located at the periphery of the tern colony to calibrate counts from aerial photography, determine patterns in seasonal colony attendance, and assess nesting chronology (dates of egg-laying, chick hatching, and chick fledging) of terns at Brooks Island in 2008.

Coded Wire Tag Recovery

Subsamples of the nesting substrate used by Caspian terns on Brooks Island during 2008 were removed and searched for CWTs in August, following the tern nesting season. Plots were randomly selected within the areas occupied by nesting terns in 2008. Substrate samples from Brooks Island consisted primarily of sand, shell fragments, guano, and bones (regurgitated fish bones or bones from chicks that died during the nesting season). Substrate was removed from 83 individual 1-m^2 plots (hereafter referred to as "plots") in the Caspian tern colony to a depth of approximately 5 cm. Substrate from each plot was collected and stored individually in 5-gallon plastic buckets for later processing.

The contents of each bucket were poured into a pre-fabricated, plastic-lined box and heaters were used to remove moisture from the sample. Substrate from each plot was ground using a mortar mixer paddle and drill to break up guano and other large, compacted material. Material was screened (3-mm mesh) to remove shell fragments, rocks, bones, and other large debris. Processed and dried material was poured over a 900 mm (length) x 50 mm (width) metal trough lined beneath with several neodymium magnets. To ensure that the substrate samples passed through the trough evenly and at a consistent rate, the trough was positioned at a shallow angle (ca. 30 degrees) and the material was fed into the trough using a cylinder-shaped hopper containing a 1-cm hole at the bottom for substrate to pass through. As the material moved through the trough, all ferrous material was captured in the trough at the location of the magnets. An illuminated magnifying glass was used to locate all CWTs within the ferrous material and tags were manually removed using a pair of magnetized tweezers. Once recovered, CWTs were cleaned with isopropyl alcohol and the tag's numeric code read using a specially-designed MagniViewer© microscope (Northwest Marine Technology, Shaw Island, Washington).

In order to quantify the efficiency of our CWT extraction technique, we sowed CWTs with known tag codes (N = 100; hereafter referred to as "test tags") into five discrete 1-m^2 plots on the Brooks Island tern colony prior to the nesting season (March; hereafter referred to as "pre-season") and after the nesting season (August; hereafter referred to as "post-season") to measure the percentage of tags deposited on-colony that were subsequently recovered. Equal numbers of test tags ($N = 50$) were sown during each release period (pre-season and post-season), into one of five on-colony plots (i.e., 10 test tags per plot). To further assess the efficiency of our recovery efforts, test tags ($N = 140$) were also sown directly into the 5-gallon buckets containing pre-processed substrate samples to assess the percentage of tags in substrate samples that were subsequently recovered. Here, too, equal numbers of test tags ($N = 10$) were sown into each of the 14 randomly-selected buckets of pre-processed substrate samples. The sowing of test tags was done under the premise that not all CWTs deposited by terns on the Brooks Island colony were subsequently recovered by researchers. For example, tags could be blown off the colony during wind or rain storms, buried deeper than 5 cm, washed away during high tides or other flooding events, or otherwise damaged or lost. Furthermore, it is reasonable to suspect that some of the recovered tags within the substrate samples were lost during the extraction process. Detection efficiency estimates (percentage of sown test tags subsequently recovered) were analyzed relative to the release location (on-colony versus in buckets) and release date (pre-season or post-season) to describe spatial and temporal variation in detection efficiency.

Impacts on Salmonid Survival

Data regarding the number, species, rearing-type (hatchery or wild), run-type (fall, late-fall, winter or spring), and release location of salmonids marked with CWT in the Sacramento and San Joaquin rivers were obtained by querying the Regional Mark Information Systems Database (RMISD 1977) on 10 March 2009. Salmonid release locations were characterized in one of three categories, based on the distance from Brooks Island and the release strategy employed by fishery agencies in the region: (1) released directly into the Sacramento River or a tributary of the Sacramento River (hereafter referred to as the "In-river" release group), (2) fish trucked to and released into the Sacramento-San Joaquin River Delta (hereafter referred to as the "Delta" release group), or (3) fish trucked to and released into San Pablo Bay (hereafter referred to as the "Bay" release group; Figure 1). The vast majority (> 95%) of fish trucked to and released into San Pablo Bay were released from net pens by the Fisheries Foundation of California; specifically, the fish were trucked from the hatchery, placed in a net pen for salt water acclimation, and then towed out to release points in eastern San Pablo Bay (FFC 2008). Fish were released from the net pens into San Pablo Bay during daylight hours and irrespective of tide stage (FFC 2008).

