Avian Predation on Juvenile Salmonids in the Lower Columbia River

1998 ANNUAL REPORT

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CONTENTS

EXECUTIVE SUMMARY

We initiated a field study in 1997 to assess the impacts of fish-eating colonial waterbirds (i.e., terns, cormorants, and gulls) on the survival of juvenile salmonids in the lower Columbia River. Here we present results from the 1998 breeding season, the second field season of work on this project. The research objectives in 1998 were to: (1) determine the location, size, nesting chronology, nesting success, and population trajectories of breeding colonies of fish-eating birds in the lower Columbia River; (2) determine diet composition of fish-eating birds, including taxonomic composition and energy content of various prey types; (3) estimate forage fish consumption rates, with special emphasis on juvenile salmonids, by breeding adults and their young; (4) determine the relative vulnerability of different groups of juvenile salmonids to bird predation; (5) identify foraging range, foraging strategies, and habitat utilization by piscivorous waterbirds; and (6) test the feasibility of various alternative methods for managing avian predation on juvenile salmonids and develop recommendations to reduce avian predation, if warranted by the results.

Populations of Caspian terns (*Sterna caspia*) and double-crested cormorants (*Phalacrocorax auritus*) in the Columbia River estuary continued to increase in 1998, while the population of glaucous-winged/western gulls (*Larus glaucescens* X *L. occidentalis*) in the estuary declined. Populations of California and ring-billed gulls (*Larus californicus* and *L. delawarensis*) at up-river colonies were stable or declined somewhat. Rice Island, a dredge material disposal island in the Columbia River estuary, again supported the largest known Caspian tern colony in North America (about 8,000 breeding pairs in 1998), and the only known breeding colony of this species in coastal Oregon and Washington. The colony of double-crested cormorants on East Sand Island in the estuary is the largest of its kind on the Pacific coast of North America.

Diet analysis indicated that juvenile salmonids were an important part of the diet of fish-eating colonial waterbirds in the Columbia River estuary. As in 1997, Caspian terns were most dependent on salmonids (74% of diet mass), followed by double-crested cormorants (21% of diet mass) and glaucous-winged/western gulls (approx. 8% of diet mass). Juvenile salmonids were especially prevalent in the diets of fish-eating waterbirds in the estuary during April and May. The diet samples from California and ring-billed gulls nesting at up-river colonies included few fish and very few juvenile salmonids.

Aerial surveys of the estuary during the Caspian tern nesting season indicated that most foraging by terns occurred within 8 km of the Rice Island colony, and 90% of all tern sightings off-colony were within 21 km of the colony. Cormorants, in particular, aggregated to feed around pile dikes, where juvenile salmonids may be more vulnerable to avian predation.

Analysis of over 49,000 smolt PIT tags recovered from the Caspian tern and double-crested cormorant breeding colonies on Rice Island revealed that avian predation rates on steelhead smolts were greater than those on coho or chinook smolts and that hatchery-reared smolts were more vulnerable to tern predation than wild smolts. For the 1998

migration year, tern predation rates on transported chinook smolts were greater than for non-transported chinook smolts, whereas predation rates on transported steelhead smolts were less than for non-transported steelhead smolts.

We estimated that Caspian terns in the Columbia River estuary consumed 10.8 million juvenile salmonids (range = 7.4 – 15.2 million), or approximately 11% (range = 8% - 16%) of the estimated 95 million out-migrating smolts that reached the estuary during the 1998 migration year. The best estimate the number of juvenile salmonids consumed by double-crested cormorants in the estuary was 4.6 million (range = 2.2 – 9.2 million), or approximately 5% of out-migrating smolts (range = 2% - 10%) that reached the estuary in 1998. A rough estimate of the number of juvenile salmonids consumed by glaucous-winged/western gulls in the estuary was 1.3 million (range = 0.4 – 3.9 million). Thus the estimated total consumption of juvenile salmonids by fish-eating colonial waterbirds in the Columbia River estuary was 16.7 million smolts (range = 10.0 – 28.3 million smolts), or 18% (range = 11% – 30%) of those smolts that reached the estuary in 1998.

Given the magnitude of smolt losses to colonial waterbirds in the estuary, it seems justifiable to develop management options that will reduce avian predation on juvenile salmonids, preferably without damaging colonial waterbird resources. Relocation of part or all of the Rice Island Caspian tern colony to sites where greater diversities of marine forage fishes are available may achieve this goal. We tested the feasibility of using social attraction (tern decoys and audio playback systems) to encourage Caspian terns to nest on a site not previously occupied. This approach succeeded in attracting terns to nest and lay eggs at the new site, but all nesting attempts failed because of intense egg predation by gulls and crows. We recommend relocation of part of the Rice Island Caspian tern colony to East Sand Island in 1999 to test whether this approach will reduce smolt losses to terns. In the longer term, it would probably benefit both salmonids and terns if much of the tern population was relocated to other coastal colony sites, possibly restored former colony sites in Grays Harbor, Willapa Bay, and Puget Sound, where greater diversities of non-salmonid prey are presumably available.

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INTRODUCTION

Published research suggests that avian predation can, under some conditions, be a substantial source of mortality for juvenile salmonids (Mace 1983; Wood 1987; Feltham 1995; Krohn and Blackwell 1996; Blackwell 1995; Kennedy and Greer 1988). As part of the Northwest Power Planning Council's 1994 Columbia Basin Fish and Wildlife Program, the Bonneville Power Administration and other agencies have been charged with monitoring and assessing bird predation on juvenile salmonids in lower Columbia and Snake river reservoirs and in the Columbia River estuary, and identifying non-lethal methods for control of piscivorous waterbird populations that are a source of significant mortality for juvenile salmonids (NPPC 1994). In 1997, a study was initiated by the Oregon Cooperative Fish and Wildlife Research Unit at Oregon State University and the Columbia River Inter-Tribal Fish Commission to assess the impacts of fish-eating colonial waterbirds (i.e., terns, cormorants, and gulls) on the survival of juvenile salmonids in the Lower Columbia River.

Study results in 1997 (see Roby et al. 1998) indicated that there were nine major breeding colonies of fish-eating birds that nest on islands in the lower Columbia River and estuary. The majority of these islands are unnatural, created by either the dumping of dredged material or by mainstem dam impoundments. Population censuses indicated that these bird populations were quite large (a total of roughly 150,000 breeding birds) and were increasing substantially each year. For example, Rice Island, a dredged material disposal island in the Columbia River estuary, supported the largest Caspian tern *(Sterna caspia*) colony in North America (over 16,000 birds) and had grown by over 600% since it was discovered in 1986. Diet analysis indicated that juvenile salmon were an important part of the diet of piscivorous waterbirds nesting in the Columbia River estuary. Of birds nesting in the estuary, Caspian terns appeared to be most dependent on salmon (roughly 85% of their diet), followed by double-crested cormorants (*Phalacrocorax auritus*) and glaucous-winged/western gulls (*Larus glaucescens* x *L. occidentalis*). California and ring-billed gulls nesting up-river (*L. californicus* and *L. delawarensis*, respectively) appeared to be the least reliant on salmonids as a food source, perhaps due to high flows in 1997 and measures implemented at Columbia River dams to reduce bird predation. We estimated that Caspian terns nesting on Rice Island in 1997 consumed 6 - 25 million juvenile salmonids or roughly 6 –25% of all out-migrating smolts that reached the estuary. There was not enough information to estimate the number of juvenile salmonids lost to other bird predators in the estuary, but preliminary data suggested it was in the millions.

The results of the 1997 field study raised a number of important questions. First, was the surprisingly high avian predation rate on juvenile salmonids in the Columbia River estuary an anomaly, or was it representative of annual smolt losses to birds? Second, can the estimates of the magnitude of smolt losses to Caspian terns be refined through collection of new and more precise data? Third, is the magnitude of smolt losses to double-crested cormorants and glaucous-winged/western gulls in the estuary of similar magnitude to smolt losses to Caspian terns? Fourth, the smolt PIT tags recovered from the Rice Island Caspian tern colony provided valuable insights to the composition of smolts consumed by terns. Could recovery of a larger sample of PIT tags from the tern colony and other colonies provide valuable new information on the relative vulnerability of juvenile salmonids to avian predation? Fifth, what are the foraging strategies that allow Caspian terns to consume such a large proportion of all juvenile salmonids that reach the estuary? Finally, short of lethal control of Caspian terns and other avian predators, are there feasible management techniques for reducing smolt losses to birds and, in particular, can relocation of breeding colonies serve as a potential management tool.

Here we present results from our second field season investigating predation by colonial waterbirds and their impacts on juvenile salmonids in the lower Columbia River. In 1998, our study focused on assessing the magnitude of avian predation, identifying conditions and locales where avian predation is most prevalent, and testing the feasibility of various non-lethal management alternatives to reduce predation by birds. Specifically, our study objectives in 1998 were to: (1) determine the location, size, nesting chronology, nesting success, and population trajectories of fish-eating waterbird breeding colonies on the lower Columbia River; (2) determine diet composition of fish-eating birds, including taxonomic composition and energy content of various prey types; (3) estimate forage fish consumption rates, with special emphasis on juvenile salmonids, by breeding adult birds and their young; (4) identify foraging range, foraging strategies, and habitat utilization by piscivorous waterbirds; (5) determine the relative vulnerability of different groups of juvenile salmonids to bird predation based on PIT tag recoveries at piscivorous waterbird colonies; and (6) test the feasibility of various alternative methods for managing avian predation on juvenile salmonids and develop recommendations to reduce avian predation, if warranted by the results.

METHODS

Study Site

We investigated all nine major breeding colonies of piscivorous waterbirds on the lower Columbia River in 1998 (Figure 1). The nine colonies were photographed from the air for the purpose of estimating the number of breeding pairs at each colony. Three representative up-river colonies - Little Memaloose Island, Klickitat County, WA; Three Mile Canyon Island, Gilliam County, OR; and Richland Island, Benton County, WA - were visited biweekly to collect information on diet composition and nesting chronology. Three islands in the Columbia River estuary: East Sand Island, Miller Sands Spit, and Rice Island (Figure 2, Clatsop County, Oregon) that support large waterbird colonies were intensively monitored and were the primary focus our research in 1998.

Population Census

As in 1996 and 1997, piscivorous waterbirds were censused in 1998 using direct counts from aerial photographs, which is the best option for estimating breeding population size of ground-nesting colonial waterbirds (Bibby et al. 1993). We censused all known large colonies (>50 nesting pairs) on the lower Columbia River, from the Columbia River estuary to the head of McNary Pool (see Figure 1). Prior to the photo census, reference points that could be detected on aerial photographs were laid out at each colony to establish an accurate scale. Aerial photographs were taken by Bergman Photographic Services Inc. (Portland, Oregon), using a high resolution (1:1200), large format camera (Zeiss RMK Top 30). Overlapping color exposures were taken of each colony from a fixed-wing aircraft flying at low altitude (approx. 350 m) and low air speed (approx. 125 km/h). Aerial photographs were taken during late incubation (as determined by ground-based surveys conducted at each colony), when maximum colony attendance of breeding birds was assumed (Bullock and Gomersal 1981, Gaston and Smith 1984). The direct count of the number of adult birds of each species was used as an index to the number of nesting pairs at each colony. Up-river colonies were photographed on 22 May between 1306 and 1442 PDT. Estuary colonies were photographed at low tide on 28 May between 1016 and 1056 PDT. Rice Island was also photographed at high tide on 28 May between 1659 and 1703 PDT.

Total breeding population size was more accurately estimated for some colonies by doubling the number of birds counted on photographs of each colony, with a correction for the number of non-breeders, failed breeders, and off-duty active breeders on the colony at the time of the photographs. This correction (described below) was used to estimate the number of nesting pairs on the Rice Island Caspian tern and double-crested cormorant colonies and the East Sand Island double-crested cormorant colony.

Analysis of photographs to estimate breeding population size for each colony was carried out by the Survey, Mapping, and Photogrammetry Department at the Bonneville Power Administration (Portland, Oregon). Overlapping diapositive emulsions of each colony were analyzed using a Zeiss P-1 Stereoplotter. Counting and classifying birds by species, mapping of natural and cultural features, and outlining vegetation areas were accomplished using Zeiss PHOCUS software. Areas (m^2) occupied by nesting and loafing birds were calculated using Plus3 TerraModel software. Because the aerial photos were taken in color and at a large scale, individual nests and birds of different species were readily identified, with the exception of several species of gulls (*Larus* spp.), which could not be distinguished. Birds were enumerated from the digitized photos and their location, along with the locations of other features (e.g., vegetation), were plotted on a map of desired scale. Direct counts of individuals on the ground within the area where nests were found was used as an index to total population size. Population indices were compared between years and among colonies.

Population indices for terns and cormorants nesting in the Columbia River estuary were corrected to more accurately assess breeding population size for the Rice Island and East Sand Island colonies (important input for bioenergetics models, see below). For Caspian terns nesting on Rice Island, ground counts were carried out on each of eight 10 X 10 m census plots on various days throughout the nesting season (see below), including the day the aerial photos were taken. In each plot, the number of incubating and non-incubating terns was counted. Non-incubating birds were assumed to be failed breeders, non-breeders, or off-duty active breeders (i.e., mate of an incubating bird)[1]. The number of active breeding pairs was estimated by multiplying the total number of adults terns counted on the colony in the aerial photos by the fraction of birds in plots that were sitting on a nest at the time the photos were taken (i.e., non-incubating birds removed from count). The number of failed breeders at the time of the photo census was estimated from the difference between the peak count of nesting birds on colony (based on plot counts) and the count of nesting birds at the time of the photo census. The same procedure was followed to estimate the number of double-crested cormorants nesting on Rice Island in 1998, except that counts of incubating adults were carried out on the entire colony (i.e., no sub-sampling required). For double-crested cormorants nesting on East Sand Island, ten 20 x 20 m plots were laid out on digitized maps created from the aerial photos. The numbers of incubating and non-incubating cormorants were counted in each plot and the total number of active breeders on the colony was estimated as described above. Because ground counts of cormorants in plots were not carried out on the East Sand Island colony in 1998, we could not estimate the number of failed breeders at the time of the photo census, nor do we know the number of non-breeding sub-adults that were in the estuary in 1998.

To assess changes in the number of individual birds in each estuary population, Caspian terns and double-crested cormorants nesting on Rice Island were censused from blinds at least twice each week throughout the breeding season. Early and late in the season, when less than 2,500 terns were on the colony, and throughout the season for double-crested cormorants, censuses were by direct counts of the number of birds on the colony. When more than 2,500 terns were on the Rice Island colony, a sub-sampling technique was used whereby Caspian terns were directly counted in twelve 10 x 10 m plots. Plots were stratified according to differences in nest density on the colony. The average number of terns per plot was used to extrapolate the total number of terns on the colony based on the total colony area occupied by nesting terns. The total area occupied by nesting terns was calculated by sketching the boundaries of the colony onto a 20-m grid map of the site. Birds were only counted when there had not been any significant colony disturbances for at least 30 minutes.

Nesting Chronology and Productivity

Nesting chronology and productivity of Caspian terns and double-crested cormorants breeding on Rice Island were determined by monitoring individual nests. Individual nests were marked and then checked twice each week from blinds. Average Caspian tern clutch size was determined by walking a transect through the colony roughly one week prior to the peak of hatching and recording the contents of 200 nests. Double-crested

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[1] Because Caspian terns do not normally breed until their third year (Cuthbert and Wires, 1999) and because one- and two-year-old subadults rarely are found at breeding colonies (D. Craig, pers. obs.; L. Wires and F. Cuthbert, pers. comm.), few non-breeding subadults are likely to be counted on the colony. This assumption is supported by only rare sightings of terns in subadult plumage on the colony.

cormorant nests were not directly inspected on Rice Island due to the potential for catastrophic nest failure associated with our disturbance on the colony. Overall nest success for both Rice Island terns and cormorants were calculated by counting the number of young that reached fledging age as a proportion of the estimated number of nesting attempts, based on the estimates of breeding pairs from the photo census. Causes for individual nest failure were difficult to determine, but in some cases blind observations allowed for documentation of the cause for individual nest failures. Measurement of nesting chronology and productivity of double-crested cormorants on channel markers near Rice Island was repeated as in 1997 (see Roby et. al 1998 for details).

To determine productivity of double-crested cormorants on East Sand Island, 70 nests on the west end of the colony were individually marked and eggs were labeled with permanent marking pens. Nests were visited at night every 10 -14 days until most chicks were covered in down. Once chicks were downy and able to thermoregulate, we visited the colony once a week during daylight in concert with diet sampling (see below). Average brood size was estimated by counting the number of chicks in a sample of 100 nests near the center of the colony. These observations were made from a blind.

Diet Composition

Terns, gulls, and cormorants feed their young at the nesting colony until nestlings are full-grown and capable of flight. The transport and delivery of meals by breeding adults to chicks at the colony provides an opportunity to determine the taxonomic composition and energy content of the diet. In cormorants and gulls, chick meals are delivered in the foregut (esophagus, proventriculus, and gizzard) of adult birds, so chick diet samples consist of semi-digested food. In terns, chick meals consist of single, whole fish that are transported in the bill. In all three taxa of fish-eating birds, diet samples can be collected non-destructively when chicks spontaneously regurgitate during handling.

Because terns transport whole fish in their bills to their mates (courtship meals) and young (chick meals), considerable information on taxonomic composition of the diet can be obtained by direct observation of adults as they return to the colony with fish (e.g., bill load observations). Observation blinds were set up at the periphery of the colony prior to the onset of egg laying so that prey items could be identified with the aid of binoculars and spotting scopes.

Additionally, destructive sampling techniques were necessary to assess the diet composition of adult birds when non-destructive methods were inadequate (e.g., to sample diet outside the chick-rearing period or to assess relative proportions of various salmonid species in the diet of terns). The best method to obtain a random sample of the diet was to shoot adult birds en route to or on the colony. A shotgun was used to collect adults as they commuted back to the colony from both down-river and up-river foraging locations, and an air rifle was used to collect adults on the colony when collecting birds in flight was not feasible. Destructive sampling techniques were used at all piscivorous waterbird colonies in the Columbia River estuary and at selected up-river colonies (i.e., Little Memaloose, Three Mile Canyon, and Richland islands).

Non-Destructive Diet Sampling

Bill load observations: Bill load observations were conducted at the Rice Island and the Three Mile Canyon Island Caspian tern colonies. Observations of the taxonomic composition of prey items brought to the colony by breeding terns were recorded from blinds located at the periphery of the colony. Observations at Rice Island (total hours = 100.5; total days = 34) were conducted from May 21 to 28 July between 0844 and 2007 PDT. Observations at Three Mile Canyon Island (total hours = 4.5; total days = 4) were conducted from May 21 to 19 June between 1216 and 1355 PDT. The target sample size was 100 bill load observations per week and 20 bill load observations every other week at Rice Island and Three Mile Canyon Island, respectively. Prey items were identified to the lowest discernible taxon using either binoculars or spotting scopes. We were confident in our ability to discern salmonids from non-salmonids and most non-salmonid taxa based on direct observations from blinds, but were less confident in our ability to differentiate between the various salmonid species, necessitating the collection of adult stomach contents and dropped fish from terns. Prey taxon, length, meal type (courtship or chick meal), date, and time of delivery were recorded. To test the assumption that tern bill loads are representative of the overall diet of terns, we compared the taxonomic composition of bill loads collected for adult terns ("dropped fish") with the stomach contents of those same adult terns (see below).

Chick regurgitations: Whenever possible, chick regurgitations were collected in lieu of destructive sampling of adult birds (see below). Chick regurgitations were collected from 20 May through 7 July between 0015 and 2330 PDT. Six to ten chick regurgitations were collected at each colony, each week. Chick diet samples were obtained by collecting spontaneous regurgitations from chicks, caused either by handling or stress associated with investigator intrusion in the colony. Samples were placed individually in labeled whirl-pak bags, weighed on an Ohaus battery-powered top-loading balance (± 0.1 g), and stored on ice in a cooler until they were placed in a freezer at the end of the day. The samples were kept frozen at -20^{o}C until laboratory analysis. All relevant diet sample data (i.e., sample number, date, time, species, colony location, and field identification of prey item) were recorded and subsequently entered into a database.

Lethal Diet Sampling

Adult stomach contents: Samples of adult stomach contents were collected from 9 April through 29 July, between 0754 and 2145 PDT. Each week approximately ten samples were collected from each cormorant and gull colony in the estuary. Six to ten samples of adult tern stomach contents were collected each week at Rice Island. Five to 10 samples per species were collected biweekly from the selected up-river colonies. Immediately after collection, body mass and wing length of each adult bird were recorded prior to dissection. Then the abdominal cavity was opened, the foregut (esophagus, proventriculus, and gizzard) removed, and the contents emptied into a whirl-pak bag.

Each sample was weighed, stored, and frozen as described above. All relevant data on collected adults (i.e., sample number, date, time, species, age, sex, body mass, wing chord, colony location, bird activity, commuting direction, and field identification of prey items) were recorded and subsequently entered into a database.

Bill Load Collection: Caspian terns returning to the Rice Island colony were shot to retrieve whole fish carried in their bills (referred to hereafter as "dropped fish") and for adult stomach contents analysis (described above). Most terns were shot as they were flying westward along the southern shoreline of Rice Island. Birds were shot roughly 0.4 km east of the colony, a location far enough removed so as not to noticeably disturb the terns on the colony. Dropped fish were collected from 14 April through 28 July, between 0835 and 1600 PDT; approximately 10 dropped fish were collected each week. Dropped fish samples were particularly important in determining the proportion of various salmonid species in the diet of terns nesting at Rice Island. Terns were shot over land so that dropped fish could be retrieved. For each dropped fish collected we noted the species, fork length, weight, and presence or absence of fin clips.

We assessed the health status and stage of smoltification of juvenile salmonids collected from terns and compared them to in-river smolts. Kidney tissue and gill filaments were collected from dropped fish collected near the Rice Island tern colony (see above) and from in-river fish collected at Bonneville Dam (see Schreck et al. 1998 for details on collection procedures). All dropped fish collected on Rice Island were fresh and, in many cases, still alive when collected. Kidney tissue and gill filaments from juvenile salmonids were stored in vials, and gill filaments were preserved in a buffered solution (Zaugg 1982). All samples were placed on dry ice and then transported to a freezer and stored at –84° C until they were analyzed. Gill filament samples were sent to Bill Gale and Robin Schrock (USGS-BRD Northwest Science Center, Columbia River Field Station) for measurement of NA^+/K^+ ATPase, an index to smoltification. Kidney samples were sent to Ron Pascho and Diane Elliot (USGS-BRD Northwest Science Center, Seattle) to be tested for the incidence and intensity of bacterial kidney disease. A more detailed description of the methods and the results from these tissue collections are presented and discussed elsewhere (Schreck and Stahl 1999).

Laboratory Analysis of Diet Samples

Because cormorants and gulls feed chicks by regurgitation, it was assumed that the taxonomic composition of adult stomach contents and chick regurgitations were similar and therefore could be pooled to describe overall diet composition. For Caspian terns, the colony-based bill load observations were used to estimate general taxonomic composition of the diet (eliminating the directional bias associated with earlier tern diet sampling efforts; see Roby et al. 1998) and dropped fish were used to estimate the relative proportions of various salmonid species in the salmonid portion of the diet.

Laboratory analysis of diet samples was conducted at the Oregon Department of Fish and Wildlife (ODFW) laboratory in Clackamas, OR. Samples were partially thawed, removed from whirl-pak bags, and re-weighed. Samples were separated into major food categories: fish, crustaceans, mollusks, insects, non-fish vertebrates, plant material, and refuse. Fish were further identified to genus and species, whenever possible. Items from each taxonomic category were weighed and enumerated. Whole or nearly intact fish were individually weighed, measured for fork length, and refrozen for proximate composition analysis to determine energy content. Semi-digested fish matter was not always clearly identifiable. Unidentifiable fish samples were artificially digested according to the methods of Peterson et al. (1990, 1991). Once digested, diagnostic bones (i.e., cleithra, dentaries, pharyngeal arches, and opercles) were removed from the sample and identified to species using a dissecting microscope (Hansel et al. 1988). Unidentified fish samples that did not contain diagnostic bones and samples comprised of bones only (i.e., no soft tissue) were not included in the diet composition analysis. The taxonomic composition of waterbird diets was expressed as % of identifiable biomass and % of identifiable prey items.

For terns, % identifiable prey items was based on identified bill loads observed from blinds, and separated into two-week periods throughout the nesting season. Then the average of the bi-weekly percentages was calculated as the annual diet composition for terns based on prey items. Percent identifiable biomass was determined by assigning a mass to each identified prey item, based on the average mass for that prey type among dropped fish and intact fish in adult stomach contents of terns. The estimated biomass of each prey type for each bi-weekly period was divided by the total estimated biomass of bill load fish to obtain % of identifiable biomass in Caspian tern diets. The average of the biweekly percentages was used, as before, to estimate the annual diet composition based on prey biomass.

For cormorants and gulls, the stomach contents of each individual adult collected (or each chick regurgitation) was the sampling unit. Each adult stomach contents (or chick regurgitation) sample was sorted by identifiable prey items and identifiable biomass, and then the percentage of each prey type that contributed to that sample's total identifiable prey items or biomass was calculated. The percentages for each sample were averaged over 4-week periods encompassing the entire breeding season. The 4-week periods used to describe seasonal cormorant and gull diets were: (1) pre-laying and laying (17 April – 14 May); (2) incubation (15 May – 11 June); (3) early chick-rearing (12 June – 9 July); and (4) late chick-rearing (10 July – 6 August). Proportions of prey types in the diet over the entire breeding season were calculated as the mean of the 4-week values.

PIT Tag Recovery

In 1998, salmon PIT (Passive Integrated Transponder) tags were recovered or interrogated on the Caspian tern colonies on Rice, Three Mile Canyon, and Crescent islands and on the double-crested cormorant colony on Rice Island. PIT tag data obtained in 1998 were appended to the PIT interrogations on bird colonies in previous years (Roby et al. 1998) and were provided to the Passive Integrated Transponder Tag Information System (PTAGIS), a centralized database maintained and operated by the Pacific States Marine Fisheries Commission Computer Service Center in Portland, Oregon. The analyses that follow are based on the information provided in the PTAGIS database at the time these analyses were completed (January 1999). Any updates to the PTAGIS database (i.e., changes in tagging records) subsequent to the completion of these analyses could change the results presented here.