Data Analysis

Analysis of the impacts of Caspian tern predation on survival of juvenile salmonids was limited to smolts marked with CWTs and released during the 2008 migration year (i.e., fish assumed to be out-migrating to the Pacific Ocean between December 2007 and July 2008). The numbers of CWT fish released (by species, rearing-type, and location) were compared to the numbers of CWTs recovered on the Brooks Island tern colony to generate minimum consumption and predation rate estimates. Odds ratio comparisons (Ramsey and Schafer 1997) and chi-square tests were used to evaluate the relative vulnerability of fish to tern predation from fish of different run-types and release locations under the null hypothesis that fish were consumed in proportion to their availability at release. A simple linear regression analysis was used to evaluate the relationship between the daily number of smolts releases from net pens and the number consumed by terns under the null hypothesis that tern consumption was not associated with fish availability.

Finally, the total number of salmonid CWTs deposited (D) by terns on Brooks Island in 2008 was estimated by dividing the number of tags recovered (r) from sampled plots (calculated for each section or sub-colony independently; see Results for details) by the proportion (p) of available habitat sampled by researchers at that sub-colony. Estimates were then further adjusted to account for tag loss and misdetection by dividing the habitat-adjusted number of tags by the average on-colony detection efficiency (e) to calculate the total number of CWTs deposited by terns as follows:

$$D = (\frac{r}{p}) / e$$

A range of possible deposition estimates were then calculated by using the variability observed in detection efficiency calculations, whereby the lowest and highest detection efficiency values (see Results) – as appose to the average – were used to calculate the total number of CWTs deposited by terns on Brooks Island in 2008.

Results

Colony Size, Nesting Density, and Chronology

Caspian terns nested in two separate areas or sub-colonies on Brooks Island, a “main” colony consisting of 517 breeding pairs and a “satellite” colony consisted of 295 pairs. The two sub-colonies were located 201 meters apart along the leeward (northeastern) shore of the low-lying sandy spit. Within the boundaries of each sub-colony, only nesting Caspian terns were present, although Western gulls (*Larus occidentalis*) and California gulls (*L. californicus*) were located within a few meters of nesting terns. Terns arrived to nest between late-March and mid-May, with the number of terns attending the colony peaking in early June. By late-July the majority of tern chicks had fledged and by early August the tern colony had been completely abandoned. Terns nesting on Brooks Island utilized a total of 713 m^2 (”main” colony = 538 m^2, satellite colony = 175 m^2) of nesting habitat, yielding an average nesting density of 1.1 breeding pairs/m^2 of nesting substrate. Nesting densities differed, however, between the two sub-colonies, with densities greater on the satellite sub-colony (1.7 nesting pairs/m^2) compared to the main sub-colony (1.0 nesting pairs/m^{-2}).

Coded Wire Tag Recovery

A total of 83 m^2 of nesting substrate from the Caspian tern colony on Brooks Island was removed and sifted for salmonid CWTs. Substrate plots were removed from both the main (N = 74) and satellite (N = 9) sub-colonies, with samples representing 13.8% of the available nesting habitat utilized by terns on the main sub-colony and 5.2% of the available nesting habitat utilized by terns on the satellite sub-colony. Overall (both sub-colonies combined), tags were removed from 11.7% of the habitat used by nesting terns in 2008. From the 83 m^2 of nesting substrate, a total of 2,340 salmonid CWTs were recovered. On average, 46.4 salmonid CWTs were recovered per 1-m^2 plot (SD = 22.1 tags per 1-m^2 plot), with the range of tags highly variable in both the main (5 to 101 tags 1-m^2 plot) and satellite (9 to 56 tags per 1-m^2 plot) colonies. Of the 2,340 CWTs recovered, the majority (88.8% or 2,079 CWTs) were from fish tagged and released during the 2008 migration year. The remaining 261 CWTs were from fish released prior to July 2007, fish that were presumably consumed by Caspian terns that nested on Brooks Island in previous years. The oldest CWT recovered was from a steelhead smolt released into the Sacramento River in December 2002. Nearly all (99.9%) of the CWTs recovered from the tern colony were undamaged (i.e., the entire numeric code was readable via microscope).

Detection efficiency of test tags intentionally sown on the colony prior to and after the nesting season averaged 40% (40/100). A difference between pre-season (20%) and post-season (60%) detection efficiency was observed. Detection efficiency of test tags placed into 5-gallon buckets of pre-processed substrate was much higher, with 91.4% (128/140) of sown tags subsequently recovered. Consequently, most of the loss of CWTs deposited on the Brooks Island Caspian tern colony occurred prior to, or during, the sampling of nesting substrate and not as a result of processing the material.

Based on the total amount of nesting substrate searched for CWTs, average on-colony detection efficiency, and the total number of 2008 migration year salmonid tags recovered, a minimum estimate of 40,143 CWTs from juvenile salmonids were deposited by Caspian terns on Brooks Island in 2008 (Table 1). Based on the variability observed in detection efficiency results, we estimate the total number of tags deposited on the tern colony was somewhere between 26,763 (using the post-season detection efficiency value of 60%) CWT tags and 80,288 (using the pre-season detection efficiency value of 20%) CWT tags. These estimates, however, are still minimum estimates of the total number of coded wire tagged salmonids consumed because an unknown proportion of CWTs from fish consumed by Brooks Island terns was deposited off colony (e.g., at loafing or staging sites not associated with the birds' nesting site).

Impacts on Salmonid Survival

Approximately 12.3 million juvenile Chinook salmon from the Sacramento and San Joaquin rivers were marked with CWTs and released in 2008 (Table 1). The vast majority of CWT fish were from hatcheries (11.8 million or 95.8% of all CWT fish) and of the hatchery CWT fish, the majority were fall-run Chinook salmon (8.3 million or 67.5% of all CWT fish). Of the remaining marked hatchery fish, 2.6 million were spring Chinook salmon (ESA-listed fish produced by the Feather River Hatchery), 0.9 million were late-fall Chinook salmon, and 0.1 million were winter Chinook salmon (ESA-listed fish produced by Coleman National Fish Hatchery; Table 1). In addition to hatchery fish, 0.3 million wild spring-run Chinook salmon (from Butte Creek, a tributary of the Sacramento River) and 0.2 million wild fall-run Chinook salmon (also from Butte Creek) were marked with CWTs and released in 2008 (Table 1). Virtually all (99.9%) of the hatchery spring, winter, and late-fall Chinook salmon released in 2008 were marked with CWTs. By comparison, an estimated 23.6 million hatchery fall Chinook salmon were not marked with CWTs (approximately 74% of all released fall Chinook salmon in the basin) and about 2.0 million hatchery steelhead were not marked with CWTs (100% of all released steelhead) in 2008. Unfortunately, the lack of CWT steelhead precludes the use of CWT recoveries on the Brooks Island tern colony to evaluate impacts of Caspian tern predation on steelhead from the Sacramento River, an ESA-listed population.

Of the total number of CWTs from 2008 migration year smolts recovered on the Brooks Island tern colony, 2,073 or 99.7% were from fish trucked to and released into San Pablo Bay (i.e., Bay release group: Table 1). Conversely, only six recovered CWTs were from fish in the In-river release group, despite in-river releases of approximately 5.7 million CWT Chinook salmon in 2008 (Table 1). The odds of recovering a CWT from a Chinook salmon in the Bay release group on the tern colony were 313 times greater (95% confidence interval (CI): 140 to 697 times greater) than recovering a CWT from a Chinook salmon in the In-river release group (χ^2 = 1860.18, P < 0.0001). No CWTs were found on the Brooks Island tern colony from fish in the Delta release group, prohibiting comparison between In-river and Bay release groups. It should be noted, however, that there were a relatively small number of fish in the Delta release group (0.3 million) compared to the In-river (5.6 million) and Bay (6.3 million) release groups.