Each colony was searched for tags once the birds had left the colony following the breeding season (August – October 1998). Established PIT tag recovery methods were used in 1998 and are described elsewhere (see Roby et al. 1998). In addition, new methods were developed by the National Marine Fisheries Service to both recover tags and interrogate tags *in situ* at piscivorous waterbird colonies (see Ledgerwood et al. in press). The new tag recovery method involved using an automated sieving machine at the Rice Island Caspian tern and double-crested cormorant colonies. Recovered tags were later read using a hand-held PIT tag detector. Also, PIT tags were interrogated *in situ* using a large flat plate PIT tag detector specially designed for PIT tag interrogation on bird colonies. The flat plate detector was deployed on the Rice Island and Crescent Island Caspian tern colonies and on the Rice Island cormorant colony. These new methods are described in detail by Ledgerwood et al. (in press).

Tagging and release information for all PIT tags found on piscivorous waterbird colonies was obtained from the PTAGIS database (PTAGIS 1998) and are summarized here. PIT tag data were analyzed to determine the relative vulnerability of various salmonid stocks, rearing types, and transported versus in–river migrants to predation by terns and cormorants nesting on Rice Island in 1997 and 1998[2]. Differences in vulnerability to bird predation were based on comparisons of the relative proportion of PIT tags found on the bird colonies from various groups of fish to those same proportions detected in-river. In-river detections of different stocks and rearing types (availability) was determined based on interrogations of PIT-tagged fish in the juvenile bypass facility at Bonneville Dam. In-river availability of transported versus non-transported fish was based on the combined sample of all PIT-tagged fish of Snake River origin that were either transported or bypassed at Bonneville Dam[3]. For each comparison, only those PIT tags that were found on colony and had also been detected in the in-river sample were used. Chi-squared tests for independence (Siegel 1988) were used for statistical comparisons of on-colony and in-river proportions of PIT-tagged fish.

Bioenergetics Model Construction and Components

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[2] Only data from the 1997 and 1998 migration years were included in these analyses due to inadequate sample sizes from previous migration years.

[3] Because differences in direct mortality associated with transportation and Bonneville Dam bypass could bias our measure of relative in-river availability of these groups, we analyzed these data using three different relative mortality assumptions; (1) transportation mortality is equal to Bonneville Dam bypass mortality, (2) transportation mortality is 10% greater than Bonneville Dam bypass mortality, and (3) transportation mortality is 10% less than Bonneville Dam bypass mortality.

We constructed bioenergetics models to obtain supportable estimates of the number of juvenile salmonids consumed by Caspian terns, double-crested cormorants, and glaucous-winged/western gulls in the Columbia River estuary (Madenjian and Gabrey 1995, Glahn and Brugger 1995, Derby and Lovvorn 1997). The conceptual model that forms the basis for the bioenergetics calculations for 1998 is shown in Figure 3. We modified the bioenergetics models used to generate estimates of smolt consumption by Caspian terns and double-crested cormorants in 1997 in order to obtain estimates in 1998 that were more accurate and precise, and hence more reliable (see Fig. 3 in Roby et al. 1998 and Fig. 3 in this report). The model starts with daily energy expenditure of an adult, modified by estimates of metabolizable energy coefficients to derive an estimate of daily energy consumption by individual birds. Individual daily energy consumption was then expanded by the estimated number of individuals in the entire population, times the number of days in the predation period, in order to estimate population energy demands during the predation period. Estimates of the numbers of juvenile salmonids and other prey types consumed to meet population energy demands were derived from measurements of the proportion (% biomass) of salmonids and other prey categories in the diet during the predation period, the mean mass (g) of individual prey items in each prey category during the predation period, and the mean energy density of items in each prey category (kJ/g fresh mass). For each input variable in the bioenergetics model, we used a range of values that were designed to produce minimum, maximum, and "best" estimates for the number of juvenile salmonids consumed by each bird population. We used empirical data, collected in 1998, for all input variables except daily energy expenditure in double-crested cormorants and glaucous-winged/western gulls and metabolizable energy coefficients for all three species. Values for these parameters were based on published studies of seabird energetics (Birt-Friesen et al. 1989, Glahn and Brugger 1995, Jackson and Cooper 1998).

We measured daily energy expenditure (DEE, kJ $bird^{-1}$ day^{-1}) directly using the doubly labeled water method (Lifson and McClintock 1966) on adult Caspian terns nesting at the Rice Island colony (N = 22). During the pipped egg stage of incubation or the first few days of the chick-rearing period (when chicks were brooded continuously by parents), we captured adult terns in noose mats placed around eggs or very young chicks. Captured adults were injected intraperitoneally with 0.9 ml of doubly labeled water ($D_2{}^{18}O$). Following injection, adults were weighed (± 0.1 g), measured (wing length ± 1 mm, culmen ± 0.1 mm, and tarsus ± 0.1 mm) and banded with USFWS stainless steel leg bands. The plumage of each adult was also dyed with rhodamine in a unique pattern so that injected adults could be easily recognized on the colony. Injected adults were held in cotton bags for one hour post-injection to allow isotopically-labeled water to equilibrate with body water. Then an initial blood sample of about 80 ul was obtained by puncturing the brachial vein and collecting blood in non-heparinized microhematocrit tubes. Adults were then released at the breeding colony. Injected adults were recaptured or lethally collected 24-48 hours following injection and a second blood sample was taken. Blood samples were also collected from non-injected adult Caspian terns for measurement of background levels of the two isotopes. Tubes with blood were flame-sealed in the field and stored at about 5^{o} C to prevent fermentation.

Isotope concentrations in distilled water from blood samples were measured in the lab of G. H. Visser, Centre for Isotope Research, University of Groningen, The Netherlands. Using the CO_2 equilibration technique, $^{18}O/^{16}O$ ratios in blood were assigned by isotope ratio mass spectrometry, as were $^{2}H/^{1}H$ ratios in H_2 gas generated from water samples using zinc as a catalyst. Isotope analyses were run in triplicate to assure accuracy of estimates of CO_2 production. Water flux rates and CO_2 production rates were calculated on the basis of equations in Nagy (1980), using an energetic equivalent of 27.33 kJ/l CO_2, appropriate for a protein-rich diet (Gessaman and Nagy 1988). Total body water (% of initial body mass) was calculated on the basis of ^{18}O dilution, using the plateau method (i.e., no extrapolation).

Daily energy expenditures (DEE) of adult double-crested cormorants and glaucous-winged/western gulls during the breeding season have not been previously measured. Therefore, we estimated DEE from published, empirically-derived allometric equations predicting field metabolic rates of seabirds as a function of total body mass. The empirical data used to generate these prediction equations were obtained by using the doubly labeled water method to measure CO_2 production in a variety of free-ranging seabirds during the breeding season, especially the chick-rearing period (Birt-Friesen et al. 1989). The estimated DEE used in the bioenergetics models for double-crested cormorants was based on average adult body mass measured on this species nesting at Rice Island and East Sand Island in the Columbia River estuary (2,486 g) and allometric equations presented in Birt-Friesen et al. (1989). Based on these published results we chose 2,700 kJ/day as the best estimate for DEE of double-crested cormorants in the estuary. This value is intermediate between the allometric predictions for seabirds using flapping flight and seabirds from cold water regions. For the maximum estimate of DEE in cormorants, we used 3,200 kJ/day, a value intermediate between the allometric prediction based on seabirds using flapping flight and that of seabirds using flapping flight from cold water regions. The minimum estimate of DEE was 2,200 kJ/day from the allometric prediction based on all seabirds combined. This minimum estimate of DEE exceeds the DEE calculated from equations in Glahn and Brugger (1995) for double-crested cormorants wintering in the Mississippi Delta, corrected for differences in bird size between the Columbia River estuary and the Mississippi Delta.

Daily energy expenditure of adult glaucous-winged/western gulls in the estuary was estimated as 1,420 kJ/day, based on the allometric equation for all seabirds (Birt-Friesen et al. 1989) and an average body mass of adults nesting in the estuary of 1,282 g. The estimated maximum DEE was 1,855 kJ/day, based on the allometric equation for seabirds using flapping flight. The estimate of minimum DEE was 1,200 kJ/day, a value intermediate between the allometric prediction for warm water seabirds and all seabirds.

Metabolizable energy coefficients for a variety of seabirds feeding on a variety of prey have been shown to average 0.75, but ranged from about 0.70 to 0.80 (Jackson and Cooper 1999). Consequently, we used 0.75 as our best estimate, 0.80 as the minimum estimate (high energy assimilation efficiencies yield low food consumption rates), and 0.70 as the maximum estimate in bioenergetics models for each of the three species.

Daily energy consumption was calculated from daily energy expenditure divided by metabolizable energy coefficients (Figure 3).

For Caspian terns and double-crested cormorants the breeding season was divided into 1-week periods and the number of predation days in each 1-week period was the product of the estimate of population size during that week and the number of days in a week (7). Weekly population estimates were obtained for the Rice Island Caspian tern colony, the Rice Island double-crested cormorant colony, and East Sand Island double-crested cormorant colony, based on counts of individuals on the respective breeding colonies (see Population Census methods). These counts were the basis for our best estimates of adult population size for both terns and cormorants. The maximum and minimum estimates of adult population size for tern was based on variation in colony attendance estimates made around the time of the aerial photo census. Three separate counts of adult birds in plots were made on each of three days around the time that the aerial photo census was conducted (i.e., the day before, day of, and day after the aerial photo census) and the coefficient of variation of these counts was calculated. For cormorants there were insufficient empirical data to estimate the variation in colony attendance around the time of the aerial photos. Hence, maximum and minimum estimates of adult population size were derived by varying the best estimate by 20%. These measures of variation were applied to weekly best estimates of adult population size for terns and cormorants to come up with maximum and minimum population estimates each week. Once the maximum, best, and minimum number of predation days had been for each 1-week period, predation days were summed biweekly so as to correspond with biweekly determinations of diet composition (see below). Total population energy consumption for Caspian terns on Rice Island and double-crested cormorants on Rice and East Sand islands were calculated as the sum of all biweekly energy consumption estimates for each colony throughout the breeding season.

The total population energy consumption includes the energy consumption of adults and the young raised during that breeding season. For the purposes of the bioenergetics models for Caspian terns and double-crested cormorants, the estimate was based on the number of young fledged during the breeding season. First we assumed the DEE for developing young averages 65% of the DEE for adults of that species. This estimate is based on measurements of the gross foraging efficiency of parent seabirds of several species while raising young (Roby 1991). We also assumed each chick that is successfully fledged spends about 50 days in the estuary before leaving on post-breeding migration. Thus the total energy consumption by nestlings was the product of (number of fledglings) X (0.65[adult DEE]) X 50 days.

No weekly estimates were available of the number of glaucous-winged/western gulls at each of the three breeding colonies in the estuary, so the number of predation days was estimated from the estimated average duration of residence by individual gulls in the estuary, times the number of breeding gulls as indicated by the aerial photo census. We chose a best estimate of 105 days (ca. 20 April to 28 July) as the average residency by adult gulls in the estuary, with minimum and maximum residency periods of 90 days (ca. 22 April to 15 July) and 120 days (17 April to 5 August), respectively. For gulls, total population energy consumption was estimated by the product of daily population energy consumption and the mean duration of individual gull residency in the estuary (in days).

Because the diets of gulls breeding on Rice Island and Miller Sands Spit are similar, gulls from these two colonies were considered as belonging to a single colony for the purposes of the bioenergetics model. The best estimate of population sizes (East Sand Island - 8,244 individuals; Rice Island/Miller Sands Spit - 3,479) were based on the total count of gulls from the aerial photos multiplied by a correction factor of 1.5 to account for off-duty adults not in attendance at the colony. Maximum population estimates for the two gull colonies (East Sand Island - 10,992 individuals; Rice Island/Miller Sands Spit - 4,638) were twice the number of gulls counted on the aerial photos. The minimum estimate of population sizes (East Sand Island – 5,496 individuals; Rice Island/Miller Sands Spit – 2,319) were based on the total count of gulls on the aerial photos. No attempt was made to explicitly census the non-breeding portion of the gull population, nor was an attempt made to incorporate the energy consumption of nestling gulls in the bioenergetics model.

The mean energy densities of each category of prey, the percent total energy consumption by prey category, the of estimate the total energy contribution by each prey category, and the remaining calculations necessary to estimate the number of juvenile salmonids consumed by a bird population were based on the same methods as in 1997 (see Roby et al. 1998). The only modifications to the 1997 bioenergetics model protocol were that in 1998 the relative proportions of each prey category in the diet were matched to their specific total biweekly energy consumption. This finer scale approach better integrates seasonal changes in both the number of birds and the relative proportion of prey types in the diet.

Foraging Ecology

Three methods were used in 1998 to quantify the foraging activities of Caspian terns in the estuary: aerial strip transect surveys, riverbank point count surveys, and on-ground counts of birds flying to and from the Rice Island colony site. Riverbank point count surveys also provided information on the distribution of double-crested cormorants and other piscivorous waterbirds in the estuary.

Aerial strip transect surveys were conducted using a Cessna 206 aircraft. The aircraft was flown at approximately 150 m AGL and at 100 knot airspeed during counting periods. Two observers counted Caspian terns seen within ca. 250 m of either side of the aircraft during 1-minute periods. Location and count data were recorded between counting periods. Flying and roosting terns were counted separately. The entire area of the estuary was covered by flight transects, from the jetties at the river mouth to approximately river kilometer 92 (Crims Island) and from riverbank to riverbank, covering the main channel, side channels, and all side bays and sloughs. Counts were conducted on seven different survey flights between 19 May and 6 July. A total of 346 1-minute counts were conducted during the seven flights, ranging from 35 to 66 counts per flight.

Each 1-minute aerial count was converted into a measurement of Caspian tern density, assuming a constant airspeed of 100 knots and a transect width of 0.5 km. This density was considered a sample of Caspian tern density at the midpoint of the strip covered by the airplane during the counting period. These densities were then sorted and averaged by river kilometer (with river kilometer 0 at the mouth) and by distance from the Rice Island tern colony. Relative density of terns in the estuary was then estimated for each river kilometer by multiplying the average of observed density at each river kilometer by the width of the river at that river kilometer.

Riverbank point count surveys were conducted weekly from early April through mid-August. Forty sites were visited weekly throughout the entire season and 11 additional sites were visited for part of the season or as time allowed. Sites were selected based on (1) accessibility by automobile, (2) views of a large portion of the estuary, (3) views of various river habitat types, and (4) proximity to presumed piscivorous waterbird foraging locations (e.g., pile dikes and hatchery release sites). A total of 21 sites were located on the Washington side of the river and 19 on the Oregon side. Rice Island was located at roughly the center of the survey area, with 22 and 18 sites located above and below the island, respectively. It was possible to sample all sites on one or the other side of the river in a single day. For any given survey day, the initial site visited was determined randomly, then the surveyor moved up-river until the most up-river site on that side had been visited. Then the surveyor drove directly to the most down-river site and proceeded up-river again until all sites on that side of the river had been visited. This sampling pattern ensured that each site was visited at different times of day and at different stages of the tidal cycle throughout the breeding season. During the 10-minute observation period at each site, all piscivorous waterbirds were counted and the maximum count of each species was recorded. Commuting and foraging terns and cormorants were counted separately and all single- or mixed-species foraging flocks (i.e., tight aggregations of five or more birds) were noted. Also recorded were arrival time of the observer to the site and several weather/visibility variables (i.e., % cloud cover, precipitation, air temperature, wind speed index, and wind direction). A total of 1,135 point counts were conducted over the season: 22 % in April, 27 % in May, 26 % in June, 17 % in July and 8 % in August.

The riverbank survey data were used to investigate the effects of two anthropogenic factors that may affect tern or cormorant foraging distribution: pile dikes and smolt releases from local hatchery facilities. To understand the effects of pile dikes, mean site attendance of both species was compared between sites having pile dikes and nearby sites not having pile dikes, but similar in habitat type (i.e., main shipping channel). To assess the effects of net pen or hatchery (non-volitional) smolt releases in the estuary on tern or cormorant foraging patterns, observational data were collected at sites down-river and in close proximity to release sites. At these sites, tern attendance on the day immediately following a release was compared to tern attendance on days prior to the release, when the availability of smolts in the area was presumably less. While it was not possible to precisely know where smolts concentrated following evening/nighttime releases, it was presumed that if smolts lingered in areas immediately down-river from release points, this would attract higher concentrations of terns and/or cormorants to these sites. If higher piscivorous bird concentrations were not seen in these areas following smolt releases, then presumably these releases had minimal effect on the foraging patterns of most terns and cormorants in the estuary. In that case, presumably the foraging patterns of only small numbers of birds searching those specific locations in the estuary at the time of releases would be affected.

Counts of terns commuting to and from the colony site were made weekly from late April until the end of July. Observers were simultaneously positioned at roughly equal distances (500 m) from the colony in both the up-river (on Rice Island, east of the colony site) and down-river (in a boat west of Rice Island) directions. All terns seen flying to or from the colony were counted during synchronized 10-minute periods. At least six counts were performed each week throughout the nesting season. Counts from up-river were then compared with those from down-river (grouped by weeks) using t-tests, to check for differences in commuting, and presumably foraging, activity up-river and down-river from the colony.

Management Feasibility Studies

We tested the feasibility of (1) discouraging Caspian terns from nesting in parts of previously occupied colony sites, and (2) encouraging Caspian terns to nest on an island not previously used by terns for nesting. We tested the efficacy of transplanted vegetation for discouraging nesting by terns on plots within the Rice Island colony. We used tern decoys and an audio playback system that broadcast tern calls to encourage nesting by terns on recently deposited dredged material (bare sand) near the Rice Island colony. The testing of these techniques was essential for determining whether a tern colony could be relocated to historic colonies outside the Columbia River estuary, and thereby reduce avian predation on juvenile salmonids in the lower Columbia River.

Methods to Discourage Nesting

Caspian terns typically select nest sites where the substrate is sand or dirt with little or no vegetation (Quinn and Sidervan 1998). We speculated that an increase in density of vegetation on portions of the existing Rice Island colony site would reduce or preclude nesting and roosting by terns.

Using aerial photographs of the Rice Island Caspian tern colony in 1997, we selected eight 10 X 10 meter plots where Caspian terns had nested the previous year. All plots were selected at random, devoid of vegetation, and a minimum of 10 m apart. On 30 March, six of these plots were planted to establish three different plant densities; high (1 plant/m^2), medium (0.36 plants/m^2), and low (0.09 plants/ m^2). Two plots were left unvegetated as controls. The plants used in the experiment, biennial rosettes of tansy ragwort (*Senecio jacobaea*), were transplanted from vegetated portions of Rice Island near the tern colony site. At transplanting, most plants were 15 – 25 cm tall. The wet conditions in the spring of 1998 resulted in 100% survivorship of plants without supplemental water or fertilizer. Observations of nesting chronology and numbers of terns in each of the eight plots were recorded at least twice each week from 20 April to 11 June, after which no new tern nests were initiated on Rice Island.

Methods to Encourage Nesting

We attempted to encourage Caspian terns to nest on Miller Sands Spit using tern decoys and an audio playback system that broadcast tern vocalizations. Caspian terns had not previously nested on Miller Sand Spit; however, terns were occasionally seen roosting at the site in 1997. This site was chosen due to its close proximity to the Rice Island tern colony (about 1.5 km) and similarities in habitat (i.e., recently deposited sand dredge spoil).

On 28 March, we assembled the audio playback system on Miller Sands Spit. The sound system consisted of one solar panel, two 12-volt golf cart batteries, one charge controller, a portable compact disk player, and a pair of patio-style outdoor speakers (audio system developed by S. Schubel, Murremaid Music Boxes). The batteries and compact disk player were housed in a locked, weather-proof box beneath the solar panel. The speakers were placed 50 m from the box and solar panel and approximately 30 m apart. The speaker wires were buried in the sand.

Caspian tern vocalizations were recorded on a compact disk and played on a continuous loop, 24 h/day. Early in the season (28 March – 17 May), we used recordings of vocalizations provided by the Cornell Laboratory of Ornithology (Ithaca, New York); later (17 May – 11 June) we used digital recordings of the Rice Island tern colony prepared by K. Turco of Alaska's Spirit Speaks.

Three-dimensional life-size Caspian tern decoys were provided by Hans Blokpoel (Canadian Wildlife Service, Nepean, Ontario, Canada) and Jim Henry (Mad River Decoys, Waitsfield, Vermont). Decoys were made of fiberglass and hand painted. Initially, the hollow decoys were filled with sand and placed on colony without additional support. Later, wooden dowels about 30-cm long were inserted in the bottom of the decoys to keep them erect in the wind. The first 12 decoys were deployed near the speakers on 20 April. On 29 April, an additional 10 decoys were added to the area, and on 8 and 9 May, 32 more decoys were deployed. Decoys were placed roughly two meters apart and surrounding the two outdoor speakers. The decoys were not deployed at the same time as the audio playback system because of manufacturing delays.

Observations of Caspian terns in the area of the decoys and speakers on Miller Sands Spit were performed three to four times a week, from 28 March through 11 June, between 0830 and 1700 PDT. The number of terns in the area surrounding the decoys was counted and their behaviors recorded from a nearby observation blind. We determined nesting chronology, number of nests initiated, number of eggs laid per nest, causes for nest failure, and hatching success. In addition, we measured kleptoparasitism rates (i.e., stealing of fish carried in the bills of terns by gulls and crows) at the Miller Sands Spit and Rice Island tern colonies. Kleptoparasitism rates at the two colony sites were compared to assess differences in the levels of interference and disturbance by gulls and crows of nesting terns. We used focal animal observations of terns carrying fish at both colonies during the same time periods and tide cycles to measure kleptoparasitism rates. For each tern observed with a fish, we recorded the fate of the fish and the time that the tern spent on the ground at the colony before the fate of the fish was determined. Fish fate was classified as either a kleptoparasitism, courtship feed, self feed, chase by gull or crow/no feed, or left colony/no feed. These observations were performed from 11 May through 11 June.

RESULTS

Population Census and Productivity

Population indices for piscivorous waterbird colonies in the lower Columbia River are listed in Table 1. In 1998, population indices for Caspian terns increased at Rice Island but decreased at both Three Mile Canyon Island and Crescent Island as compared to the previous year (Table 2). Overall, the double-crested cormorant population in the estuary continued to increase, while glaucous-winged/western gulls declined in the estuary (Table 2). Population increases for breeding Caspian terns and double-crested cormorants in the Columbia River estuary from 1996 to 1998 continue a longer term trend of expanding breeding population sizes for these two species in the estuary (Figures 4 and 5). All upriver gull colonies decreased except Richland Island (Table 2), which increased 19% from the previous year. The largest increase in population indices from 1997 to 1998 was for the East Sand Island double-crested cormorant colony, the Rice Island Caspian tern colony, and the Richland Island gull colony (21%, 19%, 19% increases, respectively; Table 2).

To estimate the total number of pairs of Caspian terns nesting on Rice Island in 1998, we estimated the proportion of adults on the colony that were incubating eggs at the time the aerial photos were taken. Ground counts of Caspian terns in census plots indicated that 64.9% of the terns counted on the aerial photo (11,223 terns) were on nests which suggests that there were about 7,284 active nests (i.e., 14,567 nesting individuals) on Rice Island at the time of the aerial photos. The remaining 35.1% or 3,939 birds counted on-colony in photos were either failed breeders, off-duty active breeders, or non-breeders. To estimate the number of failed breeders in the estuary at the time of the photo census, we estimated the peak number of active breeding pairs on the colony, based on the maximum count of terns in census plots. The maximum number of terns in census plots was on 21 May, 7 days prior to the aerial photo census (28 May). Plot counts of terns on 28 May and 21 May, indicated that there were approximately 12,551 terns on the colony on 21 May, compared with 11,223 on 28 May. The difference between these estimates (1,328 terns) is our best estimate of the number of failed breeders at the time of the photo census. Our best estimate of the breeding population size for the Rice Island tern colony in 1998 was 7,948 breeding pairs (7,284 active breeding pairs + 664 failed breeding pairs).

Ground counts of incubating and non-incubating cormorants on the Rice Island colony at the time the aerial photos were taken indicated that 73.5% of the birds counted in the photos were adults incubating eggs. This suggests that there were about 795 breeding pairs or 1,590 breeding individuals with active nests on the Rice Island colony at the time of the aerial photos. Of the remaining 26.5% or 287 birds counted on-colony in the photos, at least half were off-duty active breeders because of their close association with a nest and an incubating adult. Because there were very few unattended nests at the time of the photo census, and we observed no nests lost or new nests built before and after the photo census, respectively, it is likely that nearly all breeding pairs were accounted for in the aerial photo (i.e., few non-breeders or failed breeders in the photos or off-colony).

Counts of incubating and non-incubating birds on census plots in photos of the double-crested cormorant colony on East Sand Island indicated that 82% of the cormorants counted (6,403 birds) were on nests. This suggests that there were about 5,250 breeding pairs of cormorants with active nests (i.e., 10,500 actively breeding individuals) on East Sand Island at the time of the aerial photos. Again, because nearly all nests were occupied at the time of the photo, it is likely that there were few failed breeders unaccounted for in the aerial photo of the East Sand Island cormorant colony. We estimate there were an additional 70 nesting pairs (140 breeding cormorants) on channel markers near Rice Island and 120 nesting pairs (240 breeding cormorants) on pilings near Desdemona Sands. Our best estimate of the total breeding population of double-crested cormorants in the Columbia River estuary in 1998 was 12,470 individuals or 6,235 breeding pairs.

The weekly population censuses of Rice Island Caspian terns and double-crested cormorants (Figure 6) resulted in the documentation of changes in the breeding populations of the two species throughout the breeding season. Caspian tern numbers on the colony site rapidly increased from just a few adults in the first week of April to a peak on-colony estimate of around 12,000 terns in the third week of May. Peak colony attendance occurred soon after the peak of egg laying on Rice Island. Predation of tern eggs by gulls resulted in some terns abandoning the colony site by the end of May. With the initiation of hatching, predation by gulls on chicks increased dramatically, so that by mid-June at least 40% of adult terns had left the colony. The population was then relatively stable until adult terns began to leave en masse with their recently fledged chicks in mid-July. There were no terns left on the island by the last week of August.

Breeding chronology (i.e., egg laying dates, median hatch dates, fledging dates) of the piscivorous waterbird colonies in the lower Columbia River during 1998 were similar to 1997 (Roby et al. 1998). Numbers of Caspian terns and double-crested cormorants on the Rice Island colonies were estimated each week during the nesting season in order to monitor changes in estuary-wide populations (Figure 6). In early April, Caspian terns first began arriving in small numbers at the Rice Island colony, followed by dramatic increases in bird attendance during the latter part of April and early May. Following the onset of hatching in late May, tern colony attendance began to decline as nest failures outstripped nest initiations (see below). Colony attendance began to decline sharply in early June, when nesting failure was especially prevalent. During the late chick-rearing period in late June, colony attendance was relatively stable until chicks began to fledge in early July. The pattern of colony attendance for double-crested cormorants (Figure 6) was similar to that of Caspian terns, including a sharp decline early in chick-rearing. After the majority of young had fledged in mid- to late July, adult attendance quickly dwindled until there were no terns or cormorants on the Rice Island colonies by August 20.

The Rice Island Caspian tern colony experienced better reproductive success in 1998 than in 1997, but productivity was still lower than the average productivity of West Coast Caspian tern colonies (Table 3; Cuthbert and Wires 1999). Approximately 3,900 young were fledged from an estimated 7,984 initiated nests (0.49 fledglings/nest). Overall nesting success (percentage of initiated nests that fledged at least one young) was about 49%. The primary cause of reproductive failure was predation on eggs and young by glaucous-winged/western gulls. The Mayfield daily survival rate of nests with eggs was 0.989 (Bart and Robson 1982). Approximately 75% of closely observed, individual nests (N = 94) hatched young with an average brood size of 1.58 ± 0.62. As was observed in 1997, gulls intensely depredated young chicks (2-10 days post-hatch). Although we could not directly measure daily survivorship of chicks during this intense predation phase, we estimated that 40-60% of all chicks in that age group were consumed by gulls during colony disturbances. Most losses caused by disturbance were associated with raptors (95% bald eagles, 5% peregrine falcons), but occasionally disturbance associated with our research activities was responsible.

Nesting double-crested cormorants were moderately productive in 1998 (Table 4), as in 1997. Nests on the channel markers near Rice Island (1.59 fledglings/nest) and nests on East Sand Island (1.23 fledglings/nest) produced more young than nests on Rice Island (0.55 fledglings/nest). Similarly, overall nesting success of closely observed nests (N = 70/colony) was greater on channel markers (71.7%) and East Sand Island (74.8%) than on Rice Island (38.9%). Nests with eggs on the channel markers and on East Sand Island had Mayfield daily survival rates of 0.9947 and 0.9912, respectively. Causes of nest failure were very difficult to ascertain, but the available evidence suggested that gull predation was a major cause.

Diet Composition

We analyzed a total of 972 diet samples from piscivorous waterbirds. Of those, 262 samples were from Caspian terns (124 adult stomach contents, 138 dropped bill-load fish), 280 were from double-crested cormorants (147 adult stomach contents, 133 chick regurgitations), 248 were from glaucous-winged/western gulls nesting in the estuary (245 adult stomach contents, 3 chick regurgitations), and 182 were from California or ring-billed gulls nesting at up-river colonies (120 adult stomach contents and 62 chick regurgitations). Additionally, we identified 1,463 fish held in the bills of Caspian terns (i.e., bill load observations) on the Rice and Three Mile Canyon island tern colonies.

Diet composition varied by predator species, colony location (Tables 5 – 9, Figure 7), and seasonally (Figures 8 and 11). Caspian terns and double-crested cormorants were strictly piscivorous (Table 5 and 6), whereas gulls consumed a diverse array of food types

(Tables 7 - 9). In general, juvenile salmonids were more prevalent in the diet of piscivorous waterbirds nesting in the Columbia River estuary, compared to birds nesting up-river. For Caspian terns, however, those nesting at the up-river colony, Three Mile Canyon Island, consumed a higher proportion of juvenile salmonids than those nesting on Rice Island. Of those species of piscivorous waterbirds in the estuary, Caspian terns consumed the highest percentage of salmonids (72.8% of identified prey items, 73.6% of identified diet mass; Table 5), followed by double-crested cormorants nesting on or near Rice Island (53.1% of identified prey items, 54.6% of identified diet mass; Table 6), and glaucous-winged/western gulls nesting on or near Rice Island (12.8% of identified diet mass; Table 7). Gulls that nested up-river were less dependent on salmonids as a food source, with salmonids present in the diet samples of gulls nesting at only one of the three up-river colonies where diet composition data were collected in 1998 (Little Memaloose Island: 16.9% of identified diet mass; Table 8). The diet of double-crested cormorants differed between the two nesting colonies in the estuary (Table 6 and Figure 9). Cormorants nesting on East Sand Island, located near the mouth of the Columbia River, had fewer salmonids in their diet (14.7% of identified prey items, 15.9% of identified diet mass) as compared to cormorants nesting at locations farther up-river (Rice Island and nearby channel markers: 53.1% of identified prey items, 54.6% of identified diet mass; Table 6). This same trend was observed in glaucous-winged/western gulls collected at Rice Island compared to those from East Sand Island (Table 7, Figures 7 and 10). Similarly, terns returning to the Rice Island colony from up-river locations had a greater proportion of juvenile salmonids in their diet (Figure 7) compared to terns returning to the colony from down-river.

The relative proportions of the different salmonid species in the salmonid portion of the diet of Caspian terns (based on dropped fish) are presented in (Figure 12). Chinook and coho salmon smolts were the most prevalent species in the juvenile salmonid portion of the diet, together comprising 84% and 72% of the identifiable salmonid prey items and identifiable salmonid diet mass, respectively (Figure 12). The proportion of salmonids in the diets of piscivorous waterbirds nesting in the estuary changed as the breeding season progressed (Figure 8 – 10). In general, the proportion of the diet (by prey item) that was salmonids was highest in April and especially May, followed by a decline in June and July (Figures 8 – 10). The highest proportion of juvenile salmonids in the diet of piscivorous waterbirds generally coincided with the period of peak smolt out-migration in the estuary (FPC 1998). Biweekly comparisons of the relative proportions of different salmonid species in the diet of Caspian terns indicated that early in the breeding season the diet is comprised mostly of coho salmon and steelhead smolts, followed by a preponderance of chinook salmon smolts later in the breeding season (Figure 11).

The stomach contents samples from individual Caspian terns were compared to the fish they were transporting in their bills (dropped bill-load fish) in order to test the hypothesis that tern bill loads are a representative sample of adult tern diets. To obtain an adequate sample size for this comparison, the data from 1997 and 1998 were pooled. Of the 48 paired stomach contents/bill load samples examined, 38 (74.5%) contained similar prey items. Of the other 10 paired samples, half had salmonids in the stomach but not in the bill, while the other half had salmonids in the bill but not in the stomach. A statistical comparison revealed no significant difference in the proportion of salmonids vs. non-salmonid in the two samples ($X^2 = 0.05$, $P = 0.82$) suggesting that proportion of salmonids consumed by adult terns is similar to the proportion of salmonids in bill loads provisioned to mates and young.

PIT Tag Recovery

A total of 58,871 salmon smolt PIT tags from smolts with known tagging and release histories (PTAGIS 1998) were recovered or interrogated on piscivorous waterbird colonies over the past three years (1996 – 1998). Most (90.5 %) were recovered or interrogated by NMFS in 1998, of which roughly 98% were interrogated *in situ* using a flat plate PIT tag detector (see Ledgerwood et al. 1999). The greatest number of tags were found on the Rice Island Caspian tern colony, followed by the Rice Island double-crested cormorant colony, and the Crescent Island Caspian tern colony (Figure 13). Only 624 tags were found on the Three Mile Canyon Island Caspian tern colony; however, the flat plate detector was not used at that site. PIT tags were recovered from fish tagged in every migration year beginning with 1988 (Figure 13 and 14), but the majority (78.7%) came from migration years 1996 – 1998. Most of the PIT tags detected were from smolts known to have been tagged and released in the Snake River Basin (77.0%). Of all the tags recovered, most were from chinook salmon (48.6%), followed by steelhead (42.0%), coho salmon (8.8%), sockeye salmon (0.6%), and other or unknown fish (<0.1%). A greater number of PIT-tagged salmonids of hatchery origin (78.5%) were recovered on piscivorous waterbird colonies, as compared to salmonids of wild (8.4 %) or unknown (13.1%) origin.

Of all the PIT-tagged smolts that survived to Bonneville Dam in 1997 and 1998, 2.8% and 3.3% were subsequently found on the Rice Island Caspian tern colony, respectively. In comparison, 1.4% and 0.8% of PIT-tagged smolts that survived to Bonneville Dam were later found on the Rice Island double-crested cormorant colony in 1997 and 1998, respectively. Of those PIT-tagged smolts that survived to Bonneville Dam in 1997 and 1998 comparatively more PIT-tagged steelhead were detected on the Rice Island Caspian tern colony than those from coho, chinook, or sockeye salmon smolts (Figure 15). In comparison, PIT tags from steelhead and sockeye smolts were proportionally the most prevalent on the Rice Island double-crested cormorant colony in 1997 and 1998 (Figure 15).

PIT tag recoveries on the Rice Island tern and cormorant colonies suggested that these birds did not consume the various salmonid stocks, rearing types, and transported versus non-transported migrants in proportion to their in-river availability. PIT tags from steelhead were over-represented on the tern and cormorant colonies compared to other salmonid species in both the 1997 and 1998 migration years (Figures 16 and 17). Chinook salmon smolts comprised the large majority of PIT-tagged smolts (ca. 76%; PTAGIS 1998), but were under-represented on the tern and cormorant colonies relative to their availability compared to other salmonid species (Figure 16 and 17). PIT tags from smolts of hatchery origin were detected on the tern colony in greater numbers than expected, based on in-river availability in 1997 and 1998 (Table 10). Double-crested cormorants nesting on Rice Island in 1997 and 1998 consumed hatchery and wild PIT-tagged smolts in proportion to their availability in-river (Table 11). In 1998, PIT-tagged steelhead smolts released from barges and trucks below Bonneville Dam (i.e., transported) were under-represented on the Rice Island Caspian tern colony, compared to non-transported smolts (Table 12). In that same year, PIT-tagged transported spring/summer chinook smolts were over-represented on the tern colony, compared to non-transported smolts (Table 12). In 1997, however, there were no differences in vulnerability of transported versus non-transported smolts to Caspian tern predation (Table 12). In both 1997 and 1998, PIT-tagged transported spring/summer chinook of hatchery origin were under-represented on the Rice Island double-crested cormorant colony, compared to non-transported smolts (Table 13). In 1998, PIT-tagged transported steelhead of hatchery origin were under-represented on the Rice Island cormorant colony, compared to non-transported smolts (Table 13). PIT tags from transported and non-transported steelhead and spring/summer chinook of wild origin were detected on the colony in proportion to their availability in-river in both 1997 and 1998 (Table 13). The same trends in relative vulnerability of transported versus non-transported smolts to bird predation were apparent regardless of assumptions made regarding differential direct mortality associated with transportation and bypass around Bonneville Dam (Appendices A - D).

Bioenergetics Model Output

Bioenergetics modeling was used to estimate the total number of juvenile salmonids consumed by Caspian terns nesting on Rice Island, double-crested cormorants nesting on Rice and East Sand islands, and glaucous-winged/western gulls nesting on Rice Island, East Sand Island, and Miller Sands Spit during the 1998 breeding season. These estimates are particularly sensitive to errors in the estimation of daily energy expenditure, population size, the duration of the predation period (number of predation days), and the proportion of juvenile salmonids in the diet (% diet biomass; Madenjian and Gabrey 1995).

While the bioenergetics modeling approach is the preferred method for estimating prey consumption in forage fish/seabird systems, there are uncertainties in each input variable to the models, and these errors can be compounded in the final output of the model. Consequently, in addition to the model outputs that we think are the "best" estimates, we have provided minimum and maximum estimates for each output variable from the models. While it is difficult to vouch for the accuracy of specific best estimates generated by the models, we are confident that the actual number is between the minimum and maximum estimates provided, and is likely closer to the best estimate than to either of the extremes.

Daily energy expenditure (DEE) of Caspian terns measured using the doubly labeled water technique averaged 1,040 kJ/day (SD = 209.1, N = 24) and ranged from 632 to 1539 kJ/day. The upper and lower 95% confidence intervals (1,128 kJ/day and 951 kJ/day) were used as the maximum and minimum estimates of DEE, respectively. Twenty-two of these measurements were made during the 1998 breeding season, while the other two measurements were made in 1997. The average DEE from the two measurements from 1997 (1,044.4 kJ/day) was very close to the average for the entire sample. The average of 1,040 kJ/day is close to the maximum estimate for Caspian terns based on allometric equations in Birt-Friesen et al. (1989), indicating the importance of empirical measurements of DEE using doubly labeled water for accurate estimation of DEE.

Estimates of population size for the Rice Island Caspian tern colony were largely based on the aerial photo census, conducted at the end of the incubation stage of the nesting cycle (Table 14). The maximum and minimum population estimates for the bioenergetics model (19,692 individuals and 12,197 individuals, respectively) were based on variability in the numbers of adult terns in plots within the colony around the time of the photo census.

The estimated energy consumption of nestling and fledgling terns was included in the total energy consumption of the tern population in 1998 because of the large number of young raised in 1998 compared with 1997. Total fledgling energy consumption was an order of magnitude lower than total adult energy consumption (Table 14). This contrasts with the estimates of fledgling energy consumption in double-crested cormorants. The East Sand Island cormorant colony experienced higher productivity than the Rice Island tern colony, and total fledgling energy consumption was about one fourth of total adult energy consumption (Table 15).

The best estimate of the total energy requirement for the Rice Island Caspian tern colony was 1.72 x 109 kJ (Table 14). The comparable estimate for double-crested cormorants in the Columbia River estuary is 3.27 x 109 kJ (Table 15), or about twice the energy requirement of the Rice Island tern colony. The total energy requirement for glaucous-winged/western gulls in the estuary is intermediate between the tern and cormorant estimates (Table 16).

The mean energy densities measured for each prey category ranged from a low of 4.0 kJ/g wet mass for chinook salmon and sculpins to a high of 6.0 kJ/g wet mass for clupeids (herring, shad, and sardines; Table 17). Juvenile salmonids ranged from 4.0 kJ/g wet mass for chinook salmon smolts to 5.0 kJ/g wet mass for coho salmon smolts. Estimates of the relative contribution of juvenile salmonids to the total energy consumption of the tern population were based on the taxonomic composition (% prey items) of bill loads (fish transported in the bill of adults and identified from blinds located near the colony), and converted to % biomass of the diet based on the average mass of prey items in each prey category (Table 17). Based on the composition of bill loads, approximately 71.3% of total energy consumption by the population was juvenile salmonids (Table 17). Chinook salmon smolts contributed about 28% of total energy consumption and 40% of the energy consumed in juvenile salmonids. Coho salmon smolts contributed about 24% of total energy consumption and 33% of energy consumed in juvenile salmonids. Finally, steelhead smolts contributed about 19% of total energy consumption and 27% of the energy consumed in juvenile salmonids.

We estimated that Caspian terns in the Columbia River estuary consumed 10.8 million juvenile salmonids (range = 7.4 - 15.2 million; Table 18). The bioenergetics model indicated that 6.2 million of these juvenile salmonids were chinook smolts (57% of all juvenile salmonids consumed by terns), 3.2 million were coho smolts (30% of all juvenile salmonids consumed), and 1.4 million were steelhead smolts (13% of all juvenile salmonids consumed).

The estimate of the number of juvenile salmonids consumed by double-crested cormorants in the estuary was 4.6 million (range = 2.2 - 9.2 million; Table 18). A rough estimate of the number of juvenile salmonids consumed by glaucous-winged/western gulls in the estuary was 1.3 million (range = 0.4 - 3.9 million; Table 18). Thus the estimated total consumption of juvenile salmonids by fish-eating colonial waterbirds in the Columbia River estuary was 16.7 million smolts (range = 10.0 - 28.3 million smolts).

The confidence intervals about the best estimates of smolt consumption are markedly different for the three avian predator species. The much narrower relative confidence interval about the estimate of smolt consumption for Caspian terns reflects the better quality and quantity of data available as input to the bioenergetics model. Similarly, the extremely wide confidence interval (relative to the best estimate) for the estimate of smolt consumption by glaucous-winged/western gulls reflects the scarcity of empirical data for this system.

Foraging Ecology

Aerial surveys indicated that the foraging activity of Caspian terns was mostly centered around the Rice Island colony site (river km 34; Figure 18). Spikes of activity were also observed near Taylor Sands (river km 26), Clatsop Spit (river km 12), and East Sand Island (river km 8), and at the mouth of Youngs Bay (river km 19: Figure 18). Activity of terns above river km 92 was not quantified; however, opportunistic observations while in flight to and from the study area indicated only occasional tern presence in this area during the breeding season. Fifty percent of all terns seen off-colony were within 8 km of Rice Island, 75% within 15 km, and 90% within 21 km (Figure 19). A circle with 21-km radius centered on the Rice Island colony site reaches to Skamakowa, WA and Clifton, OR in the up-river direction and to East Sand Island in the down-river direction (Figure 19). During the incubation and chick-rearing periods, 52.4% of activity was observed down-river from the colony and 47.6% was up-river from the colony. Most sightings of foraging terns (66.5%) occurred between river kilometers 24 and 46, with 17.7% of the sightings below river km 24 and 15.8% above river km 46.

During riverbank surveys, the highest densities of terns were seen in the main shipping channel and in shallow bays and other tidal-influenced areas (Table 19). Somewhat lower densities were seen in side channel areas, tributaries, and small sloughs. Similar trends in habitat-related foraging densities were observed for double-crested cormorants (Table 19).

Caspian terns and double-crested cormorants were commonly observed foraging at high densities near pile dikes in the estuary. Nine survey sites along the main shipping channel had views of pile dikes. Two of these sites were down-river from Rice Island and did not have substantially different site attendance compared to other nearby sites. Pile dikes adjacent to East Sand Island and West Sand Island (also below Rice Island) occasionally had large numbers of terns and cormorants foraging nearby, but these areas were not visible from any of the regularly monitored survey sites and thus were not included in the analysis. The remaining seven survey sites that included pile dikes were up-river from Rice Island. Attendance at several of these sites, particularly by cormorants, was high early in the nesting season but dropped off substantially in early June. For example, mean attendance by cormorants at Pillar Rock Island was 73.7 individuals in April and May, but only 17.4 individuals in June and July. At the Eureka Bar site, cormorant attendance for April and May averaged 50.0 individuals, but averaged only 8.0 individuals in June and July. The same seasonal trend was seen for Caspian terns at some pile dike sites, but at other pile dike sites there was no trend or somewhat higher attendance by Caspian terns in June and July. Mean April and May attendance by terns and cormorants at these pile dike sites and the other main shipping channel survey sites above Rice Island are presented in Table 20. Site attendance by double-crested cormorants was more related to the presence of pile dikes than was attendance by Caspian terns (Table 20). Terns had high attendance at pile dike locations, such as Miller Sands Spit, Pillar Rock Island, and even at the pile dike above Eureka Bar; however, terns also exhibited relatively high attendance at other sites without pile dikes, such as Cooper Point/Cape Horn. The highest attendance sites for double-crested cormorants along the shipping channel up-river from Rice Island all had pile dikes, and no aggregations of cormorants were observed at sites that lacked pile dikes (Table 20). This pattern was observed as far up-river as km 75. The pile dikes near Crims Island (river km 92) had low attendance by both cormorants and terns, possibly because they were outside the foraging range of most terns and cormorants nesting in the estuary. Of the 22 up-river sites regularly surveyed (including all habitat types), the highest cormorant attendance was observed at Miller Sands Spit, Pillar Rock Island, Pancake Point on Puget Island, and Eureka Bar, all sites with pile dikes. The Miller Sands Spit site, where there are 4 pile dikes within 3 km of the Rice Island cormorant colony, had the highest average cormorant attendance of all 51 sites surveyed in the estuary.

Large increases in site attendance by Caspian terns were seen only once in areas down-river from hatchery or net pen release points in the estuary. Following a 1 May release of smolts from net pens in Youngs Bay, a combined count of terns from three observation points increased from 83 prior to the release to 241 the day following the release. Overall, however, tern counts increased five times, decreased five times and were approximately the same five times, when comparing observations before and after releases. For double-crested cormorants, no post-release increases comparable to the increase in terns following the 1 May release were observed. Cormorant counts increased six times, decreased four times, and were approximately the same five times.

By tracking the direction of tern departures from and approaches to the Rice Island colony, it was possible to detect trends in tern usage of the estuary during the breeding season. Three distinct phases of usage were observed. Initially, during the last week of

April and the first week of May, significantly more terns were seen departing toward and returning from sites up-river of Rice Island (*P*<0.001). During the latter three weeks of May, the activity levels above and below the colony were statistically indistinguishable (*P*>0.05). For the remainder of the monitoring period (all of June and July), significantly more activity was seen down-river from Rice Island (*P*<0.001). Within this later period, foraging down-river from the colony increased to a maximum of 91% of all activity seen during the week just prior to fledging. Additional observations support this general trend of foraging mostly up-river of the colony early in the season and increasing usage of foraging areas down-river of the colony (including marine habitats) later in the season. For example, no terns were seen at the South Jetty at the mouth of the Columbia River until 20 May. In Seaside, the first Caspian tern observations (after spring migration) were during the first week of June. By 10 June, dozens of terns were seen in Willapa Bay. It is unknown how many of these far-ranging terns were breeding birds, as opposed to non-breeders or failed-breeders. There was a general trend of decreasing numbers of foraging terns at up-river sites throughout the season, in agreement with this trend of increasing usage of more marine habitats as the season progressed.

Management Feasibility Studies

The plots of transplanted vegetation on the Rice Island Caspian tern colony did not deter or preclude nesting by terns, compared with control plots. Surprisingly, the transplanted vegetation appeared to attract terns to nest in higher densities in the experimental plots. The two high-density vegetation plots had the highest nesting densities of Caspian terns of all eight plots. Nesting densities on the medium- and low-density vegetation plots were similar, and the lowest nesting densities were observed in the two control plots (Figure 20). The high-density vegetation plots were occupied by nesting pairs of terns approximately one week after the other six plots were occupied. All other plots were occupied by nesting terns at roughly the same time. The higher nesting densities on the high-density vegetation plots were apparently the result of terns being attracted to nest at the base of each transplanted tansy plant.

Attempts to attract terns to nest on Miller Sands Spit using decoys and an audio playback system were successful. After the playback system was installed on the Miller Sands Spit experimental colony site on 28 March, Caspian terns were observed flying over the site, some with fish held in the bill. No terns were observed roosting on the site, however, until 21 April, the day following the placement of 12 tern decoys on the colony site. A total of 130 terns were observed roosting on the colony site during high tide on that day. On every subsequent day up to 11 June when we made observations at the experimental colony, terns were observed roosting and/or nesting on the colony site (Figure 21). As many as 500 terns were observed roosting at the experimental colony site and breeding behaviors, including courtship feeding, scrape digging, and copulation, were commonly observed at the site.

On 26 May, six tern nest scrapes with eggs and 75 empty nest scrapes were observed on the experimental tern colony on Miller Sands Spit. From 26 May to 6 June, a total of 17 different nest scrapes with eggs were observed on the colony. None of the 17 nests survived long into the incubation period. We suspect that as many as 30 nests with eggs were initiated on Miller Sands Spit; many eggs were apparently depredated before we detected them. The high rate of nest failure on Miller Sands Spit was largely attributable to interference from and nest predation by gulls and crows.

We measured kleptoparasitism rates at both the Miller Sands Spit and Rice Island tern colonies between 11 May – 11 June. We observed 464 different courtship feeding attempts at the Miller Sands Spit colony and 468 feeding attempts at the Rice Island colony. There was a significantly higher occurrence of gull and crow interference (i.e., kleptoparasitism or chases) on Miller Sands Spit as compared to Rice Island (36.8% and 20.7%, respectively; $X^2 = 5.21$, $P = 0.05$**).** On both the Miller Sands Spit and Rice Island tern colonies, interference by gulls was greatest during early nest initiation and incubation. On Miller Sands Spit, northwestern crows (*Corvus caurinus*) were commonly seen on-colony and, compared to Rice Island, the impact of crows on tern nesting success was much greater. Two instances of tern egg predation by crows were directly observed on the Miller Sands Spit colony (2 June and 8 June), whereas egg predation by crows was observed only very infrequently on the Rice Island colony.

DISCUSSION

Population Estimates and Productivity

The Caspian tern colony on Rice Island, a dredged material disposal island in the Columbia River estuary, is currently the largest of its kind in North America (about 8,000 nesting pairs), and perhaps the world (Cuthbert and Wires 1999). This colony has increased by over 600% since 1986, when nesting by Caspian terns on Rice Island was first discovered (G. Dorsey, USACE, pers. comm.); annual growth in the tern colony is currently about 15 – 20%. The colony has apparently expanded at the expense of other Caspian tern colonies formerly located in Grays Harbor, Willapa Bay, and northern Puget Sound, as well as East Sand Island near the mouth of the Columbia River.

Breeding colonies of Caspian terns were not recorded for coastal Washington and Oregon until the late 1950s. During the first half of this century Caspian terns were known as a breeding species in the Pacific Northwest only from inland lakes, marshes, and impoundments (Gill and Mewaldt 1983). The first breeding record on the coast was a small colony discovered on Goose Island, Grays Harbor, Washington in 1957 (Alcorn 1958). This colony peaked in size at about 1,000 pairs in 1973, and had been abandoned by 1976 (Speich and Wahl 1989; E. Cummins, WDFW, unpubl. data). Beginning in 1974, a Caspian tern colony became established on Whitcomb Island, also in Grays Harbor, that increased in size to 1,240 pairs by 1976, but this colony was abandoned by 1981. Beginning in 1976, Sand Island, another island in Grays Harbor, was used by nesting Caspian terns. By 1981 over 2,000 pairs were nesting on Sand Island, the largest known Caspian tern colony anywhere along the Pacific Coast of North America (Gill and Mewaldt 1983). In 1987 the number of nesting pairs was estimated at 4,000, but this colony in turn disappeared by 1993 (J. Smith, WDFW, pers. comm.). During the 1990s there has been no confirmed successful nesting by Caspian terns in Grays Harbor, although nesting attempts by small numbers of terns have been noted (M. Zahn, WDFW, unpubl. data).