Of the CWTs recovered on Brooks Island from 2008 migration year smolts, 2,037 or 98.0% were from fall Chinook salmon (Table 1), indicating a high susceptibility to tern predation for this run-type relative to the other Chinook salmon run-types (spring, winter, and late-fall) released in 2008. Even after accounting for differences in release location, fall Chinook salmon were still the run-type most susceptible to predation from Brooks Island Caspian terns. For example, of the Bay release group, CWTs from fall Chinook salmon were 13 times (95% CI: 9 to 17 times) more likely to be recovered on the tern colony compared to spring Chinook salmon (χ^2 =417.33, P < 0.0001). The overall small numbers of CWTs from the In-river release group (N = 6; all run-types combined) and the lack of tags from the Delta release group, precludes statistical comparisons among run-types. A total of 41 CWTs or 2.0% of recovered CWTs were from spring Chinook salmon and one CWT or < 0.1% of recovered CWTs were from late-fall Chinook salmon (Table 1). No tags from hatchery winter Chinook salmon, wild spring Chinook salmon, or wild fall Chinook salmon were recovered on the Brooks Island tern colony. Overall (all run-types and rear-types combined), < 0.1% (2,079/12,262,077) of CWT Chinook salmon released in the basin were subsequently recovered on the Brooks Island Caspian tern colony. This proportion increases to 0.3% (40,143/12,262,077) after adjustments are made for detection efficiency and the proportion of the total tern colony area that was sampled for CWTs (Table 1).

Finally, we observed a positive association between the number of CWT smolts released from net pens in San Pablo Bay and the number of CWTs recovered on the Brooks Island tern colony, suggesting that terns responded functionally and/or numerically to increased prey densities associated with the net pen releases in San Pablo Bay (r^2 = 0.70, P < 0. 0001; Figure 2). Chinook smolts were released from net pens into San Pablo Bay, either on a weekly or daily bases, from 4 April to 12 June, 2008; a period that completely overlaps with the tern nesting season on Brooks Island (i.e., April through July).

Discussion

Coded Wire Tag Recovery

Results of this study demonstrate that CWTs implanted in juvenile salmonids can be recovered from a Caspian tern breeding colony and used to evaluate impacts of this avian predator on survival of juvenile salmonids, for runs where a substantial proportion of smolts are marked with CWTs. Although previously published studies have successfully recovered passive integrated transponder (PIT) tags from piscivorous waterbird colonies to assess impacts of avian predation on marked salmonid stocks (Collis et al. 2001; Ryan et al. 2003; Antolos et al. 2005), to our knowledge this is the first published study to utilize CWT recoveries from a bird nesting colony to assess impacts on fish stocks. Virtually all of the CWTs recovered were readable, such that the fish species, stock, run, rearing-type, release date, and release location could be determined. This finding demonstrates that CWTs are not damaged during digestion of the CWT fish and can remain readable for several years after being deposited on a colony (as demonstrated by the 261 CWTs found on the colony in 2008 from smolts released in 2002 to 2007). Lovvorn et al. (1999) found that CWTs recovered from Double-crested cormorant castings were also readable, although these were from castings that had recently been regurgitated (within several days) and removed from the colony. Efforts to recover fish tags after birds have left the breeding colony avoids disturbing the birds during the breeding season, which can negatively affect nesting success and, in some cases, cause colony abandonment (Ellison and Cleary 1978; Tremblay and Ellison 1979; Burger 1984). Furthermore, the use of fish tag recoveries to assess the diet of piscivorous waterbirds avoids either lethal collection or live capture and handling of chicks or adults to collect diet samples.