In 1976 several hundred pairs of Caspian terns were discovered nesting on Gunpowder Island, near the mouth of Willapa Bay, Washington. By 1982 the Gunpowder Island tern colony had peaked at about 1,500 nesting pairs (Speich and Wahl 1989). Thereafter the Gunpowder Island colony declined, and the last confirmed nesting was by about 150 pairs in 1989 (E. Cummins, WDFW, unpubl. data).

In 1984 a colony of about 1,000 pairs of Caspian terns was noted breeding on East Sand Island in the Columbia River estuary (G. Dorsey, USACE, pers. comm.). This was apparently the first nesting record for Caspian terns anywhere in the Columbia River estuary. By 1987 the colony on East Sand Island had been abandoned, and all breeding pairs had apparently shifted to Rice Island, a large, sandy dredge disposal island 21 km further up-river.

The Rice Island Caspian tern colony increased rapidly from the initial estimate of 1,000 pairs in 1986 to about 6,200 pairs in 1991 (A. Clark, USFWS, pers. comm.). The current population estimate of about 8,000 nesting pairs at the Rice Island colony is larger than the estimate of the entire Pacific Coast population of Caspian terns 15 years ago (Gill and Mewaldt 1983). The initial rapid buildup of this colony in the late 1980s and early 1990s apparently was due to shifting of breeding pairs from Sand Island in Grays Harbor, Gunpowder Island in Willapa Bay, and East Sand Island near the mouth of the Columbia River to the single large colony at Rice Island. After 1991 colony growth appeared to slow, but there was a substantial jump in the size of the Rice Island tern colony between 1995 and 1996 (Fig. 4). This increase coincided with the reported demise of a large Caspian tern colony (ca. 1,500 – 3,000 pairs) in northern Puget Sound, on the grounds of the U.S. Naval Base at Everett, WA (G. Dorsey, USACE, pers. comm.). Although details are sketchy, this colony was apparently precluded from using the former colony site in 1995 by new construction on-site. There are no subsequent reports of Caspian terns nesting in the northern Puget Sound area. This suggests that the Everett Caspian tern colony was subsumed in the Rice Island colony during the 1996 breeding season.

Other than the Rice Island colony, there were no confirmed Caspian tern breeding colonies along the coast of Washington or Oregon in 1998. Nesting was suspected, however, at a mainland site on the shores of Commencement Bay, southern Puget Sound, near Tacoma, Washington (M. Tirhi, WDFW, pers. comm.). The site is fenced off because of heavy metal contamination, and is slated for soil removal and remediation as an EPA superfund site in 1999. This site should be closely monitored to ascertain whether nesting occurs.

Some evidence from band returns supports our interpretation of the origins of the Rice Island Caspian tern colony. In 1997 and 1998, we collected a total of 10 banded adult Caspian terns on or adjacent to the Rice Island colony. All had been banded as young chicks on the Sand Island colony in Grays Harbor during the late 1970s or early 1980s. Washington Department of Fish and Wildlife banded approximately 500-1,500 Caspian tern chicks annually on Sand Island during this period (Gill and Mewaldt 1983, J. Smith, WDFW, pers. comm.). These banded adults were 17 (N = 2), 18 (N = 1), 19 (N = 3), 20 (N = 1), and 21 (N = 3) years-old at the time that they were collected on Rice Island. The number of banded adults (N = 5) in the sample of randomly collected adults for diet composition analysis in the two years (N = 304) suggests that about 250 banded adult terns nested on the Rice Island colony in 1997 and 1998.

In summary, the history of the Caspian tern breeding population along the Washington and Oregon coasts has been a short one (ca. 40 years) of rapid expansion, low philopatry (nest site fidelity), and large colony sizes compared with other areas of North America. This is part of a general trend for Pacific Coast Caspian terns of (1) shifting breeding colonies from inland, natural sites to coastal anthropogenic sites (dredged material disposal islands), (2) shifting from nesting in small groups within larger colonies of gulls to nesting in large, single-species colonies, (3) dramatic overall population increase, and (4) rapid northward range expansion.

The two Caspian tern colonies in the up-river portion of the study area (Three Mile Canyon Island in John Day Pool and Crescent Island in McNary Pool) are about an order of magnitude smaller than the Rice Island colony and have not exhibited a clear population trend in the last three years. Between 1996 and 1997, there was a two-fold increase in number of Caspian terns breeding at Three Mile Canyon Island and a three-fold increase at Crescent Island, suggesting that these two colonies were undergoing rapid expansion. Between 1997 and 1998, however, there was about a 40% decline in numbers of breeding terns at both colonies. These two inland colonies are ecologically more typical of Caspian tern colonies, a smaller number of terns nesting amidst a large colony of California and ring-billed gulls. Unlike the larger glaucous-winged/western gulls that nest around the Caspian tern colony on Rice Island, these two species of gulls rarely prey on Caspian tern eggs and chicks, nor are they highly kleptoparasitic on Caspian terns. Three Mile Canyon Island and Crescent Island were created by dam impoundment and dredged material disposal, respectively, and so, like Rice Island, are anthropogenic islands. We have few data on the diets of terns nesting at these two up-river colonies, but the diet data from Three Mile Canyon Island and the large number of smolt PIT tags recovered at Crescent Island suggest that terns nesting at these two up-river colonies are as or more specialized on juvenile salmonids as a food source compared with terns nesting on Rice Island.

The breeding population of double-crested cormorants in the Columbia River estuary increased again in 1998. Despite a substantial decline in the Rice Island cormorant colony (-25%) compared with 1997, the increase in the East Sand Island cormorant colony more than compensated. The estuary-wide population of double-crested cormorants increased in 1998 by an estimated 15% over 1997.

This population trend is part of a continuing expansion of populations of double-crested cormorants along the Pacific coast (recently reviewed by Carter et al. 1995) and throughout North America following persecution and habitat destruction in the late 1800's and early 1900's. But the dramatic increase in the size of the East Sand Island colony over the last decade is unparalleled elsewhere in the Pacific Northwest. The East Sand Island colony was first discovered in 1987 and in 1989 there were 91 active nests (D. Bell, pers. comm. to R. Lowe, USFWS) at the site that supported about 5,250 nesting pairs during the 1998 breeding season. Thus the population of double-crested cormorants in the Columbia River estuary, like the Caspian tern population, experienced rapid growth in the early 1990s. The cormorant colony on Rice Island was first noted in 1988, soon after Caspian terns colonized the site. Again, the rapid initial build-up of these breeding colonies indicates that breeders were recruited from other colonies. Unlike Caspian terns, however, no large colonies of double-crested cormorants along the coast of Washington or Oregon declined or disappeared concurrent with increases in the Columbia River estuary (Carter et al. 1995; R. Lowe, USFWS, pers. comm.). Instead, it appears that the rapid influx of double-crested cormorants to the estuary occurred at the expense of inland colonies (e.g., Malheur NWR), where large colonies were adversely affected by prolonged draught in the late 1980's and early 1990's, which resulted in a dramatic decline in forage fish availability (G. Ivey, USFWS, pers. comm.). The double-crested cormorant colonies at East Sand Island (ca. 5,250 pairs) and Rice Island (ca. 800 pairs) are currently the two largest known colonies of this species on the Pacific Coast of North America (Carter et al. 1995). Furthermore, there have recent dramatic increases in the number of glaucous/western gulls in the Columbia River estuary. Since 1989, when 1,760 gulls were counted on East Sand Island (D. Bell, pers. comm. to R. Lowe, USFWS) the direct count of gulls on East Sand has increased by more than a factor of three by 1998. These data suggest that all populations of piscivorous colonial waterbirds have been increasing in the Columbia River estuary in the last decade.

Nesting success of Caspian terns breeding at Rice Island in 1998 (ca. 0.49 young fledged per breeding pair) was considerably higher than in 1997 (ca. 0.05 young fledged per pair), but lower than average productivity at other Pacific Coast colonies (ca. 1.1 young fledged per pair; Cuthbert and Wires 1999). As in 1997, the proximate cause of most nest failure was gull predation on eggs and chicks, but the ultimate cause(s) of such high nest predation rates are less apparent. There are several potential explanations for the higher productivity at the Rice Island Caspian tern colony in 1998 compared with 1997. First, the field research crew took further steps to minimize disturbance to the tern colony during incubation and early chick-rearing. Tunnels were constructed to the observation blinds so that observers could access the blinds without disturbing incubating or brooding terns on the colony. Also, in 1997 we monitored nest success, productivity, and chick growth rates by fencing in samples of nests on the colony and checking them periodically; this work was discontinued in 1998. Another factor influencing nesting success in 1998 was the lower frequency and intensity of harassment and predation on adult terns by bald eagles. Bald eagle nesting productivity in the vicinity of the Rice Island tern colony was higher in 1998 (0.55 young per occupied nest site, N = 11 sites) compared to 1997 (0.20 young per occupied nest site, N = 10 sites; Isaacs and Anthony 1999). The section of the Columbia River centered on Rice Island is one of high bald eagle nesting densities and generally low productivity. Nesting eagles experienced an especially poor year in 1997, with only one nest in 10 successfully raising young. This may have reflected a food scarcity in 1997 that caused eagles to switch to preying more on Caspian terns at the Rice Island colony. Alternatively, actively nesting pairs of eagles may have remained closer to their respective nest sites throughout the breeding season in 1998 and made fewer foraging trips to the Rice Island tern colony (R. Anthony and F. Isaacs, ORCFWRU, pers. comm.). Finally, river flows were closer to normal in 1998 and much lower than in 1997, a year of record flows in the lower Columbia River, and this may have enhanced food availability, foraging efficiency, and, ultimately, nesting success among terns breeding at Rice Island.

Both bald eagles and glaucous-winged/western gulls have apparently played roles in the demise of former Caspian tern colonies on islands in Grays Harbor and Willapa Bay. The history of short-lived colonies and shifting breeding sites, plus observations of increasing gull and eagle disturbance at former Caspian tern colonies (J. Smith, WDFW, pers. comm.), suggests that low nest site fidelity may be related to the gradual build-up of predator populations once a colony is established. Predation by gulls and eagles is not the sole explanation, however, because some colonies have been lost primarily due to habitat degradation and loss. Caspian terns prefer to nest on bare or sparsely vegetated sand, so colony sites are frequently situated where sand accretion and erosion are persistent processes that maintain non-vegetated substrate. Such sites can be washed away during winter storm tides, leaving no area above high spring tides. This was a major factor in the demise of the Gunpowder Island colony in Willapa Bay and the Whitcomb Island colony in Grays Harbor. Finally, Caspian tern colonies that become established on dredged material are usually constrained by encroaching vegetation within a few years of dredged material deposition. The demise of the East Sand Island tern colony after 1984 has been attributed to vegetation succession, combined with aerial seeding by the U.S. Army Corps of Engineers.

Productivity of double-crested cormorants nesting on Rice Island (0.55 young fledged per nesting pair) was similar to that of Caspian terns nesting on Rice Island (0.49 young fledged per nesting pair). Productivity of cormorants nesting on East Sand Island (1.23 young fledged per pair) was over twice as high as on Rice Island. The relatively low nesting success of Rice Island cormorants was at least partly a result of researcher disturbance over a 4-day period when adult Caspian terns were being captured in the adjacent tern colony. The first colony inspection following this disturbance (5 days later) indicated that approximately 30 - 40% of nests on the cormorant colony had either lost their nest contents or had been abandoned.

Smolt Consumption Estimates

The results from 1998, the second year of this investigation, suggest that the high levels of bird predation on out-migrating smolts in the Columbia River estuary during 1997 were not anomalous. Our estimates of the magnitude of avian predation on juvenile salmonids in the estuary were refined in 1998, compared with 1997, yet the 1998 estimates were still well within the range of the 1997 estimates.

Estimates of the numbers of juvenile salmonids consumed by the Rice Island Caspian tern colony in 1998 were in the range of 7.7% to 15.8% of the estimated 96.6 million smolts that reached the estuary in 1998 (H. Pollard, NMFS, pers. comm.). The best estimate of smolt consumption by the tern population was 11.2% of those smolts that survived to the estuary. The salmonid portion of Caspian tern diets was further subdivided into various salmonid species. Estimates of the number of chinook smolts consumed by terns in 1998 (6.2 million) was 9.3% of the estimated number of chinook smolts to reach the estuary. Consumption of coho smolts by terns (3.2 million) was about 16.5% of the estimated number to reach the estuary. Finally, consumption of steelhead smolts by terns (1.4 million) was about 15.6% of the estimated number to reach the estuary.

Smolt consumption by double-crested cormorants nesting in the estuary was in the range of 2.3% to 9.6% of those smolts that reached the estuary in 1998, with a best estimate of 4.7%. Finally, a rough estimate of the number of juvenile salmonids consumed by glaucous-winged/western gulls in the estuary was 0.4% to 4.1% of the smolts that reached the estuary in 1998, with a best estimate of 1.3%. Thus the estimated total consumption of juvenile salmonids by fish-eating colonial waterbirds in the Columbia River estuary was 10% - 30% of those smolts that reached the estuary in 1998, with a best estimate of 17%. These results are in close agreement with our rough estimate from the 1997 field season that piscivorous colonial waterbirds in the estuary consumed about 10% - 30% of the smolts that reached the estuary (Roby et al. 1998).

Relative Vulnerability of Smolts to Predation

The PIT tag data suggest that Caspian terns and double-crested cormorants nesting on Rice Island are not foraging at random on the various groups of juvenile salmonids available in-river. For both the 1997 and 1998 migration years, PIT tags from steelhead smolts were over-represented on the tern and cormorant colonies, based on the relative proportion of PIT-tagged steelhead versus other PIT-tagged species found in-river. We estimated that over 8% and 11% of the PIT-tagged steelhead that survived to the estuary in 1997 and 1998, respectively, were found on Rice Island bird colonies. The PIT tags found on-colony underestimate predation rates on PIT-tagged steelhead because some PIT tags consumed by birds nesting on Rice Island are excreted off-colony and some PIT tags deposited on the colony are lost due to breakage and wind transport. Terns and cormorants may prefer steelhead smolts to other juvenile salmonid species because of their larger size. Alternatively, steelhead smolts may be more susceptible to bird predation due to some behavioral trait (e.g., tendency to migrate near the surface) or condition factor (e.g., high intensity of disease) prevalent in that species. All other species were either under-represented on the Rice Island colonies or were found in proportion to their availability in-river.

A large body of evidence suggests that hatchery-reared juvenile salmonids suffer greater mortality in the wild than naturally-produced smolts (Wales 1954, Miller 1954, Reisenbichler and McIntyre 1977, Chilcote et al. 1986). Low survivorship of hatchery smolts can be attributed in part to behavioral and physical traits that render them more vulnerable to some predators (Dickson and MacCrimmon 1982, Olla et al. 1990, Johnsson and Abrahams 1993, Berejikian 1995). Hatchery-reared smolts, as compared to wild smolts, have been shown to have elevated stress levels associated with handling (Schreck 1981, Olla and Davis 1989), lack both innate and learned predator avoidance behaviors (Olla and Davis 1989, Suboski and Templeton 1989, Berejikian 1995), and are more surface-oriented (Vincent 1960, Moyle 1969), all of which could contribute to the greater susceptibility of hatchery smolts to avian predation.

PIT tag detections on the Rice Island Caspian tern colony suggested that terns did not forage on juvenile salmonids of hatchery origin in proportion to their availability in-river. Hatchery-reared steelhead and spring/summer chinook migrating in 1997 and 1998 were over-represented on the Caspian tern colony as compared to wild fish. Conversely, double-crested cormorants foraged on hatchery and wild smolts in proportion to their in-river availability. These results support the hypothesis that hatchery smolts may be more vulnerable to tern predation due to their surface orientation (i.e., terns are plunge-divers, foraging at or near the surface, whereas cormorants are pursuit-divers and forage throughout the water column). If factors such as elevated stress levels or lack of predator avoidance abilities were the primary factors responsible for higher susceptibility of hatchery fish to tern predation, then a difference in the susceptibility of hatchery-reared smolts to predation by terns versus predation by cormorants would not be expected.

In 1998, spring/summer chinook smolts that were transported (barged or trucked around dams) were over-represented on the Rice Island tern colony compared to non-transported smolts, regardless of hatchery or wild origin. Studies have shown that there are species differences in the affects of transportation on smolt quality (Congleton et al. in press) and that different condition factors (i.e., levels of disease, stress, and smoltification) affect predator avoidance and survival in smolts (Mesa 1994, Handeland et al. 1996, Mesa et al. 1998, Schreck and Stahl 1999). Congleton et al. (in press) investigated stressors associated with transportation in yearling chinook and steelhead smolts. Stress levels in yearling chinook were positively correlated with steelhead loading density in the barge or truck, whereas stress levels in steelhead were not correlated with loading densities. Steelhead are generally larger and more aggressive than yearling chinook. Due to agonistic interactions that occur between the two species when transported together, steelhead may negatively affect both the stress levels and physical condition of chinook smolts. This is one possible explanation for the greater susceptibility of transported yearling chinook to tern predation, as compared to non-transported chinook. Other potential explanations are that transported chinook smolts have greater incidence and intensity of disease or are less smolted and tend to have a longer residence time in the estuary (increasing exposure to predation) than non-transported chinook smolts.

In contrast, transported steelhead smolts were less susceptible to predation by terns as compared to non-transported steelhead in 1998. Unlike yearling chinook, transportation does not appear to adversely affect the condition of steelhead smolts (Congleton et al. in press) and may instead benefit steelhead. Following release, transported smolts tend to migrate down-river in tighter aggregations compared with run-of-the-river smolts (Ledgerwood et al. 1997), which may serve to swamp predators and increase survival compared to non-transported fish. Steelhead smolts, because they are larger and more fully-developed than yearling chinook, are also likely to move through the estuary more rapidly, regardless of whether they are transported.

In 1997 there was no difference in the prevalence of transported and non-transported chinook or steelhead smolts on the Rice Island tern colony. Further study is necessary to determine what factors are important in explaining the differences in susceptibility of transported versus non-transported fish to tern predation, and why these differences may exist in some migration years but not in others.

Management Feasibility Studies

The first step in evaluating the feasibility of colony relocation as a management alternative is to determine whether Caspian terns nesting at Rice Island can be attracted to nest elsewhere. In 1998, we tested the feasibility of using tern decoys and audio playbacks of tern vocalizations to attract Caspian terns to nest on Miller Sand Spit, a dredge spoil island not previously used by terns as a nesting site and located only 1.5 km from the Rice Island tern colony. Eggs were laid by Caspian terns in at least 17 different nest scrapes on Miller Sands Spit, but all nesting attempts failed early in incubation due to kleptoparasitism and predation on eggs by gulls and crows. These results suggested that social attraction can be used to relocate Caspian terns currently nesting on Rice Island to a new colony site, but colony establishment and successful breeding (i.e., fledging of young) may depend on measures implemented to protect nesting terns from interference and predation by gulls and other nest predators (Cuthbert 1988). Control of gulls has been a critical component of successful tern colony restoration in the Gulf of Maine (see Kress 1983).

Another important facet of any management plan to relocate the Rice Island Caspian tern colony is effective techniques to dissuade terns from nesting at the current colony site on Rice Island. Over the short 40-year history of Caspian tern breeding along the coast of the Pacific Northwest, at least six different colony sites have been occupied and abandoned (i.e., Goose, Whitcomb, and Sand islands in Grays Harbor; Gunpowder Island in Willapa Bay; a mainland site at the Everett Naval Base; and East Sand Island in the Columbia River estuary). A number of factors have contributed to low philopatry and frequent changes in colony sites by Caspian terns nesting along the Pacific Coast of North America (Gill and Mewaldt 1982, Cuthbert 1988). Purported factors responsible for colony abandonment include: loss of nesting habitat due to winter storms and/or dredging operations, intense disturbance and predation by gulls and bald eagles, vegetation encroachment on colony sites, and harassment by humans (see Roby et al. 1998). In 1987, the East Sand Island tern colony, a dredged material disposal site, was abandoned after only 3 years due to the rapid invasion of the site by volunteer vegetation, aided by the intentional seeding of the site by U.S. Army Corps of Engineers.

Our test of the feasibility of using transplanted vegetation to discourage Caspian terns from nesting on portions of the current colony site at Rice Island demonstrated that even the highest plant density used in experimental plots was not sufficient to deter nesting by terns. Scattered plants at densities of one per m^2 apparently attracted terns to nest at higher densities than in adjacent areas devoid of vegetation. The results suggest that for vegetation to deter tern nesting on Rice Island, a continuous, dense mat would have to be established. If soil conditions are not conducive to establishment of dense vegetation in a short timeframe, other methods to deter nesting may be required. Other potential techniques include covering the substrate with plastic or landscape fabric, erecting vertical fencing in rows throughout the colony site (Pochop et al. 1999), and use of eagle decoys and other scare tactics.

Foraging Ecology of Terns and Cormorants

The efficacy of colony relocation as a means to reduce smolt losses to terns in the Columbia River estuary depends on the magnitude of shifts in foraging distribution and diet associated with a shift in breeding site. Previous studies have reported Caspian tern foraging distributions in relation to the breeding colony, but most published results present the maximum foraging range (Bergman 1953, Soikkeli 1973, Gill 1976) and not the mean or modal distribution of foraging terns around the breeding colony. In 1998, we initiated a study of the foraging distribution of Caspian terns nesting on Rice Island. Aerial surveys throughout the estuary indicated that foraging activity of Caspian terns was mostly concentrated near the Rice Island colony site. Most sightings of Caspian terns off-colony were within 8 – 10 km of the colony, suggesting that, all else being equal, a shift in colony location by as little as 20 km might result in substantial shifts in foraging distribution. The distribution of foraging terns in the Columbia River estuary changed seasonally and seemed to be related to shifts in the distribution and availability of forage fish. These results are consistent with other published studies that suggest that Caspian terns are opportunistic, central place foragers (Sirdevan and Quinn 1997) that prefer to feed in close proximity to the colony if food availability allows. Assuming that alternative prey are readily available near any restored tern colony site, optimal foraging theory (Stephens and Krebs 1986) predicts that there would be a change in foraging distribution associated with colony relocation. Further study is necessary to adequately test this hypothesis for Caspian terns nesting in the Columbia River estuary.

Site-specific predation on juvenile salmonids has been well documented for a variety of different predators at various sites in the Columbia River Basin (Ruggerone 1986, Rieman et al. 1991, Steuber et al. 1993, Collis et al. 1995, Jones et al. 1996, Schaeffer 1991 and 1992). On the upper Columbia River, avian predators congregate to feed on juvenile salmonids in areas where smolts are concentrated and vulnerable to predation (e.g., near hydroelectric dams and at hatchery release points; Ruggerone 1986, Steuber et al. 1993, Jones et al. 1996, Schaeffer 1991 and 1992). In the estuary, avian predators have been known to concentrate in areas where hatchery fish are released (J. Hill, Clatsop Economic Development Council, and B. Davies, Sea Resources, pers. comm.). No systematic, estuary-wide investigations have been conducted, however, to determine the site-specific foraging activities of piscivorous waterbirds in relation to concentrations of juvenile salmonids. Our investigations of the foraging distributions of piscivorous waterbirds in the Columbia River estuary suggest that pile dikes and, to a lesser extent, hatchery release points are hot-spots for avian predation, particularly for double-crested cormorants. Cormorants were commonly seen roosting on and foraging near pile dikes, and observations of cormorants foraging near pile dikes indicate that juvenile salmonids are especially vulnerable in those areas.

MANAGEMENT IMPLICATIONS

Study results to date indicate that Caspian terns nesting on Rice Island have had a significant impact on survival of juvenile salmonids in the Columbia River estuary during the 1997 and 1998 migration years. Our estimate of smolt consumption by terns in 1998 suggests that the comparable estimate in 1997 was not anomalous, and perhaps is representative of current annual losses of juvenile salmonids to Caspian terns in the Columbia River estuary. Population censuses over the past three years indicate that the Caspian tern colony on Rice Island is growing at perhaps 15 – 20% annually, and if this trend continues, the impact of the Rice Island tern colony on survival of juvenile salmonids in the estuary is likely to increase. In 1998, our data also suggest that double-crested cormorants are impacting smolt survival in the Columbia River estuary and that the estuary-wide population of these predators appears to be increasing by 5 – 10% annually.

Most Columbia Basin salmonid runs are listed as threatened or endangered under the Endangered Species Act of 1973. Large investments have been made in habitat restoration, hatchery production, and dam bypass to help mitigate for the losses of wild fish. Management alternatives aimed at reducing or limiting the size of the Caspian tern and double-crested cormorant populations in the estuary are being considered by managers, along with other means to reduce avian predation (e.g., modification of hatchery practices), as components of a comprehensive plan to restore salmonids throughout the Columbia Basin.

Several management alternatives have been previously used in attempts to reduce avian predation on fisheries stocks (Thomas 1972, Draulans 1987**,** Dolbeer et al. 1996). These techniques include: (1) lethal control of adult birds (Elson 1962, Bédard et al. 1995), (2) curtailing the production of fish-eating birds (Christens and Blokpoel 1991, Morris and Siderius 1990, Pochop et al. 1998), (3) hazing of adult birds in areas where they nest and forage (Bayer 1989, Schaeffer 1992), (4) protecting fish in areas where they are vulnerable to bird predation (Ostergaard 1981, Blokpoel and Tessier 1984, Steuber et al. 1993), and (5) changing rearing practices in hatcheries to produce more viable and "predator-wary" fish (Suboski and Templeton 1989, Olla et al. 1990, Wiley et al. 1993, Berejikian 1995). Regional fish and wildlife managers are currently considering these different management alternatives to increase smolt survival in the Columbia River Basin. Here we discuss the 1998 data as it pertains to the feasibility of these different options, primarily the option of relocating the Rice Island Caspian tern colony to reduce predation by terns in the Columbia River estuary.

Our results from both 1997 and 1998 suggest that relocation of the Rice Island tern colony can reduce smolt losses to terns. In both years, we compared the diet composition of double-crested cormorants nesting on East Sand and Rice islands (located at river kilometers 8 and 34, respectively) and found significant differences, presumably associated with the proximity of East Sand Island to the ocean. Cormorants nesting on East Sand Island consumed fewer juvenile salmonids and their diets included a greater proportion of forage fish with marine affinities compared to cormorants nesting on Rice

Island (Roby et al. 1998; Figure 9). The diets of glaucous-winged/western gulls nesting on the two islands exhibited a similar trend, only less pronounced (Figure 9). Finally, there was a large difference in the proportion of juvenile salmonids in the diet of Caspian terns returning to the colony from up-river versus down-river, with more juvenile salmonids in the diet of terns foraging in the up-river direction.

The potential efficacy of tern colony relocation as a management option requires that (1) suitable tern nesting habitat can be provided at the new site, (2) terns can be moved from one nesting colony site to another, (3) relocation of terns leads to significant changes in their foraging distribution and diet, and (4) terns can nest successfully at the new site so that breeding pairs tend to return to the new site in subsequent years. Recent work restoring tern breeding colonies both in the Gulf of Maine (Kress 1983) and in the Great Lakes region (Lampman et al. 1996, Quinn et al. 1996) suggests that new breeding colonies can be established. Historical breeding colonies of common, arctic, and roseate terns have been successfully restored along the coasts of Massachusetts, New Hampshire, Maine, and New Brunswick (Kress 1983) and new Caspian tern colonies have been established on artificial islands in Lake Ontario using social attraction (Lampman et al. 1996, Quinn et al. 1996). A combination of habitat improvements, tern decoys, audio playbacks of tern vocalizations, and limited gull control were used to establish and maintain tern colonies at sites that were newly established or had not been used by nesting terns for decades (see Kress 1983 for full description of social attraction methods). Although these studies did not attempt to relocate breeding colonies from one site to another, social attraction techniques in conjunction with methods to discourage nesting at Rice Island might be effective in relocating the Rice Island Caspian tern colony to a different site or multiple alternative sites.

The Rice Island colony is the largest Caspian tern colony in North America and perhaps the world, representing as much as 75% and 25% of the Pacific Coast and continent-wide nesting populations, respectively (Cuthbert and Wires 1999). The rapid expansion of the Rice Island colony since 1986 is largely due to the loss of other tern nesting habitat along the Pacific Coast and the shifting of nesting pairs from those former colonies to Rice Island (Roby et al. 1998, this report). Rice Island, a dredge material disposal island, provided one of the few suitable colony sites for Caspian terns along the entire Pacific Coast of North America. Furthermore, annual releases of over 150 million juvenile salmonids from Columbia Basin hatcheries has provided a reliable and readily available food supply for terns nesting in the estuary. Despite what appears to be highly favorable nesting conditions for terns in the estuary, the productivity of Caspian tern nesting pairs at the Rice Island colony has been low over the past two years (0.05 and 0.49 young fledged per nesting pair in 1997 and 1998, respectively), well below the regional average (1.1 young fledged per pair; Cuthbert and Wires 1999) . Rice Island terns also exhibit unusually high levels of intra-specific aggression and did not defend their eggs and chicks from predators with the same tenacity as has been observed at other Caspian tern colonies (Cuthbert and Wires 1999, C. Collins, California State University, Long Beach, personal observation). Our results suggest that breeding conditions for Caspian terns on the Rice Island colony are far from optimal, and that the unprecedented size of the colony may be a key factor. Furthermore, because a large portion of the continent-wide population of Caspian terns nests at one location, the risks to that population (i.e., from disease, storms, predators, human disturbance, or other local events) are substantially greater than if the population was more widely distributed at a number of smaller breeding colonies.

Results of our management feasibility studies in 1998 suggest that colony relocation may be a feasible management technique. Additional study is needed, however, to determine if relocating nesting terns will lead to significant changes in foraging distribution and diet. Previous diet studies on Caspian terns nesting in Grays Harbor, Washington in 1975 and 1976 revealed that terns consumed mostly marine fish and few riverine fishes, with juvenile salmonids comprising less than 20% of prey items (Smith 1978, Penland 1981). This suggests that relocating part of the Rice Island Caspian tern colony to Grays Harbor, and perhaps elsewhere along the coast, may reduce the overall impact of the terns on smolt survival in the Columbia Basin without shifting similar levels of predation to other salmonid stocks. But if managers seek to relocate Rice Island Caspian terns to restored habitat outside the Columbia River estuary (e.g., Grays Harbor), these efforts should be carefully conceived and coordinated with regional resource managers to ensure that new resource conflicts due to tern colony relocation are minimized.

Our data (i.e., PIT tag returns from Rice Island and observations of foraging birds) also suggests that the magnitude of avian predation on juvenile salmonids in the Columbia River estuary might be reduced by reducing the vulnerability of smolts to predation. Changes in hatchery rearing practices (e.g., subsurface feeding and predator avoidance training) may mitigate the higher susceptibility of hatchery-raised smolts to tern predation (Vincent 1960, Moyle 1969, Olla and Davis 1989, Suboski and Templeton 1989, Berejikian 1995). Changes in transportation practices (barging and trucking smolts around dam impoundments) may also reduce smolt losses to birds in the estuary. New approaches, such as not transporting chinook smolts with steelhead smolts or reducing fish loading densities in barges (Congleton et al. in press), may decrease the vulnerability of transported smolts to tern predation in the estuary. Finally, the use by double-crested cormorants of pile dikes as favored foraging sites suggests that removal or modification of these channel maintenance structures may produce benefits for out-migrating smolts in the Columbia River estuary.

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TABLES

Table 1. Population indices for piscivorous waterbird colonies on the lower Columbia River as determined by aerial photography in 1998.

		Population Indices[1]		
Ref#[2]	Location	Terns[3]	Gulls[4]	Cormorants[5]
1	East Sand Is.	--	5,496	6,403
2	Rice Is.	11,223	1,576	920
3	Miller Sands Spit	--	742	--
4	Little Memaloose Is.	--	357	--
5	Miller Rocks	--	2,179	--
6	Three Mile Canyon Is.	339	11,102	--
7	Crescent Is.	575	4,597	--
8	Richland Is.	--	22,348	--
9	Island #18	--	12,669	--
	TOTALS	12,137	61,066	7,323[6]

[1] Indices are direct counts of the number of adults on the ground from high resolution aerial photographs taken late in the incubation period. These numbers are a liberal estimate of the number of breeding pairs at each colony.

[2] Numbers refer to locations on map of study area (Figure 1).

[3] Caspian tern

[4] California gull, ring-billed gull, glaucous-winged/western gulls

[5] Double-crested cormorant

[6] Another 70 pairs nested on channel markers in the Columbia River Estuary near Rice Island and an additional 120 pairs nested on pilings near Desdemona Sands.

Table 2. Direct counts of on-colony individuals and percent change in population indices for piscivorous waterbird colonies on the lower Columbia River, 1996 - 1998.

Species Location	**1996**	**1997**		**1998**	
Caspian tern					
Rice Island	8,148	9,415	(+16%)	11,223	(+19%)
Three Mile Canyon	277	571	(+106%)	339	(-41%)
Crescent Island	331	990	(+199%)	575	(-42%)
California & ring-billed gull					
Little Memaloose Is.	542	939	(+73%)	357	(-62%)
Miller Rocks	1,599	3,783	(+126%)	2,179	(-42%)
Three Mile Canyon	8,828	13,305	(+51%)	11,102	(-17%)
Crescent Island	3,334	5,769	(+73%)	4,597	(-20%)
Richland Is.	17,793	18,820	(+6%)	22,348	(+19%)
Island 18	17,096	14,495	(-15%)	12,669	(-13%)
Glaucous-winged/western gull					
Rice Island	1,046	1,583	(+51%)	1,576	(0%)
Miller Sands Spit	n/a	1,268	n/a	742	(-41%)
East Sand Island	6,775	7,106	(+5%)	5,496	(-23%)
Double-crested cormorant					
East Sand Is.	5,356	5,271	(-2%)	6,403	(+21%)
Rice Is.	636	1,221	(+92%)	920	(-25%)

Table 3. Caspian tern nesting productivity on Rice Island and Miller Sands Spit in 1998. Averages are expressed as Mean ± SD.

	Colony		
	Rice Island	Miller Sands Spit	Range
Sample size (no. observed nests)	94	17	
Average clutch size	2.01 ± 0.81	1.40 ± 0.50	1 – 4
Hatching success[1]	75.0%	0.0%	
Average brood size near hatching[2]	1.58 ± 0.62	0	0 – 3
Nesting success[3]	49%	0%	
Productivity[4]	0.49	0	

[1] Proportion of initiated nests hatching at least 1 egg

[2] When nestlings approximately 1 – 5 days old

[3] Proportion of initiated nests fledging at least 1 young. An estimated 3,900 chicks were fledged from the Rice Island Caspian tern colony.

[4] Number of young fledged per nest based on the total number of nests initiated (ca. 7,948) and the estimated number of fledglings produced on the colony.

Table 4. Double-crested cormorant nesting productivity on East Sand Island, Rice Island, and Channel Markers in 1998. Averages are expressed as Mean ± SD.

	Colony			
	East Sand Island	Rice Island	Channel Markers	Range
Sample size (no. observed nests)	70	70	70	
Average clutch size	4.11 ± 1.42	n/a	4.18 ± 1.18	2 – 8
Hatching success[1]	79.9%	n/a	86.2%	
Average brood size near hatching[2]	n/a	n/a	3.00 ± 1.45	2 – 5
Average brood size near fledging[3]	1.58 ± 0.67	1.36 ± 0.63	2.22 ± 0.69	0 – 3
Nesting success[4]	74.8%	38.9%	71.6%	
Productivity[5]	1.23	0.55	1.59	

[1] Proportion of initiated nests hatching at least 1 egg

[2] When nestlings approximately 1 - 5 days old

[3] When nestlings approximately 20 - 30 days old

[4] Proportion of initiated nests fledging at least 1 young. An estimated 6,833 chicks, 420 chicks, and 111 chicks were fledged from the East Sand Island, Rice Island, and channel marker cormorant colonies, respectively.

[5] Number of young fledged per initiated nest, based on the sample of nests observed.

Table 5. Diet composition of Caspian terns nesting on Rice and Three Mile Canyon islands in the Columbia River Estuary in 1998, based on identifiable prey items in bill loads or adult stomach contents. Percent mass of prey categories in the diet of Caspian terns nesting on Rice Island was derived by multiply the average mass of individual prey types (based on whole fish collected from terns) by the total number of fish identified in the corresponding prey category.

	Rice Island		**Three Mile Canyon Island**		
	Bill Load Observations		Stomach Samples		Bill Load Observations
Prey Type	% Mass	% No.	% Mass	% No.	% No.
Shad, herring, sardine[1]	12.3	10.6	0.0	0.0	0.0
Peamouth, pike minnow[2]	2.5	1.9	0.0	0.0	0.0
Smelt[3]	4.6	6.2	0.0	0.0	0.0
Sucker[4]	0.0	0.0	0.0	0.0	2.9
Salmonid[5]	**73.6**	**72.8**	**84.5**	**88.5**	**80.2**
Sculpin[6]	0.7	1.2	0.0	0.0	0.0
Pacific lamprey[7]	0.1	0.8	0.0	0.0	0.0
Shiner perch[8]	5.6	5.6	0.0	0.0	0.0
Yellow perch[9]	0.0	0.0	0.0	0.0	1.5
Bass[10]	0.0	0.0	3.5	3.8	15.4
Other[11]	0.5	1.0	12.0	7.7	0.0
Observation and sample no.	1376		26		60
Total mass and no. of prey	37,748g	1376	760.0g	26	60

[1] Clupeidae, [2] Cyprinidae, [3] Osmeridae, [4] *Catostomus* sp., [5] *Oncorhynchus* sp., [6] Cottidae, [7] *Lampetra tridentata*, [8] *Cymatogaster aggregata*, [9] *Perca flavescens*, [10] *Micropterus* sp., [11] starry flounder (*Platichthys stellatus*), stickleback (Gasterosteidae), Pacific sand lance (*Ammodytes hexapterus*), or unidentified non-salmonids

Table 6. Diet composition of double-crested cormorants nesting on East Sand and Rice islands in the Columbia River Estuary in 1998, based on analysis of adult stomach contents and chick regurgitations.

	East Sand Island		**Rice Island**	
Prey Type	% Mass	% No.	% Mass	% No.
Shad, herring, sardine[1]	33.6	32.0	4.2	4.2
Peamouth, pike minnow[2]	7.2	5.7	10.9	10.1
Smelt[3]	8.9	8.2	0.0	0.0
Sucker[4]	5.8	5.5	3.9	4.5
Salmonid[5]	**15.9**	**14.7**	**54.6**	**53.1**
Sculpin[6]	4.9	5.6	2.7	3.5
Pacific sand lance[7]	1.8	4.2	0.0	0.0
Shiner perch[8]	5.3	4.3	0.0	0.0
Stickleback[9]	2.3	4.7	16.8	20.2
Starry flounder[10]	11.0	11.6	5.8	4.4
Other[11]	3.3	3.5	1.1	0.1
Samples examined	111		60	
Total mass and no. of prey	11,944g	665	8,406g	360

[1] Clupeidae, [2] Cyprinidae, [3] Osmeridae, [4] *Catostomus* sp., [5] *Oncorhynchus* sp., [6] Cottidae, [7] *Ammodytes hexapterus*, [8] *Cymatogaster aggregata*, [9] Gasterosteidae, [10] *Platichthys stellatus*, [11] unidentified non-salmonid

Table 7. Diet composition of glaucous-winged/western gulls on East Sand and Rice islands in the Columbia River Estuary in 1998, based on the analysis of adult stomach contents and chick regurgitations. Percent of identifiable prey items (% No) in the diet is calculated for the fish portion of the diet only.

	East Sand Island		**Rice Island**	
Prey Type	% Mass	% No.	% Mass	% No.
Crustacean	0.0		0.0	
Mollusk	12.0		4.3	
Insect	0.7		0.0	
Vertebrate (non-fish)	0.0		1.0	
Plant material	16.7		6.0	
Refuse	30.1		66.2	
Fish eggs	3.1		0.0	
Fish	37.3		22.5	
Shad, herring, sardine[1]	16.3	45.2	2.5	11.1
Peamouth, pike minnow[2]	1.0	2.4	4.4	22.2
Smelt[3]	0.2	1.2	0.0	0.0
Sucker[4]	1.0	2.4	0.0	0.0
Salmonid[5]	**6.0**	**15.5**	**12.8**	**52.8**
Sculpin[6]	1.4	4.8	0.0	0.0
Pacific sand lance[7]	0.1	1.6	0.0	0.0
Shiner perch[8]	0.0	0.0	0.0	0.0
Stickleback[9]	0.7	2.4	0.0	2.8
Starry flounder[10]	0.4	1.2	0.0	0.0
Other[11]	10.2	23.4	2.8	11.1
Samples examined	106	42	88	18
Total mass and no. of prey	3,471g	77	3,259g	21

[1] Clupeidae, [2] Cyprinidae, [3] Osmeridae, [4] *Catostomus* sp., [5] *Oncorhynchus* sp., [6] Cottidae, [7] *Ammodytes hexapterus*, [8] *Cymatogaster aggregata*, [9] Gasterosteidae, [10] *Platichthys stellatus*, [11] unidentified non-salmonid

Table 8. Diet composition of California gulls nesting on Little Memaloose Island, Three Mile Canyon Island, and Island 18 in the lower Columbia River in 1998, based on the analysis of adult stomach contents and chick regurgitations.

	Little Memaloose Is.	**Three Mile Canyon Is.**	**Island 18**
Prey Type	% Mass	% Mass	% Mass
Crustacean	0.0	1.8	0.0
Mollusk	17.7	2.5	28.0
Insect	3.8	6.5	22.6
Vertebrate (non-fish)	0.0	0.0	0.0
Plant material	26.4	22.1	44.6
Refuse	32.3	65.6	4.8
Fish eggs	0.0	0.0	0.0
Fish	19.8	1.5	0.0
Peamouth, pike minnow[1]	2.9	0.0	0.0
Salmonid[2]	**16.9**	**0.0**	**0.0**
Bass[3]	0.0	1.5	0.0
Samples examined	59	58	22
Total mass	1,155g	1,055g	244g

[1] Cyprinidae, [2] *Oncorhynchus* sp., [3] *Micropterus* sp.

Table 9. Diet composition of ring-billed gulls nesting on Three Mile Canyon Island and Island 18 in the lower Columbia River in 1998, based on the analysis of adult stomach contents and chick regurgitations.

	Three Mile Canyon Is.	**Island 18**
Prey Type	% Mass	% Mass
Crustacean	0.0	0.0
Mollusk	0.0	15.1
Insect	30.0	30.0
Vertebrate (non-fish)	10.0	0.0
Plant material	20.0	45.8
Refuse	40.0	9.1
Fish eggs	0.0	0.0
Fish	0.0	0.0
Salmonid[1]	**0.0**	**0.0**
Samples examined	10	31
Total mass	144g	182g

[1] *Oncorhynchus* sp.

Table 10. Relative vulnerability of PIT-tagged wild vs. hatchery-reared juvenile salmonids to predation by Caspian terns nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. Significant negative values for % diff. indicate higher vulnerability of hatchery-reared smolts to tern predation, as compared to wild smolts.

	In-River[1]			On-Colony[2]				
	N_H[3]	N_W[4]	$\%_W$[5]	N_H[3]	N_W[4]	$\%_W$[5]	% diff[6]	*P*
1997								
Spring/summer chinook	3,204	181	5.4	81	0	0.0	- 5.4	0.03
Steelhead	6,684	408	5.7	463	12	2.5	- 3.2	0.003
1998								
Spring/summer chinook	8,893	1,419	13.8	168	7	4.0	- 9.8	0.0002
Steelhead	4,113	1,316	24.2	642	168	20.7	- 3.5	0.03

[1] "In-river" refers to PIT tags detected at Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island Caspian tern colony.
[3] N_H = Number of hatchery-reared fish in the sample.
[4] N_W = Number of wild fish in the sample.
[5] $\%_W$ = percent of total fish in the sample that were wild.
[6] %diff = $\%_W$ on-colony - $\%_W$ in-river.

Table 11. Relative vulnerability of PIT-tagged wild vs. hatchery-reared juvenile salmonids to predation by double-crested cormorants nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries.

	In-River[1]			On-Colony[2]				
	N_H[3]	N_W[4]	$\%_W$[5]	N_H[3]	N_W[4]	$\%_W$[5]	% diff[6]	*P*
1997								
Spring/summer chinook	3,290	199	5.7	65	2	3.0	- 2.7	0.34
Steelhead	7,043	405	5.4	194	18	8.5	+ 3.1	0.06
1998								
Spring/summer chinook	8,403	1,373	14.0	57	8	12.3	- 1.7	0.69
Steelhead	4,567	1,438	23.9	108	29	21.2	- 2.7	0.45

[1] "In-river" refers to PIT tags detected at Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island cormorant colony.
[3] N_H = Number of hatchery-reared fish in the sample.
[4] N_W = Number of wild fish in the sample.
[5] $\%_W$ = percent of total fish in the sample that were wild.
[6] %diff = $\%_W$ on-colony - $\%_W$ in-river.

Table 12. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by Caspian terns nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass and transportation around dams by barge or truck are equal ($M_B = M_T$). Significant positive values for % diff. indicate higher vulnerability of transported smolts to tern predation, as compared to non-transported smolts. Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to tern predation, as compared to transported smolts.

	In-River[1]			On-Colony[2]				
$M_B = M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,229	24,211	91.6	49	472	90.6	- 1.0	0.42
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	5,849	2,560	30.4	338	146	30.2	- 0.2	0.90
Wild	356	360	50.3	9	6	40	- 10.3	0.43
1998								
Spring/summer chinook								
Hatchery	5,951	51,118	89.6	105	1,523	93.5	+ 3.9	<0.0001
Wild	908	1,112	50.1	2	11	84.6	+ 34.5	0.03
Steelhead								
Hatchery	2,398	3,077	56.2	316	315	50.0	- 6.2	0.003
Wild	949	1,389	59.4	99	63	38.9	- 20.5	<0.0001

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island Caspian tern colony.
[3] N_B = Number of Bonneville Dam bypassed fish in the sample.
[4] N_T = Number of transported fish in the sample.
[5] $\%_T$ = percent of total fish in the sample that were transported.
[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.

Table 13. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by double-crested cormorants nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass and transportation around dams by barge or truck are equal ($M_B = M_T$). Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to cormorant predation, as compared to transported smolts.

	In-River[1]			On-Colony[2]				
$M_B = M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,236	25,450	91.9	42	289	87.3	- 4.6	0.002
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	6,027	2,957	32.9	161	60	27.1	- 5.8	0.07
Wild	349	369	51.4	16	12	42.9	- 8.5	0.37
1998								
Spring/summer chinook								
Hatchery	5,988	30,831	83.7	46	165	78.2	- 5.5	0.03
Wild	896	841	48.4	7	7	50.0	+ 1.6	0.91
Steelhead								
Hatchery	2,570	3,146	55.0	100	68	40.5	- 14.5	0.0002
Wild	1,006	1,216	54.7	26	23	46.9	- 7.8	0.28

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island cormorant colony.
[3] N_B = Number of Bonneville Dam bypassed fish in the sample.
[4] N_T = Number of transported fish in the sample.
[5] $\%_T$ = percent of total fish in the sample that were transported.
[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.

Table 14. Input parameters of a bioenergetics model for estimating the total population energy consumption of Caspian terns nesting on Rice Island, Columbia River Estuary in 1998.

	Maximum	Best	Minimum
Daily energy expenditure (kJ $bird^{-1}$ day^{-1}) [1]	1,128	1,040	951
Metabolizable energy coefficients	0.70	0.75	0.80
Daily energy consumption (kJ $bird^{-1}$ day^{-1})	1,611	1,386	1,189
Population size (individual adults)	19,692	15,896	12,197
Number of fledglings	3,950	3,900	3,850
Total predation days[2]	1.38×10^{6}	1.12×10^{6}	8.58×10^{5}
Total adult energy consumption (kJ)	2.23×10^{9}	1.55×10^{9}	1.02×10^{9}
Total fledgling energy consumption (kJ)	2.02×10^{8}	1.73×10^{8}	1.49×10^{8}
Total population energy consumption (kJ)	2.24×10^{9}	1.72×10^{9}	1.17×10^{9}

[1] Daily energy expenditure (DEE) is based on measurements made on breeding adults using the doubly labeled water technique. The best estimate of DEE is the mean of all measurements. The maximum and minimum estimates of DEE are the mean ± 2 SE, respectively.

[2] Based on the aerial photo census and weekly colony attendance measurements throughout the breeding season.

Table 15. Input parameters of a bioenergetics model for estimating the total population energy consumption of double-crested cormorants nesting on East Sand Island and Rice Island, Columbia River Estuary in 1998.

	East Sand Island[1]			**Rice Island**[2]		
	Maximum	Best	Minimum	Maximum	Best	Minimum
Daily energy expenditure (kJ bird^{-1} day^{-1})[3]	3,200	2,700	2,200	3,200	2,700	2,200
Metabolizable energy coefficients	0.70	0.75	0.80	0.70	0.75	0.80
Daily energy consumption (kJ bird^{-1} day^{-1})	4,571	3,600	2,750	4,571	3,600	2,750
Population size (individual adults)	12,888	10,740	8,592	2,076	1,730	1,384
Number of fledglings	9,364	7,803	6,242	637	531	425
Total predation days[4]	1.22×10^6	1.01×10^6	8.12×10^5	1.71×10^5	1.43×10^5	1.14×10^5
Total adult energy consumption (kJ)	4.09×10^9	2.88×10^9	1.88×10^9	5.48×10^8	3.85×10^8	2.51×10^8
Total fledgling energy consumption (kJ)	1.03×10^9	7.24×10^8	4.72×10^8	6.63×10^7	4.66×10^7	3.04×10^7
Total population energy consumption (kJ)	5.12×10^9	2.88×10^9	2.35×10^9	6.14×10^8	3.85×10^8	2.81×10^8

[1] Estimates of population size, predation days, and population energy consumption include cormorants nesting near East Sand Island on the Desdemona Sands pilings (120 breeding pairs).

[2] Estimates of population size, predation days, and population energy consumption include cormorants nesting near Rice Island on channel markers (70 breeding pairs).

[3] Daily energy expenditure (DEE) is estimated on the basis of average double-crested cormorant body mass in the Columbia River Estuary (2,486 g) and allometric equations in Birt-Friesen et al. (1989).

[4] Based on the aerial photo census and weekly colony attendance measurements throughout the breeding season.

Table 16. Input parameters of a bioenergetics model for estimating the total population energy consumption of glaucous-winged/western gulls nesting on East Sand Island, and Rice Island /Miller Sands Spit, Columbia River Estuary in 1998.

	East Sand Island			**Rice Island & Miller Sands Spit**		
	Maximum	Best	Minimum	Maximum	Best	Minimum
Daily energy expenditure (kJ $bird^{-1}$ day^{-1}) [1]	1,855	1,420	1,200	1,855	1,420	1,200
Metabolizable energy coefficients	0.70	0.75	0.80	0.70	0.75	0.80
Daily energy consumption (kJ $bird^{-1}$ day^{-1})	2,650	1,893	1,500	2,650	1,893	1,500
Population size (individuals)	10,992	8,244	5,496	4,636	3,477	2,318
Total predation days[2]	1.32×10^6	8.66×10^5	4.40×10^5	5.56×10^5	3.65×10^5	1.85×10^5
Total adult energy consumption (kJ)	2.45×10^9	1.23×10^9	5.28×10^8	1.03×10^9	5.19×10^8	2.23×10^8

[1] Daily energy expenditure (DEE) is estimated on the basis of average glaucous-winged/western gull body mass in the Columbia River Estuary (1,282 g) and allometric equations in Birt-Friesen et al. (1989).

[2] Based on the aerial photo census and the estimated average duration of residency of individual gulls in the estuary.

Table 17. Percentage of total energy consumption by prey category for Caspian terns breeding on Rice Island in 1998 and used as input parameters for the bioenergetics model. See Diet Composition section for percent biomass of each prey category.

	Energy Density (kJ/g wet mass)		Mass of Individual Prey Items (g)[1]		% Total Energy Consumption
	N	Mean	N	Mean	
All Salmonids					**71.3**
Chinook salmon[2]	12	4.0	51	16.0	28.2
Coho salmon[3]	12	5.0	44	30.7	23.7
Steelhead[4]	12	4.6	18	59.6	19.4
Shad, Herring, Sardine[5]	11	6.0	14	26.1	11.9
Shiner Perch[6]	6	4.3	8	23.6	6.0
Smelt[7]	1	4.9	7	24.8	4.8
Peamouth, Pike Minnow[8]	12	5.7	10	31.3	4.1
Sculpin[9]	12	4.0	6	14.1	1.3
Pacific Lamprey[10]	2	5.0	2	2.0	0.6

[1] Based on average mass of intact fish in the dropped fish and stomach contents samples.
[2] *Oncorhynchus tshawytscha*, [3] *Oncorhynchus kisutch*, [4] *Oncorhynchus mykiss*, [5] Clupeidae, [6] *Cymatogaster aggregata*, [7] Osmeridae, [8] Cyprinidae, [9] Cottidae, [10] *Lampetra tridentata*

Table 18. Estimates of the number of juvenile salmonids consumed by Caspian terns, double-crested cormorants, and glaucous-winged/western gulls nesting in the Columbia River Estuary in 1998. Bioenergetics models were used to derive consumption estimates (see methods section for details).