Detection efficiency trials aimed at quantifying the rate of CWT loss and missed detection suggest that a large percentage (ranging from 40% to 80%) of the CWTs deposited on the tern colony were not detected. More research is needed to determine whether missed detections were primarily a result of environmental factors during the nesting season (e.g., wind and water erosion removing a proportion of tags from the colony) or of substrate sampling techniques (i.e., removal of just the top 5 cm of nesting substrate misses tags that are on-colony but at a greater depth). The detection efficiency of CWTs associated with the processing of substrate samples (i.e., the passing of colony substrate over magnets) was quite high (> 90% of test tags sown), suggesting that the methods used were effective at finding the vast majority of CWTs within the collected substrate. By measuring the detection efficiency of CWTs sown on-colony and by knowing the proportion of the total tern colony area that was sampled for CWTs, adjustments can be made to estimate the total number of CWTs deposited by terns on the colony. Predation rates on different groups of salmonids marked with CWTs can then be estimated by dividing the estimated total number of CWTs deposited on-colony by the total number of tags released. These estimated predation rates, however, are still minimum estimates because an unknown proportion of all CWTs consumed by terns nesting on the colony are either regurgitated or defecated off-colony. Collis et al. (2007) estimated that about 35% of smolt PIT tags ingested by Caspian terns are deposited off-colony. Despite this caveat, our results regarding the relative susceptibility of CWT salmonid smolts from the Sacramento and San Joaquin rivers should not be biased due to either the loss of CWTs deposited on-colony or the off-colony deposition of ingested CWTs.

Impacts on Salmonids

Overall, we estimate that very small percentage (0.3%) of the available CWTs from juvenile Chinook salmon from the Sacramento and San Joaquin rivers were deposited on the Brooks Island Caspian tern colony in 2008. Of the fish consumed by terns, there was over-whelming evidence that smolts released directly into San Pablo Bay from net pens were the most susceptible, with CWTs from Bay release group fish over 300 times more likely to be recovered on the tern colony than CWTs from In-river release group fish. The proximity of the net pen release locations to the Brooks Island tern colony (~25 km), the timing of releases (during daylight hours), the duration of releases (April to June), and the large numbers of hatchery-reared juvenile salmonids in each net pen release are all likely explanations for the much higher susceptibility of the Bay release group to tern predation. Previous studies have shown that Caspian terns tend to forage on the most available prey-types when raising young (Lyons et al. 2005). Furthermore, hatchery-reared juvenile Chinook salmon have been shown to be more vulnerable to Caspian tern predation as compared to their wild counterparts (Collis et al. 2001; Ryan et al. 2003). An examination of numbers of smolts released from net pens in San Pablo Bay indicates that Caspian terns consumed juvenile Chinook salmon in rough proportion to their relative availability across the migration period, suggesting a functional and/or numerical response (Solomon 1949; Holling 1959) to varying prey density.

Of the various run-types of CWT Chinook salmon (spring, winter, fall, and late-fall), fall-run Chinook salmon were the most likely be consumed by Brooks Island Caspian terns; 98.0% of all recovered CWTs were from fall-run Chinook salmon, yet fall Chinook salmon comprised just 67.9% of all released fish (see Table 1). The large numbers of hatchery-reared fall Chinook salmon released into San Pablo Bay is one reason for this greater susceptibility. Even after accounting for differences in release location (In-river, Delta, or Bay release groups), fall Chinook salmon were still consumed at a higher proportion than spring Chinook salmon. For example, for Bay release group Chinook salmon, CWTs from fall Chinook were 13 times more likely to be recovered on the tern colony than those of spring Chinook salmon. The timing of release and out-migration for fall Chinook smolts is likely one reason for this higher susceptibility, as fall Chinook were available to terns for at least a three-month period (April to June), while Bay released spring Chinook smolts were available for just the month of April (see Table 1). Also, the energy demands of the Caspian tern colony on Brooks Island likely reached its peak in early June, when adults were feeding rapidly growing chicks and colony attendance of adult terns was still at a high level.

Data presented here suggest that the impacts of Caspian terns on wild or naturally produced juvenile Chinook salmon from the Central Valley of California were minimal in 2008. None of the approximately 311,000 wild spring-run or 207,000 wild fall-run Chinook salmon marked with CWTs and released in the Sacramento River were subsequently recovered on the Caspian tern colony on Brooks Island. Furthermore, a very small number (N=6) and proportion of all Chinook salmon released in-river were recovered on the Brooks Island tern colony, a finding that supports the conclusion of minimal impacts to wild fish because all wild salmon in the region (tagged and untagged) migrate in-river. Life history data on wild, ESA-listed Chinook salmon populations from the Sacramento River (i.e., winter and spring-run Chinook) indicate that smolt out-migration timing from the stream to the estuary takes place primarily between November and May (Yoshiyama et al. 1998), a time period that only partially over-laps with the Caspian tern nesting season on Brooks Island. Conversely, both wild and hatchery fall Chinook salmon out-migrate to the estuary between March and July (Yoshiyama et al. 1998; Weber and Fausch 2004), a period that completely over-laps with the tern nesting season.