	Maximum	Best	Minimum
Caspian tern[1]			
Chinook salmon	8,593,004	6,188,574	4,303,054
Coho salmon	4,583,775	3,202,509	2,128,273
Steelhead	2,066,314	1,443,154	958,551
All salmonids	**15,243,093**	**10,834,237**	**7,389,878**
Double-crested cormorant[1]			
All salmonids – East Sand Island[2]	6,747,740	3,330,618	1,587,596
All salmonids – Rice Island[3]	2,491,566	1,229,800	586,197
All salmonids - both colonies[2,3]	**9,239,306**	**4,560,418**	**2,173,793**
Glaucous-winged/western gull			
All salmonids – East Sand Island	2,125,633	709,997	199,334
All salmonids – Rice Island and Miller Sands Spit	1,860,908	587,751	155,274
All salmonids - both colonies	**3,932,541**	**1,296,747**	**354,608**

[1] Smolt consumption estimates include estimates of consumption by young of the year.

[2] Smolt consumption estimates include estimates of consumption by adult cormorants nesting near East Sand Island on the Desdemona Sands pilings (120 breeding pairs).

[3] Smolt consumption estimates include estimates of consumption by adult cormorants nesting near Rice Island on channel markers (70 breeding pairs).

Table 19. Observed densities of foraging Caspian terns and double-crested cormorants in various habitat types in the Columbia River Estuary in 1998.

	Average Foraging Density, Birds/Km^2	
River Habitat Type	Caspian Terns	Double-crested Cormorants
Shallow Bay/Tidal Flats	2.51	2.56
Main (Shipping) Channel	2.37	3.35
Side Channel	1.59	0.83
Tributaries/Small Sloughs	1.55	1.77

Table 20. Attendance at various Columbia River shipping channel sites up-river from Rice Island by Caspian terns and double-crested cormorants during April and May, 1998, in relation to the presence or absence of pile dike structures.

Site	River Km	Distance from Rice Is. (Km)	# of Pile Dikes at site	Average Attendance: Caspian Terns	Average Attendance: Double-crested Cormorants
Miller Sands Spit	37	4.0	4	33.3	272.8
Pillar Rock Island	43	8.0	2	21.5	73.7
Skamokowa	53	19.2	0	6.0	0.7
Elochoman River Outlet	56	20.8	0	12.5	2.0
Puget Island/West End	60	23.2	2	24.3	53.6
Puget Island/Pancake Pt.	71	27.8	4	0.9	30.9
Jones Beach	76	33.2	3	3.2	16.0
Cooper Pt./Cape Horn	79	34.4	0	30.6	0.0
Eureka Bar	82	37.8	3	7.0	50.0
Crims Island	92	44.2	5	0.9	0.3

FIGURES

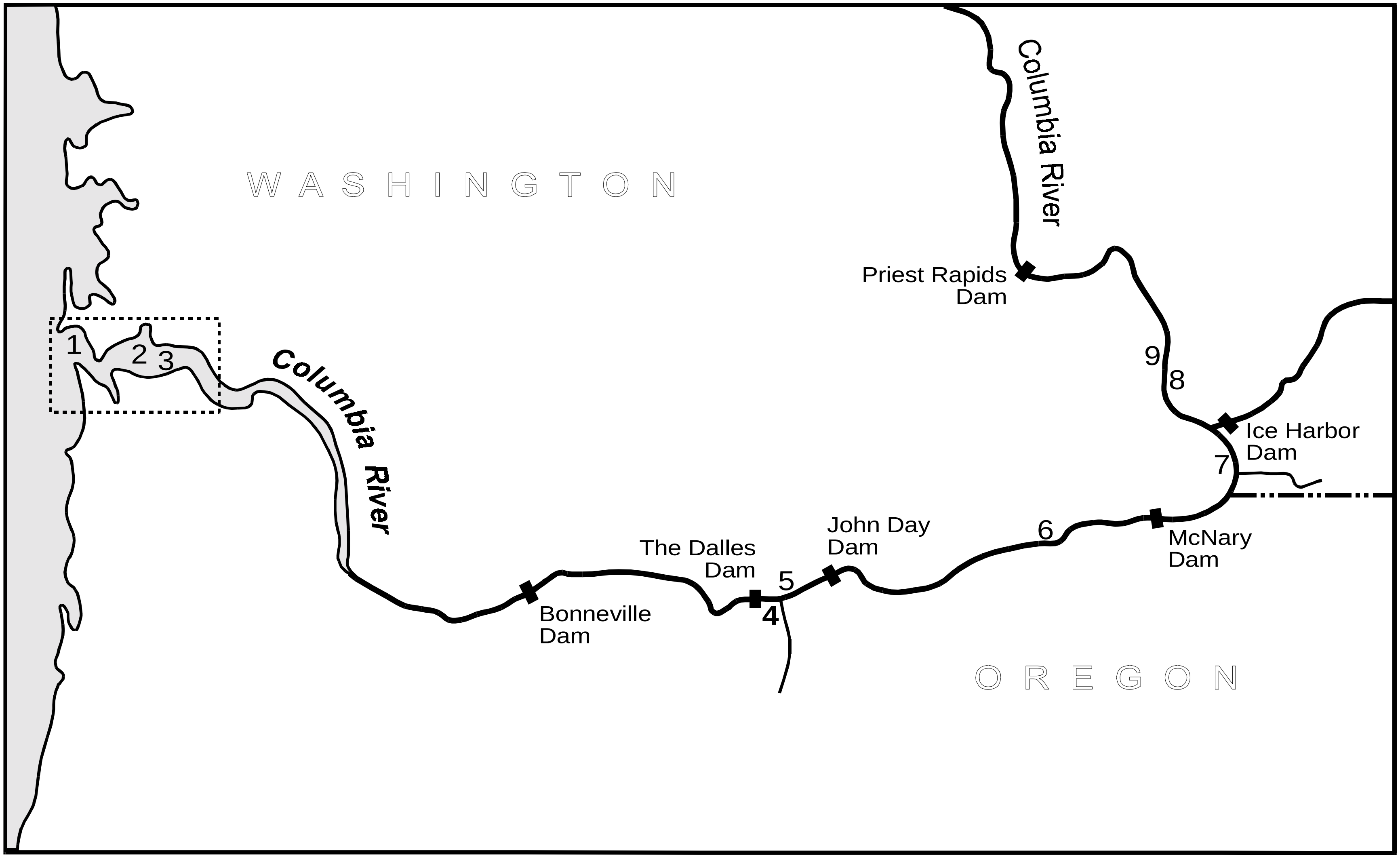


Figure 1. Lower Columbia River study area and locations of piscivorous waterbird colonies (estuary shown in dashed box). Colony locations are: 1 = East Sand Island; 2 = Rice Island; 3 = Miller Sands Spit; 4 = Little Memaloose Island; 5 = Miller Rocks; 6 = Three Mile Canyon Island; 7 = Crescent Island; 8 = Richland Island (Island 20); and 9 = Island 18.

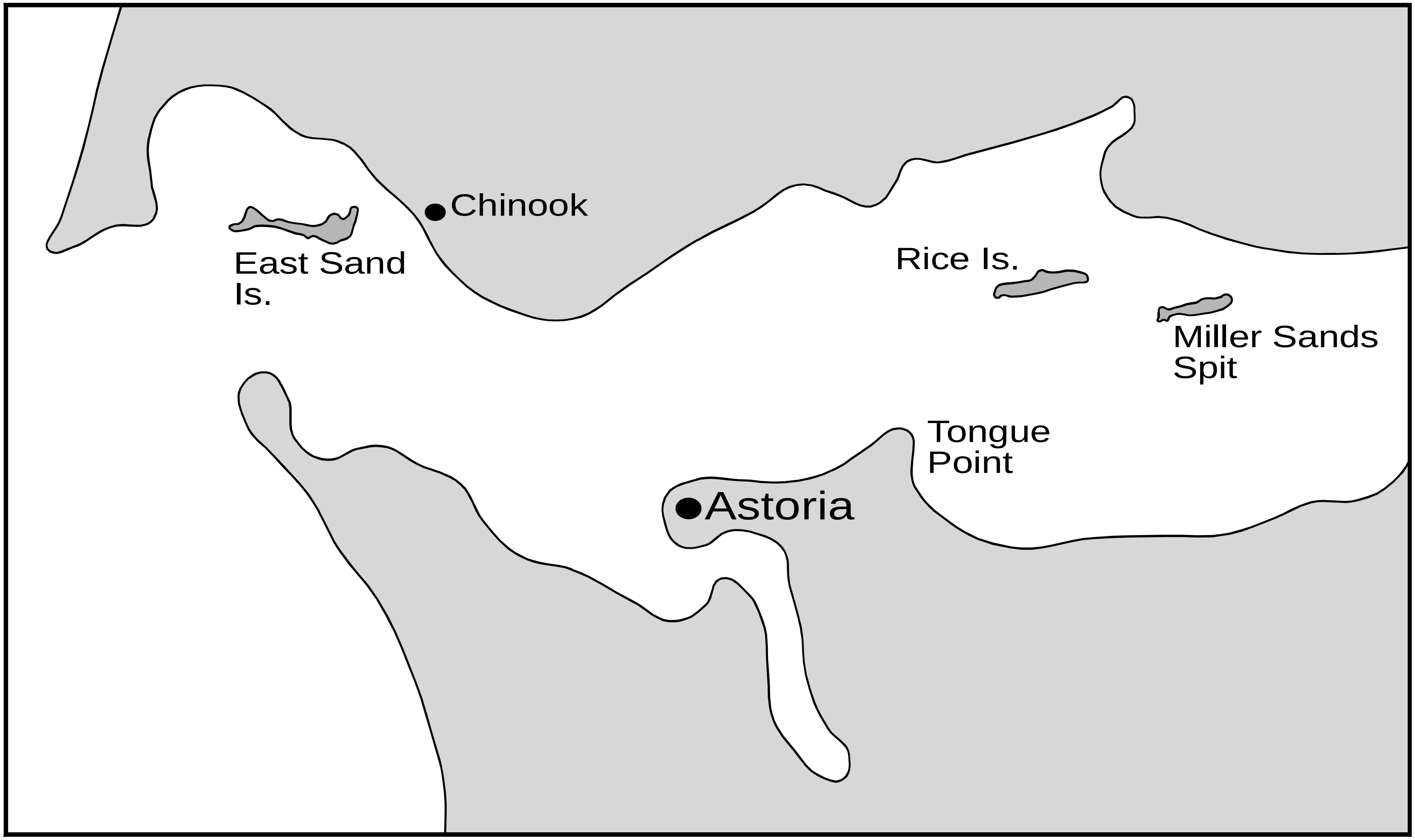


Figure 2. Columbia River estuary study area and island locations of piscivorous waterbird colonies.

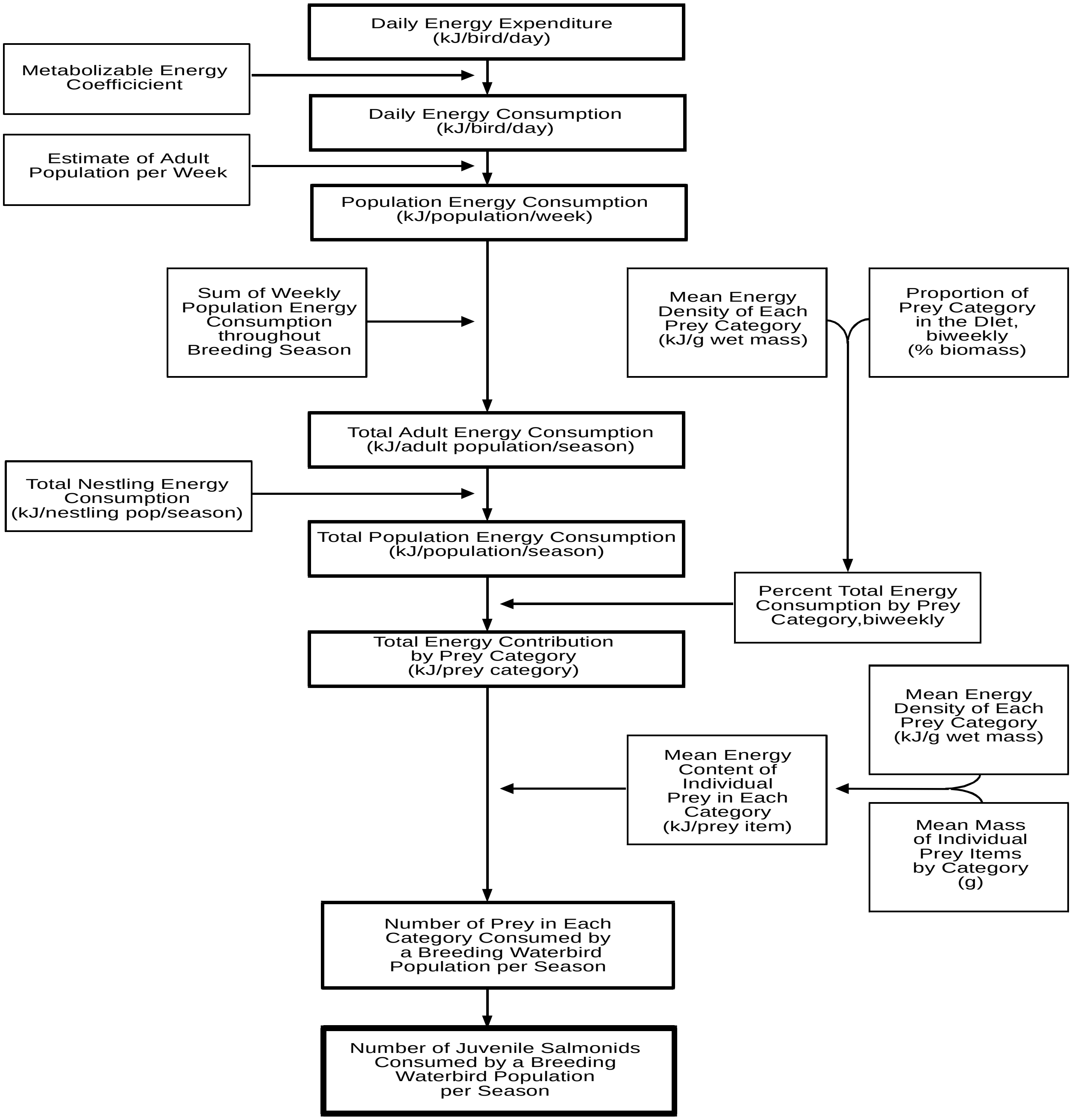


Figure 3. A bioenergetics model for estimating the number of juvenile salmonids consumed by piscivorous waterbirds in the lower Columbia River.

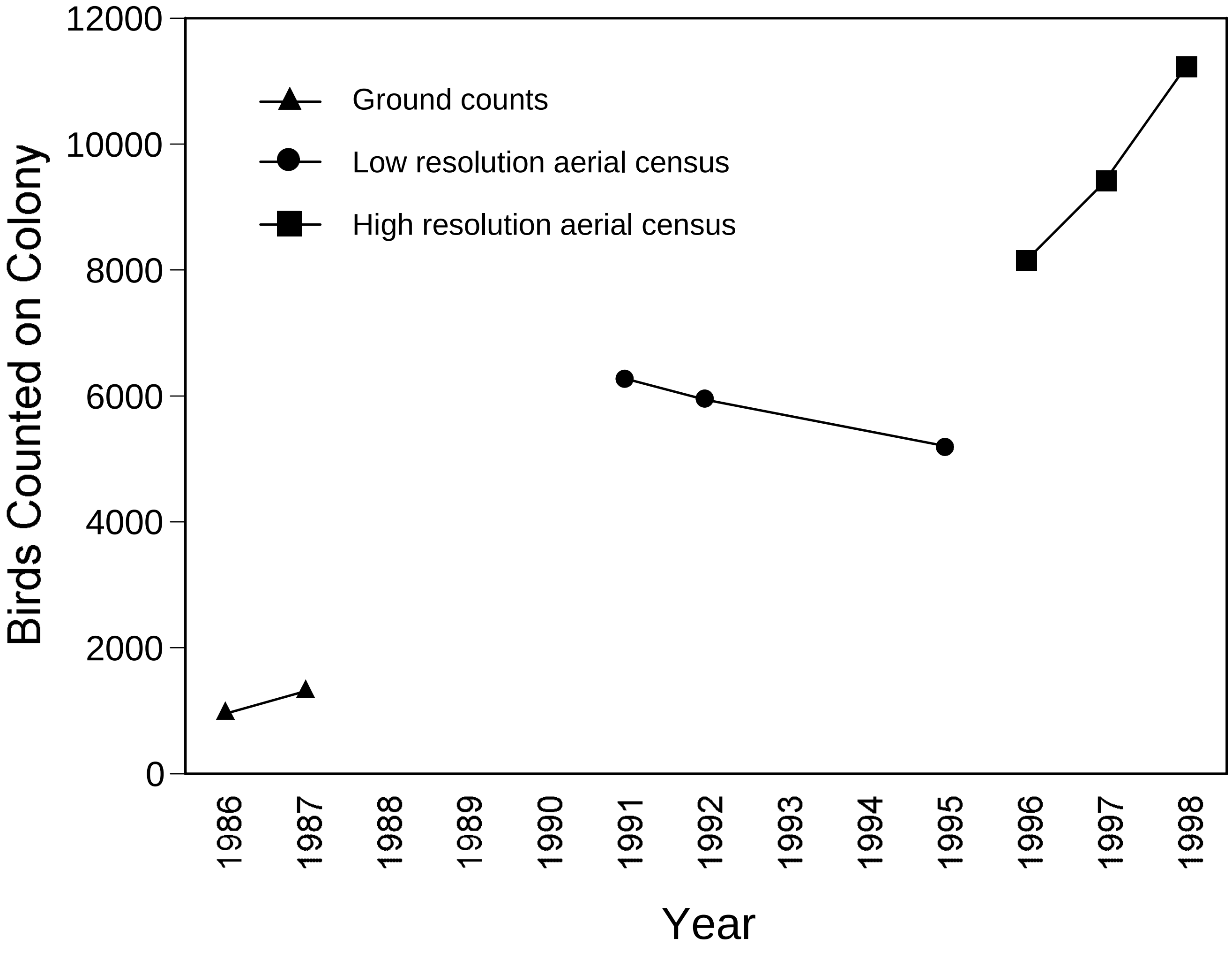


Figure 4. Population estimates (direct counts of birds on-colony) for Caspian terns nesting on Rice Island in the Columbia River Estuary, 1986 - 1998.

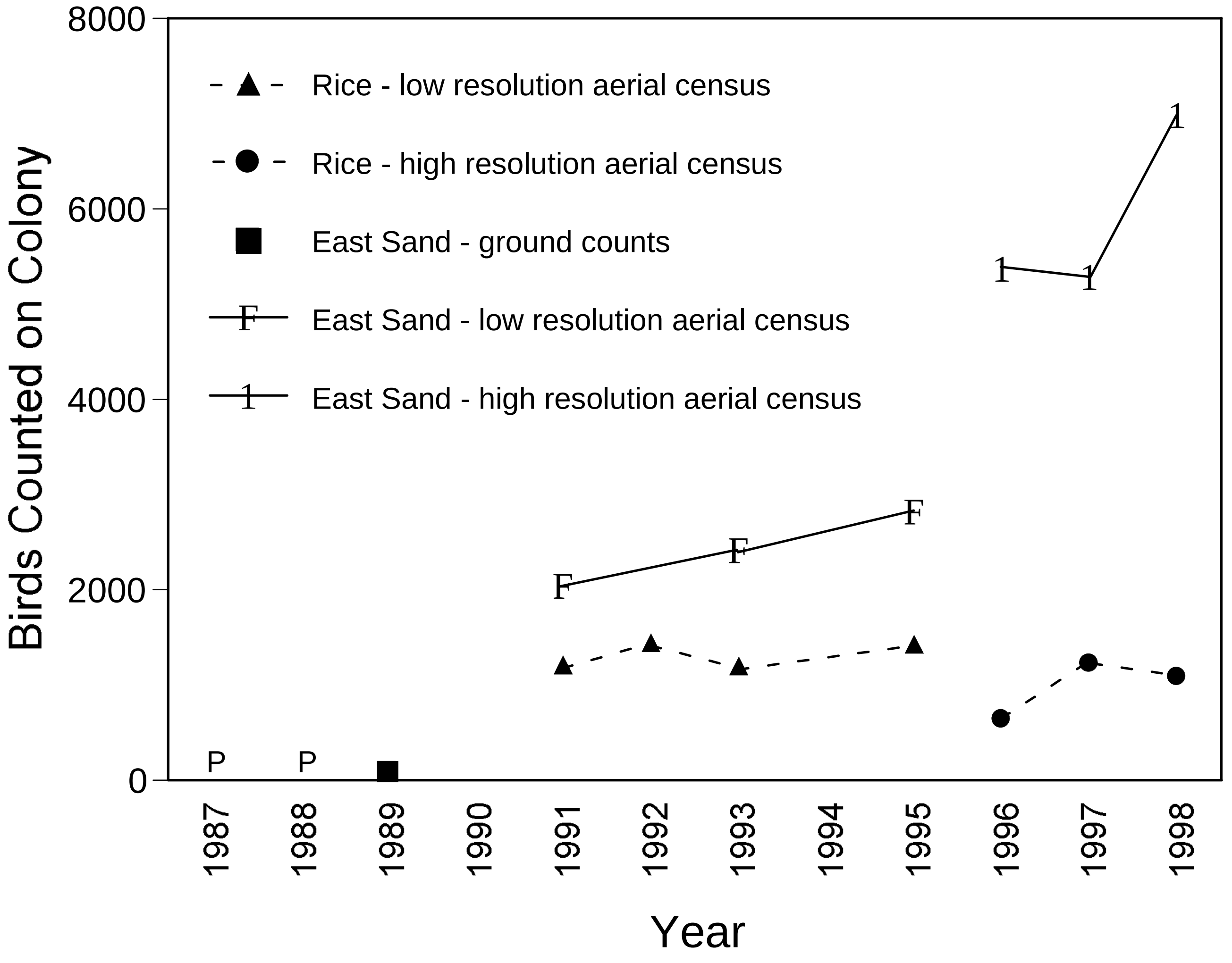
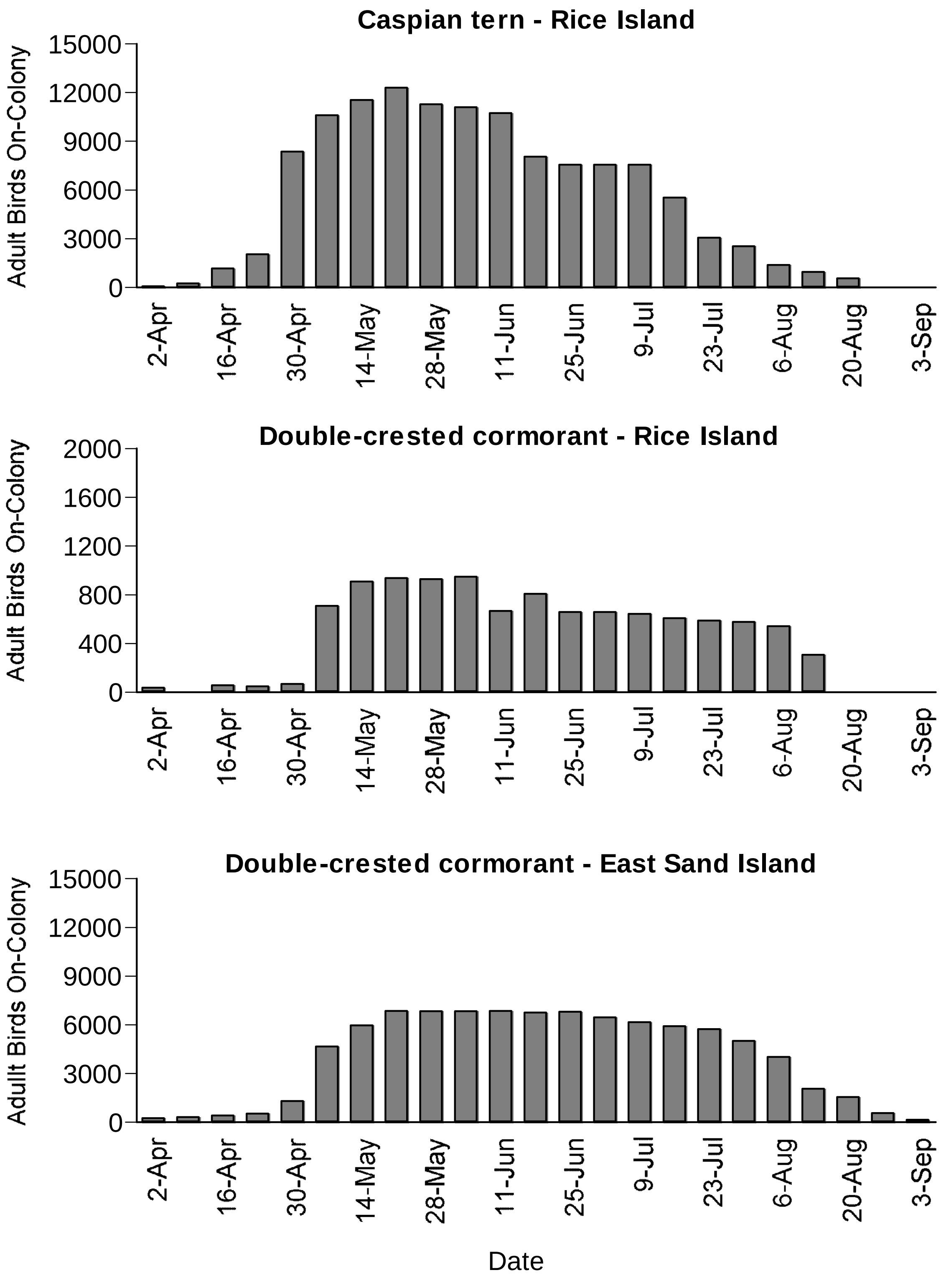


Figure 5. Population estimates (direct counts of birds on-colony) for double-crested cormorants nesting on East Sand and Rice islands in the Columbia River estuary, 1987 - 1998. Breeding birds were present (P) on East Sand and Rice islands in 1987 and 1988, respectively; however, breeding population estimates are not available.


Caspian tern - Rice Island

Double-crested cormorant - Rice Island

Double-crested cormorant - East Sand Island

Figure 6. Estimates of total colony attendance (by week) throughout the breeding season for the Rice Island Caspian tern and double-crested cormorant colonies and the East Sand Island double-crested cormorant colony. Note different scales on Y-axes.

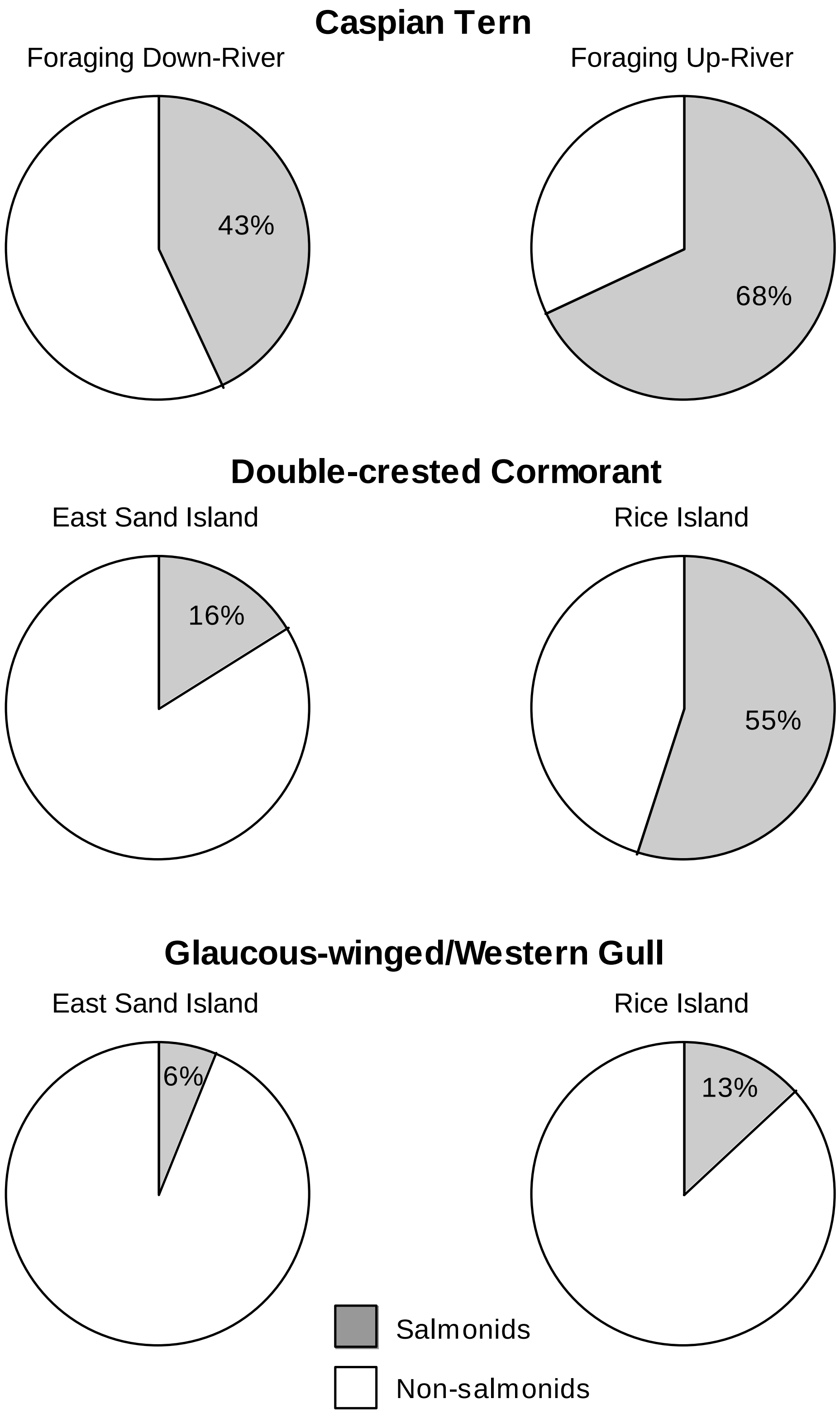


Figure 7. Percent biomass of salmonids and non-salmonids in the diet of terns foraging up- or down-river from Rice Island, and cormorants and gulls nesting on Rice Island (upper estuary) or East Sand Island (lower estuary) in the Columbia River Estuary.

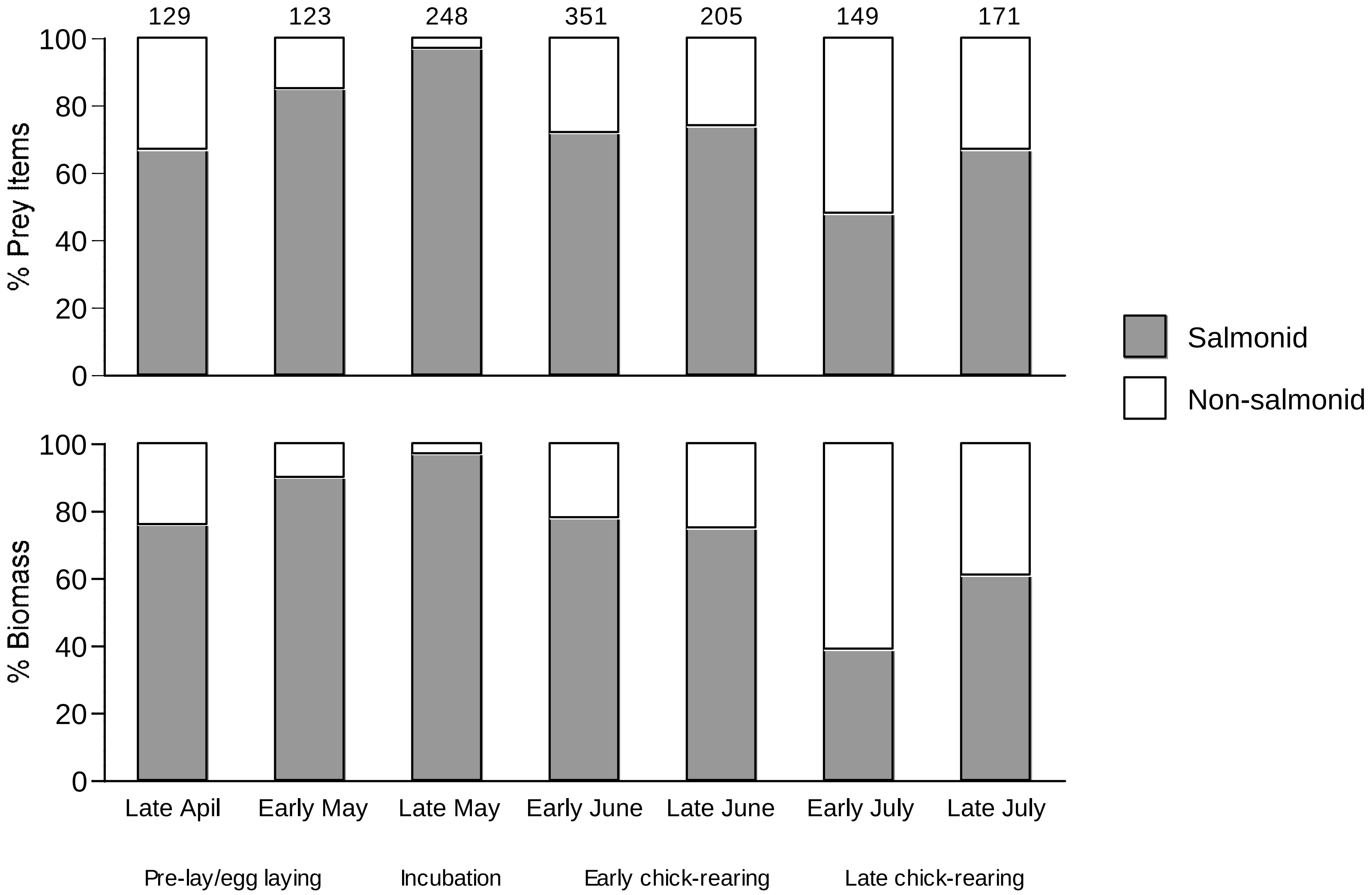


Figure 8. Percent identifiable prey items and estimated percent biomass of salmonids and non-salmonids in the diet of Caspian terns based on bill load observations at the Rice Island colony in 1998. Number of identified fish in bill load observations are presented over the bars for each sample period.

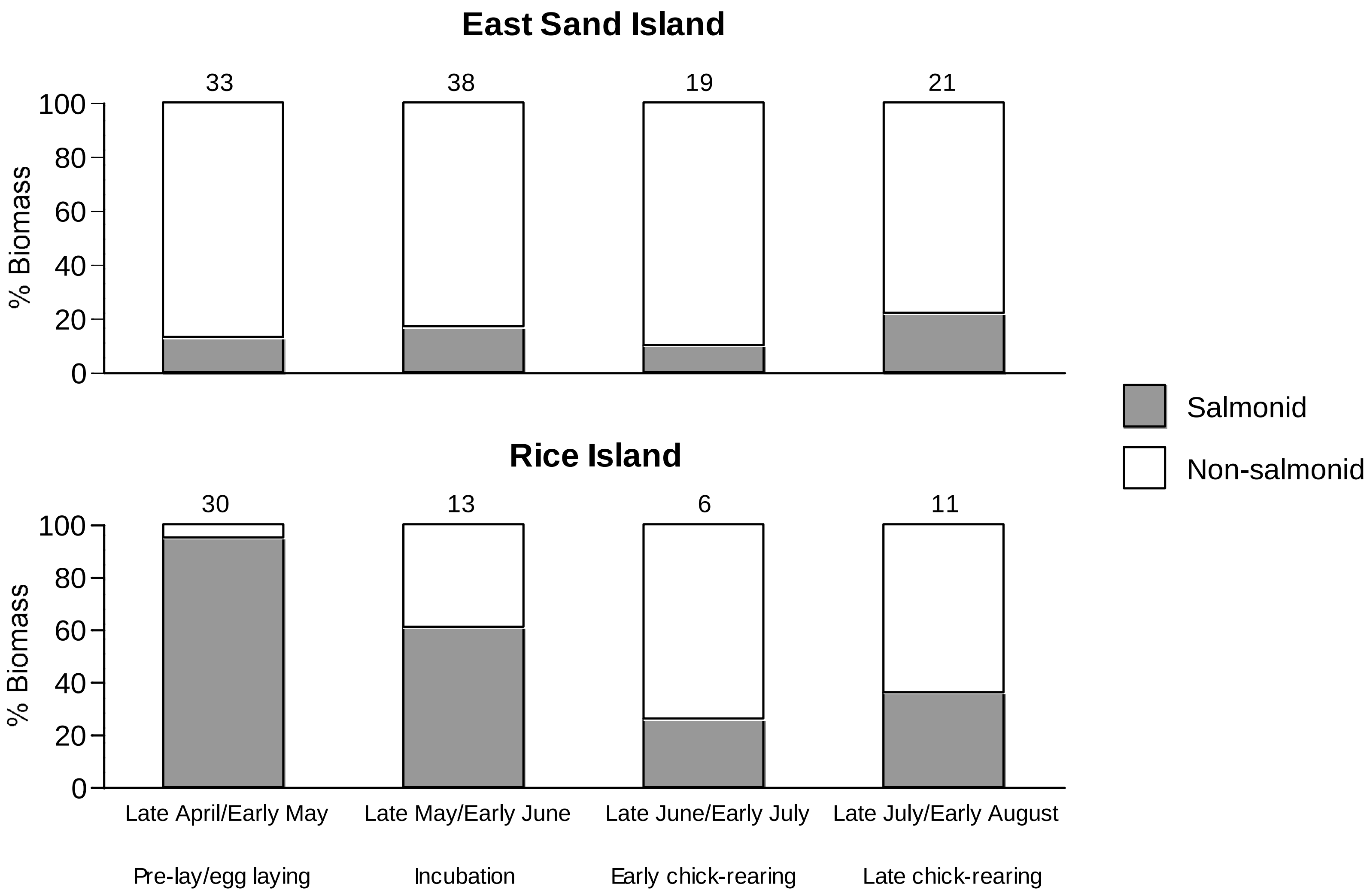


Figure 9. Percent biomass of salmonids and non-salmonids in the diet of double-crested cormorants nesting on East Sand and Rice islands based on the analysis of adult stomach contents and chick regurgitations in 1998. Number of adult stomach contents and chick regurgitation samples with identifiable fish are presented over the bars for each sample period.

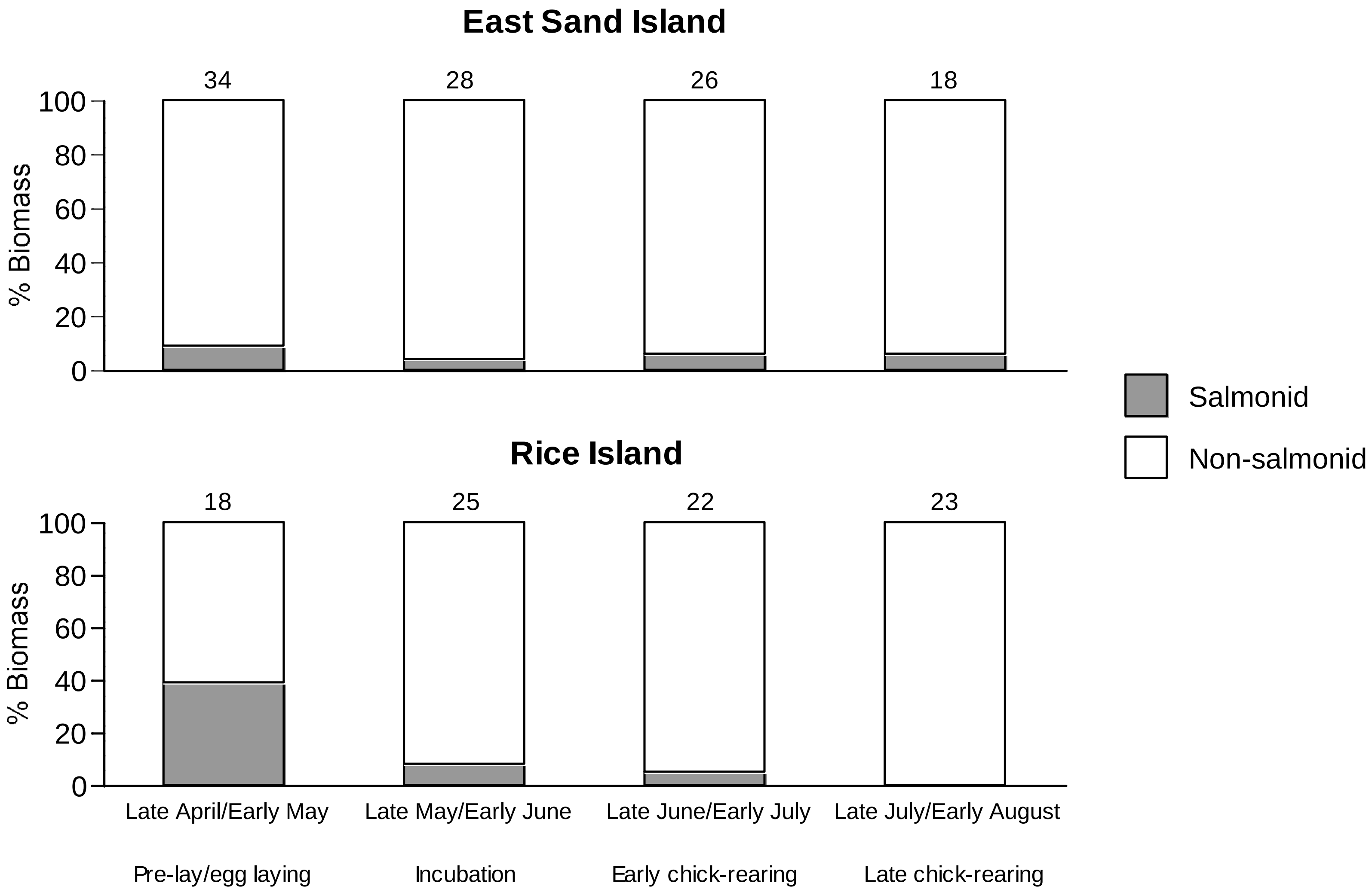


Figure 10. Percent biomass of salmonids and non-salmonids in the diet of glaucous-winged/western gulls nesting on East Sand and Rice islands based on the analysis of adult stomach contents and chick regurgitations in 1998. Number of adult stomach contents and chick regurgitation samples with identifiable prey types are presented over the bars for each sample period.

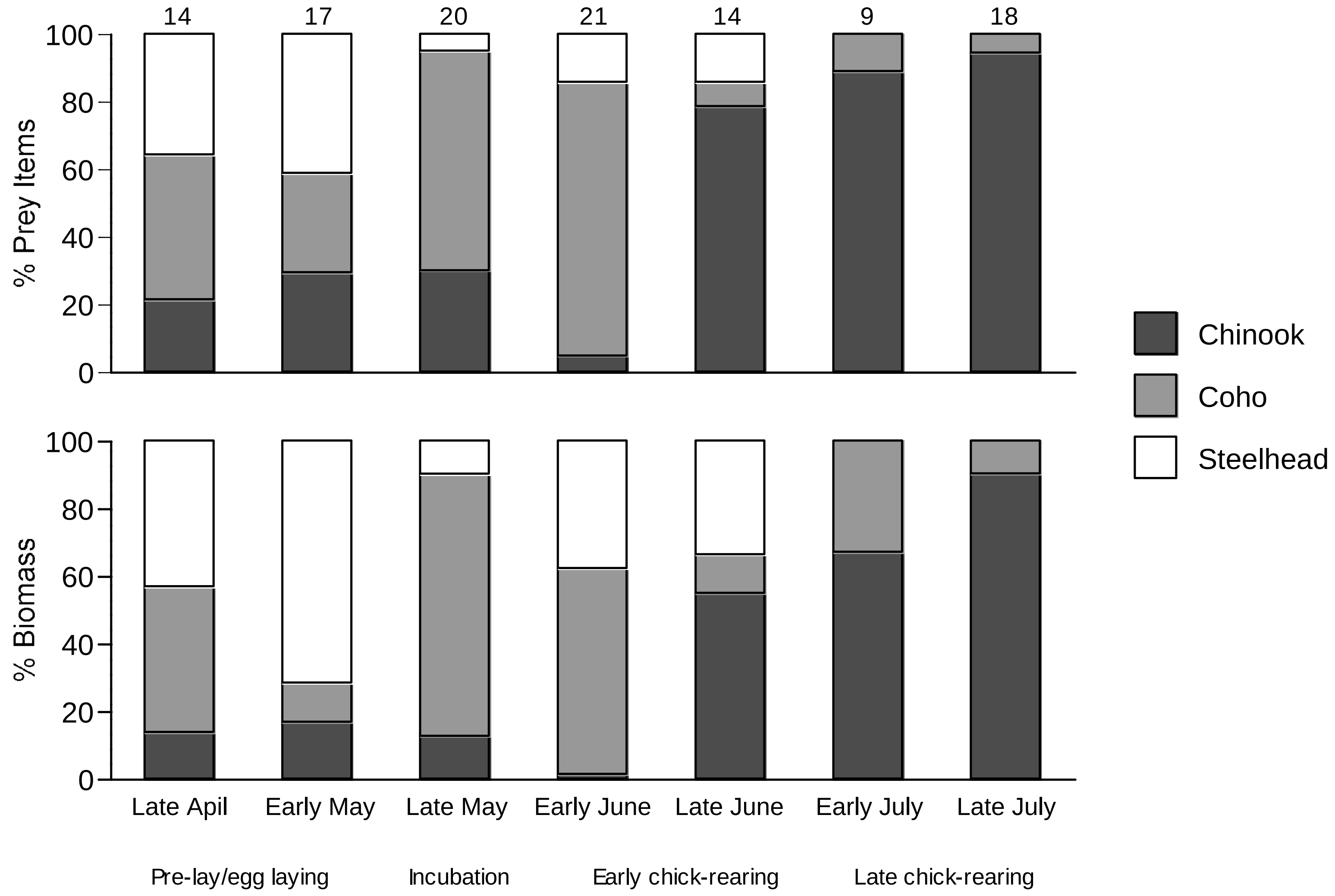
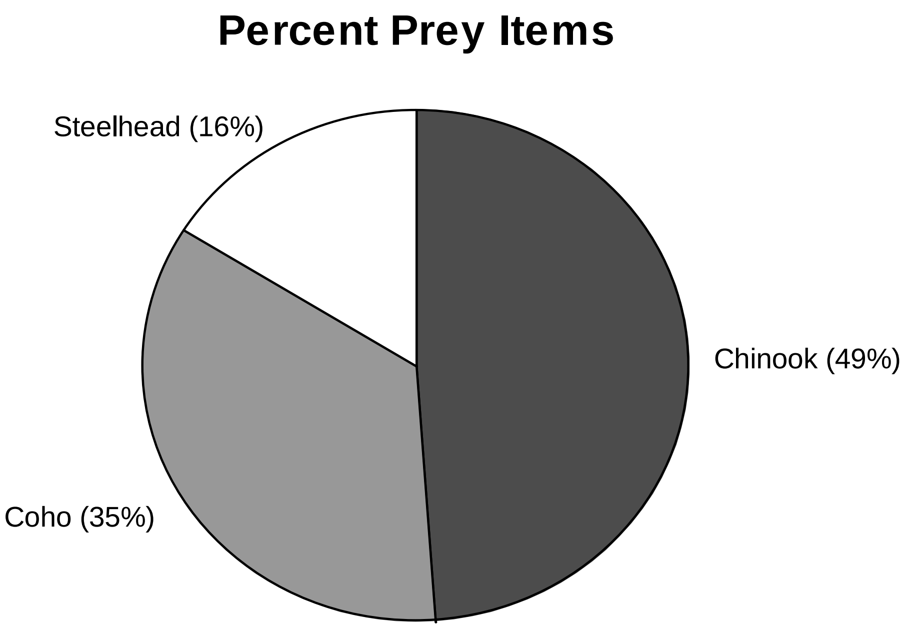


Figure 11. Percent prey items and percent biomass of chinook, coho, and steelhead in the salmonid portion of the diet of Caspian terns nesting on Rice Island based on the collection of bill load fish in 1998. Number of dropped juvenile salmonids being transported in the bill are presented over the bars for each sample period.



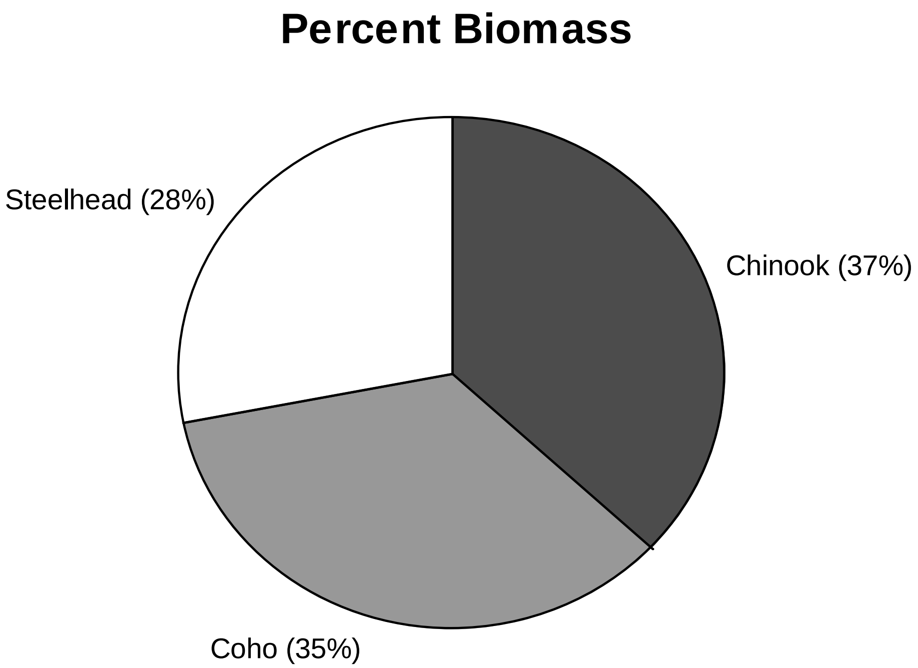


Figure 12. Percent prey items and percent biomass of chinook, coho, and steelhead in the salmonid portion of the diet of Caspian terns nesting on Rice Island based on the collection of bill load fish in 1998. Analysis based on a total sample size of 113 dropped juvenile salmonids being transported in the bill.