Differences in fish size, density, and behavior may also limit the impact of Caspian tern predation on survival of wild Chinook salmon relative to their counterparts that are raised in hatcheries. Weber and Fausch (2004) reported that hatchery-reared Chinook salmon released into the upper Sacramento River were larger (fork length), emigrated later, and were more numerous than wild Chinook salmon of the same run-type. Data aimed at evaluating the in-river survival and timing of ocean entry – as opposed to emigration timing to the estuary – by wild and hatchery-reared smolts from the Sacramento and San Joaquin rivers would help to better quantify and more thoroughly evaluate differences in susceptibility to Caspian tern predation between wild and hatchery Chinook smolts.

Unfortunately, we are unable to evaluate the susceptibility of juvenile Chinook salmon relative to the susceptibility of juvenile steelhead to predation from Brooks Island Caspian terns, because steelhead were not marked with CWTs in 2008. Data from Caspian tern colonies in the Columbia River basin suggest that steelhead smolts are particularly susceptible to Caspian tern predation (Collis et al. 2001; Ryan et al. 2003; Antolos et al. 2005). Observations of the species of fish being delivered by Caspian terns to the Brooks Island colony (Caspian terns capture and deliver in their bills whole fish to their mates and young) in 2008 indicated that only a small percentage of the salmonids delivered to the colony were steelhead (2.5%; Collis et al. in review). Whether these steelhead belonged to the threatened Central Valley or Central California Coast ESUs or to several other non-listed steelhead ESUs in the region is unknown, but the overall impact of Brooks Island Caspian terns on steelhead survival in 2008 was likely minimal given the scarcity of steelhead in the diet of nesting terns.

Results presented here provide overwhelming evidence that Caspian terns nesting on Brooks Island consumed primarily non-listed, hatchery-reared fall Chinook salmon that were released en masse into San Pablo Bay from net pens. Of the 41 CWTs from ESA-listed hatchery spring Chinook salmon recovered on the tern colony, 40 were from the Bay release group and just one was from the In-river release group. In total, just six of the 12.3 million Chinook smolts from the In-river release group were recovered on-colony, indicated losses to naturally migrating Chinook smolts (both hatchery and wild) were minimal in 2008. Future research will focus on refining our CWT recovery techniques, improving detection efficiency trials to better address and correct for potential biases in CWT loss, and collection of CWTs from other tern colonies in the Bay Area to assess geographical differences in tern diets and impacts to salmonid smolt survival. Estimates of the total number of smolts consumed by Caspian terns nesting at Brooks Island and other Caspian tern colonies in the region are also needed to fully evaluate salmonid losses. Together, these results will help guide resource managers in their efforts to enhance or restore Caspian tern colonies in the San Francisco Bay area, while protecting declining salmonid populations of conservation concern. Data on diet composition, smolt consumption, and CWT recoveries from Brooks Island compared to other Caspian tern colonies in the Bay Area will help determine the advisability of providing more tern nesting habitat at Brooks Island versus the creation of new nesting habitat for terns in the South Bay, further removed from sites where smolts from the Sacramento and San Joaquin rivers are released.

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Tables

Table 1.– Coded wire tagged juvenile Chinook salmon from the Sacramento and San Joaquin rivers released and subsequently recovered on the Brooks Island Caspian tern colony. In-river fish were released directly into the Sacramento River or a tributary of the Sacramento River between 160 and 640 river kilometers (Rkm) upstream of Brooks Island. Delta fish were released into sloughs below the confluence of the Sacramento and San Joaquin rivers between 105 and 115 Rkm upstream of Brooks Island. Bay fish were released directly into San Pablo Bay between 25 and 35 km from Brooks Island. The estimated number of tags deposited by terns is calculated from the number recovered, after adjustments for tag loss and sampling effort are made.

Release Location	Run-type	Rear-type	Release Period	Number Released	Number Recovered	Est. Number Deposited (% Released)
In-river	Winter	Hatchery	January	69,144	0	-
	Spring	Hatchery	April	1,378,941	1	19 (<0.01)
		Wild	Jan. to March	311,061	0	-
	Fall	Hatchery	April to June	2,987,604	4	77 (<0.01)
		Wild	Jan. to March	206,998	0	-
	Late-Fall	Hatchery	January	725,650	1	19 (<0.01)
Delta	Fall	Hatchery	April - June	101,458	0	-
	Late-Fall	Hatchery	Dec. to Jan.	209,523	0	-
Bay	Spring	Hatchery	April	1,242,388	40	772 (0.06)
	Fall	Hatchery	April to June	5,029,315	2,033	39,256 (0.78)
TOTAL				12,262,077	2,079	40,143 (0.33)

Figures

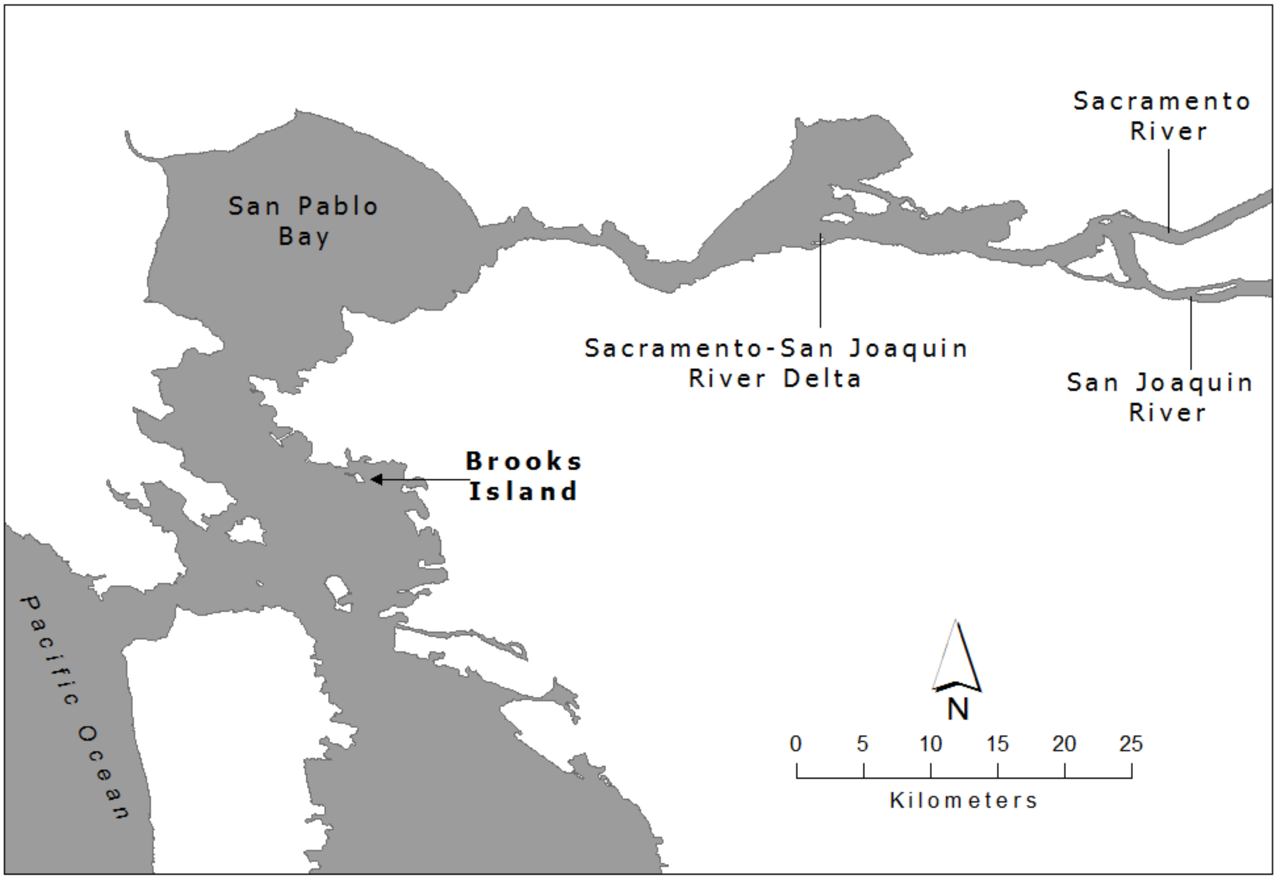

Figure 1.– Map of northern San Francisco Bay, California. Brooks Island is located in central San Francisco Bay, with the Sacramento and San Joaquin rivers entering the Bay from the northeast.

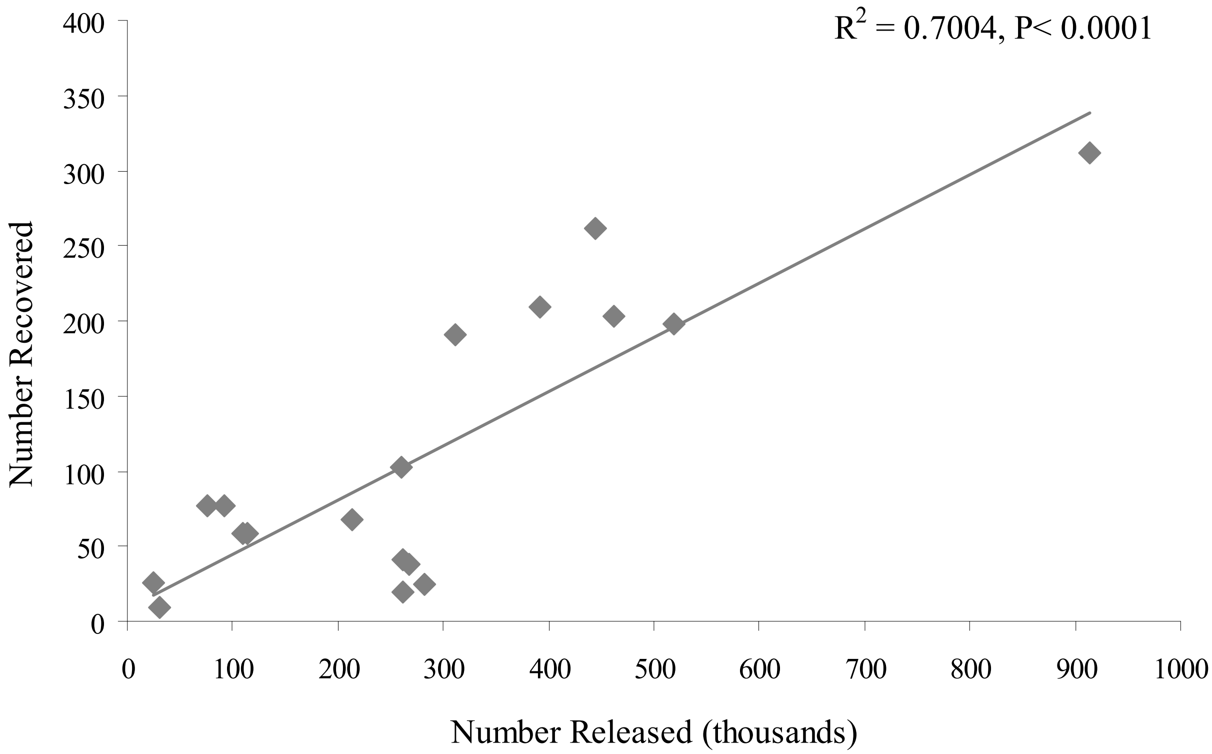

Figure 2.– The relationship between the number of coded wire tagged fall Chinook salmon released and the number consumed by Caspian terns nesting on Brooks Island in 2008. Tagged salmon were released from net pens directly into eastern San Pablo Bay from 4 April to 12 June, 2008. The number of fall Chinook salmon tags recovered on the tern colony were from a sub-sample (ca. 11.7%) of the nesting substrate used by terns on Brooks Island in 2008.