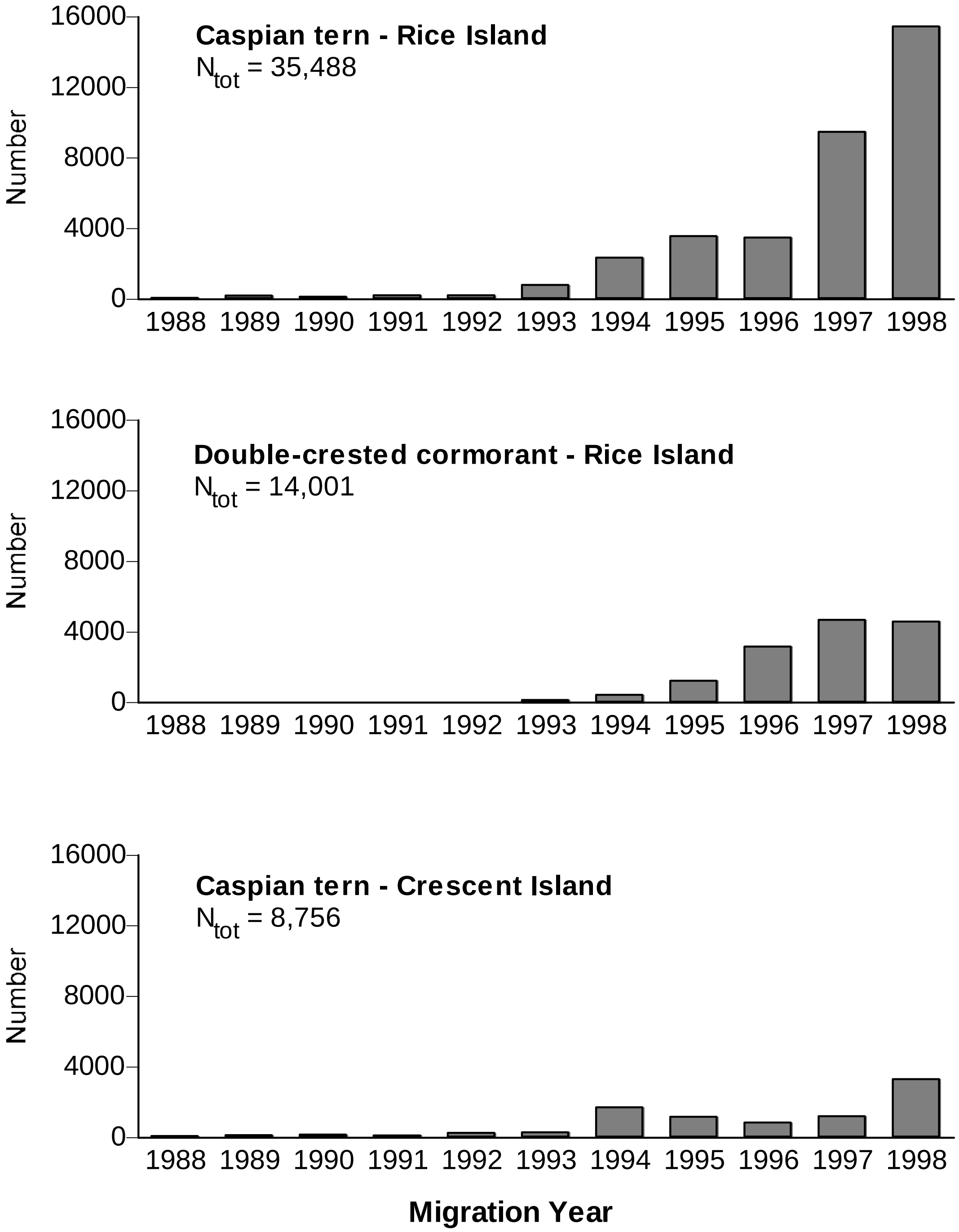


Figure 13. Number of smolt PIT tags detected on the Rice Island Caspian tern and double-crested cormorant colonies and the Crescent Island Caspian tern colony as a function of migration year.

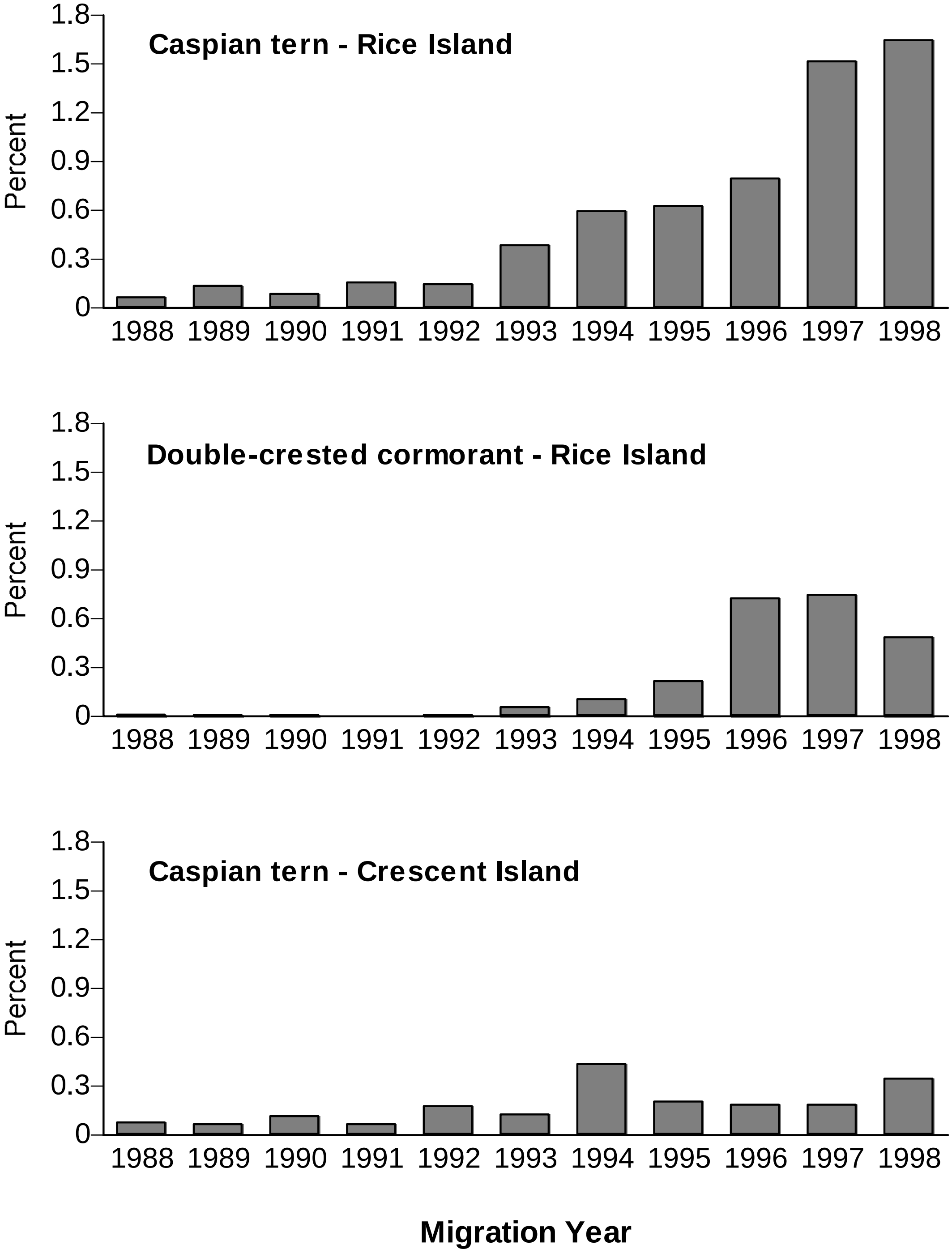


Figure 14. Percent of total released smolt PIT tags that were detected on the Rice Island Caspian tern and double-crested cormorant colonies and the Crescent Island Caspian tern colony as a function of migration year.

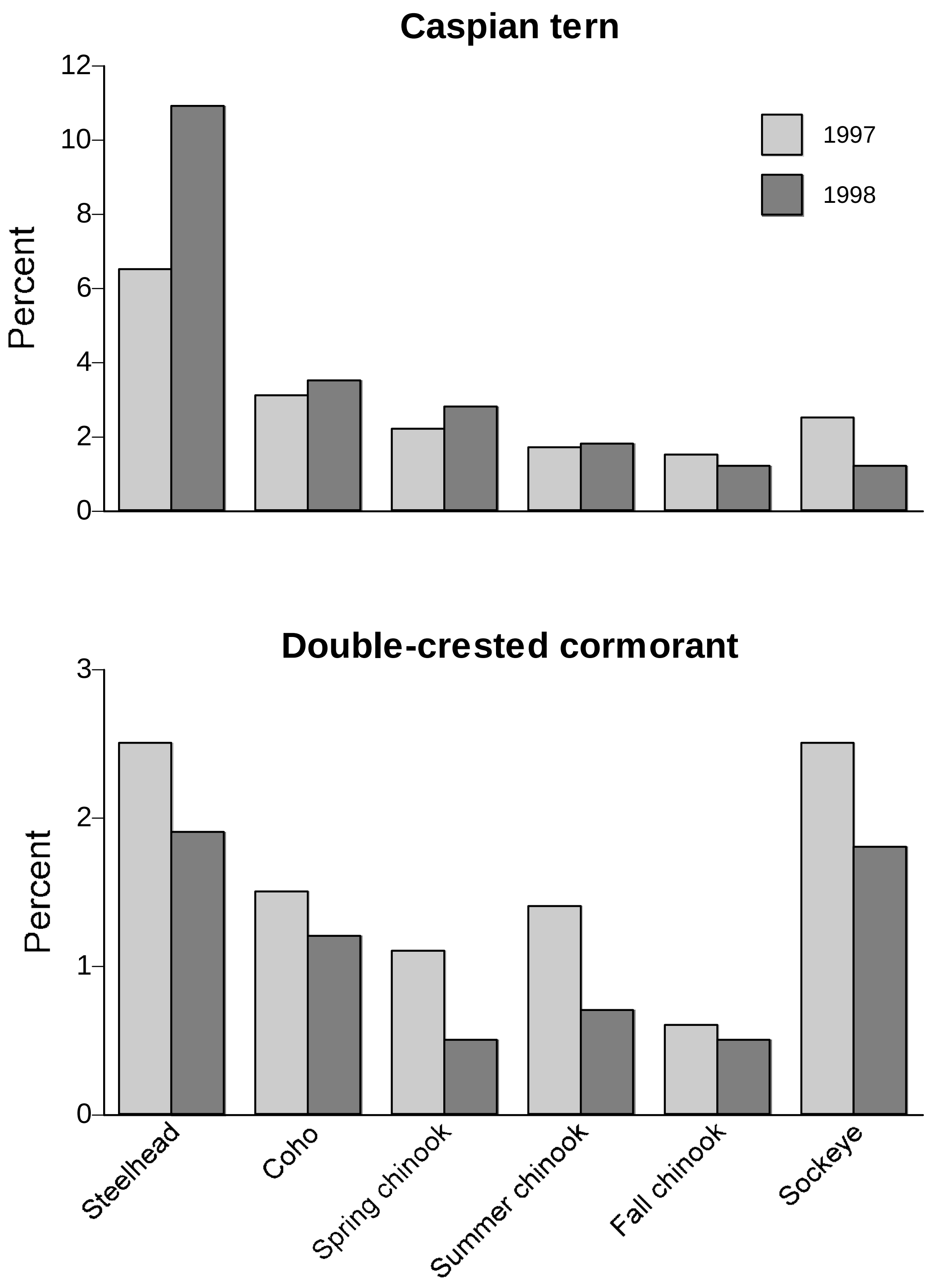


Figure 15. Percent of smolt PIT tags from different salmonid species detected at Bonneville Dam that were subsquently found on the Caspian tern and double-crested cormorant colonies on Rice Island. Note differences in Y-axis scales.

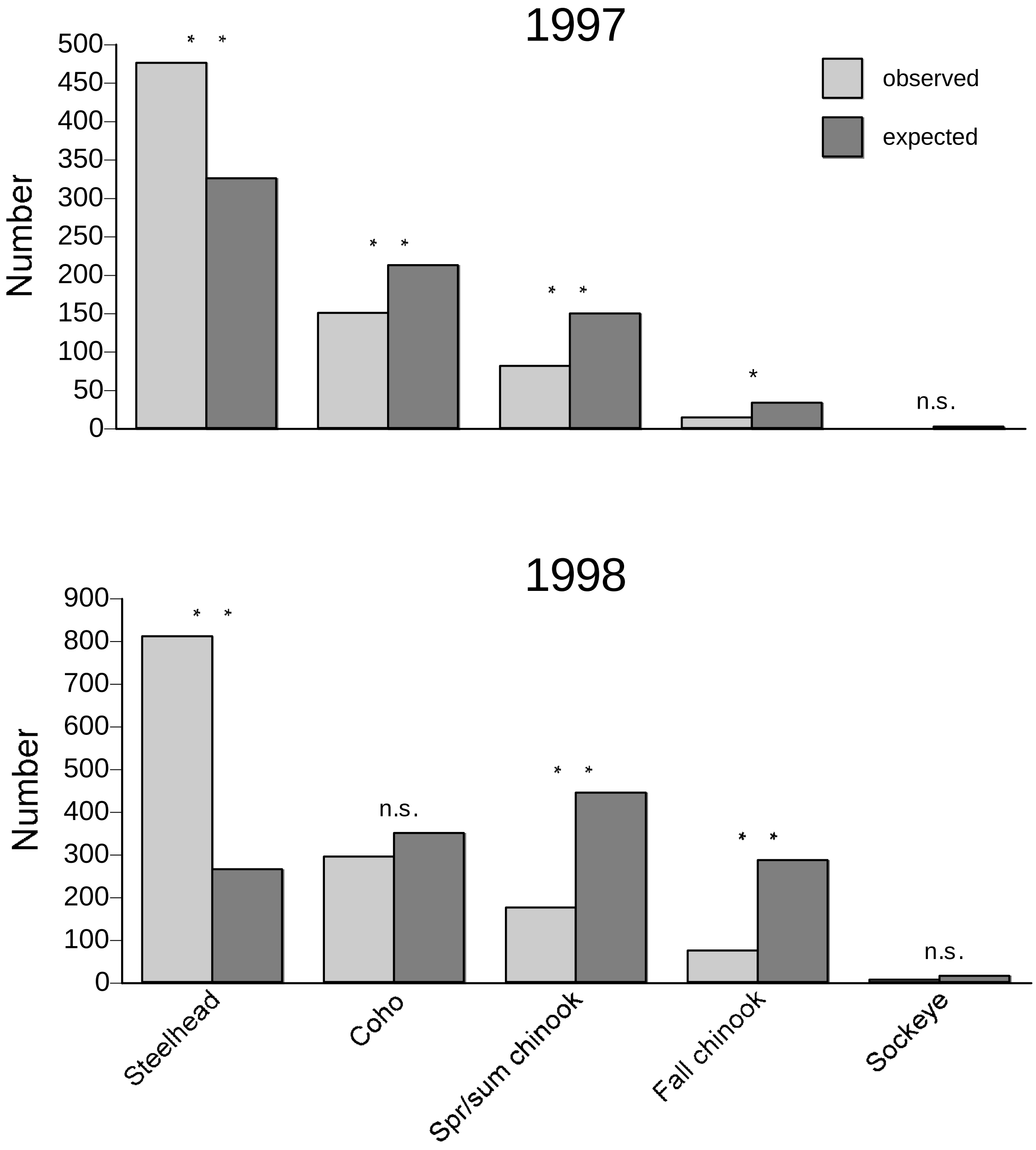


Figure 16. Relative vulnerability of different salmonid stocks to predation by Caspian terns nesting on Rice Island in 1997 and 1998. One and two asterisks above bars denote significant differences using a Chi-square test (*P*<0.05 and P<0.01, respectively). Higher observed values compared to expected values indicate greater vulnerability to tern predation than expected based on availability.

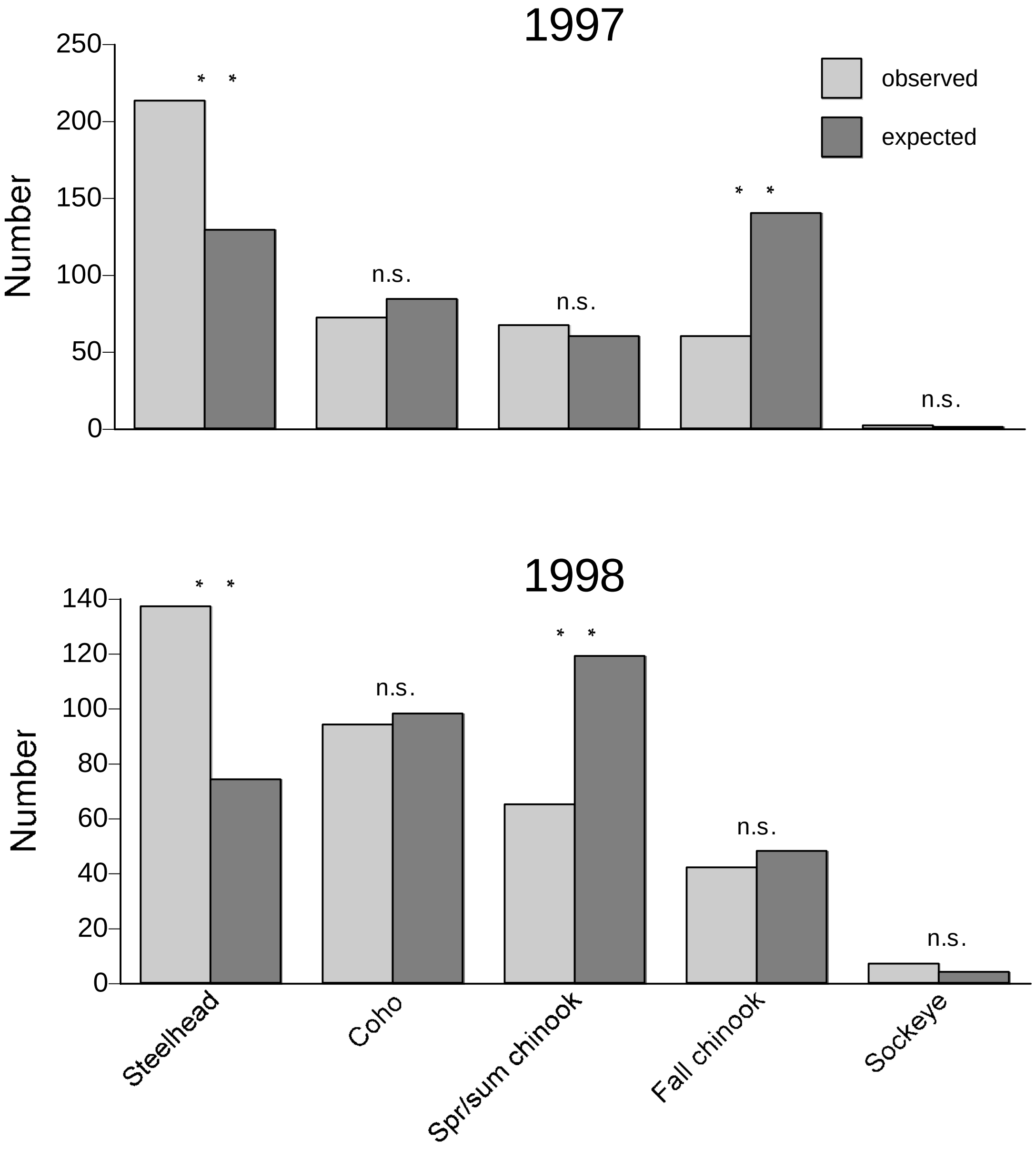


Figure 17. Relative vulnerability of different salmonid stocks to predation by double-crested cormorants nesting on Rice Island in 1997 and 1998. One and two asterisks above bars denote significant differences using a Chi-square test (P<0.05 and P<0.01, respectively). Higher observed values compared to expected values indicate greater vulnerability to cormorant predation that expected based on availability.

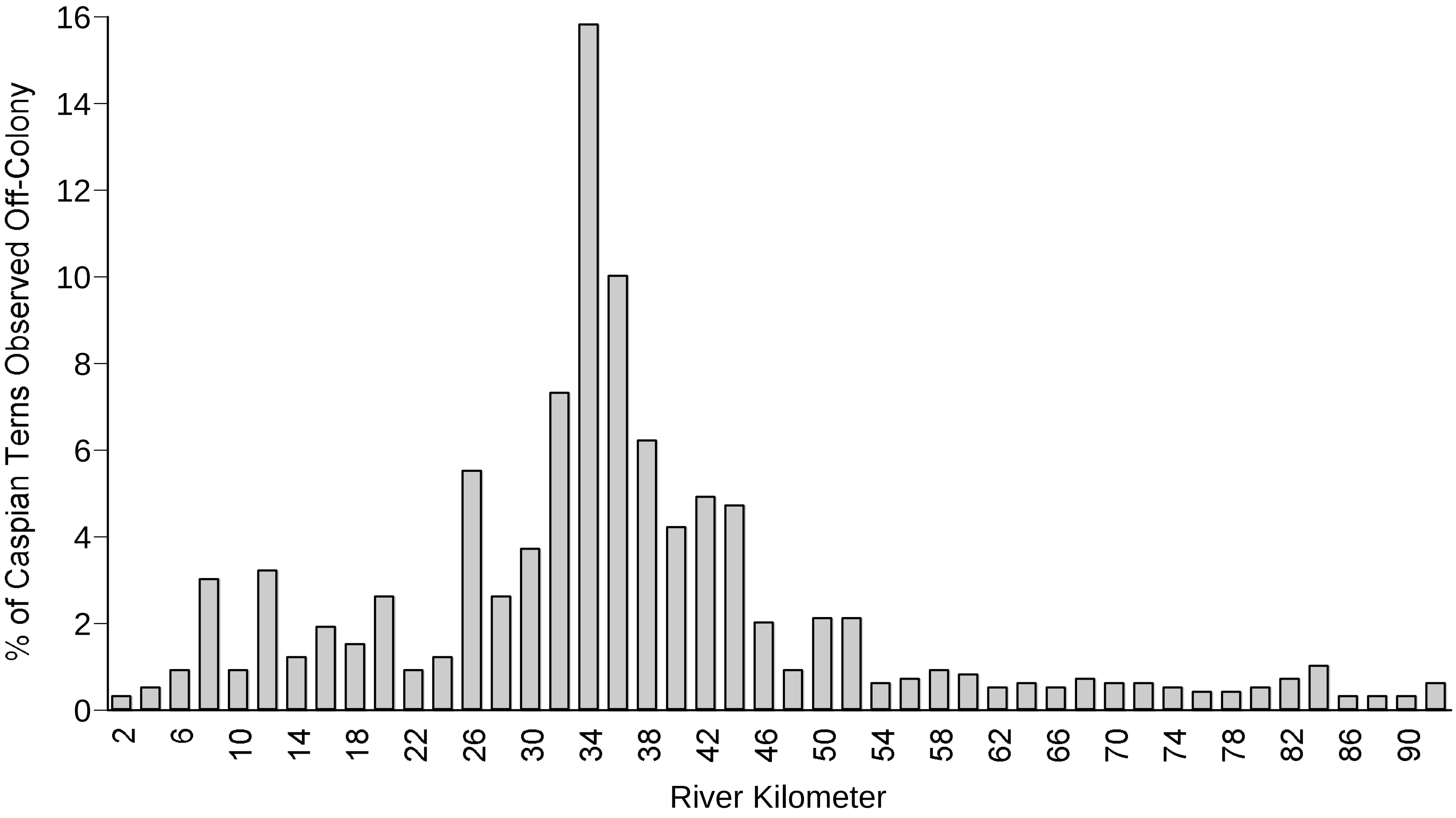


Figure 18. Distribution of foraging Caspian terns in the Columbia River estuary by river kilometer in 1998. The Rice Island Caspian tern colony is located at river kilometer 34, and the mouth of the Columbia River is at river kilometer 0.

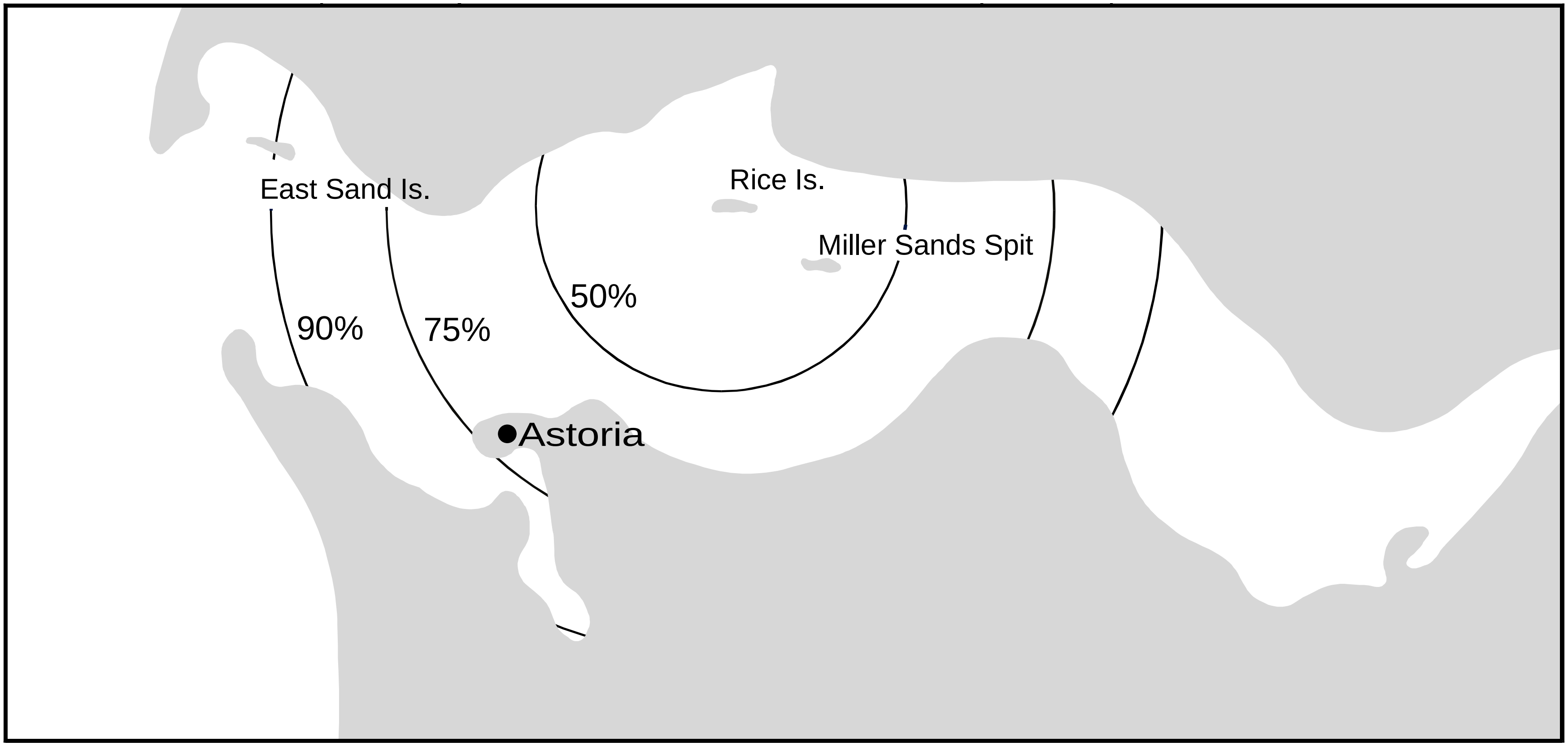


Figure 19. Caspian tern percentile foraging distribution around the Rice Island breeding colony in the Columbia River Estuary in 1998.

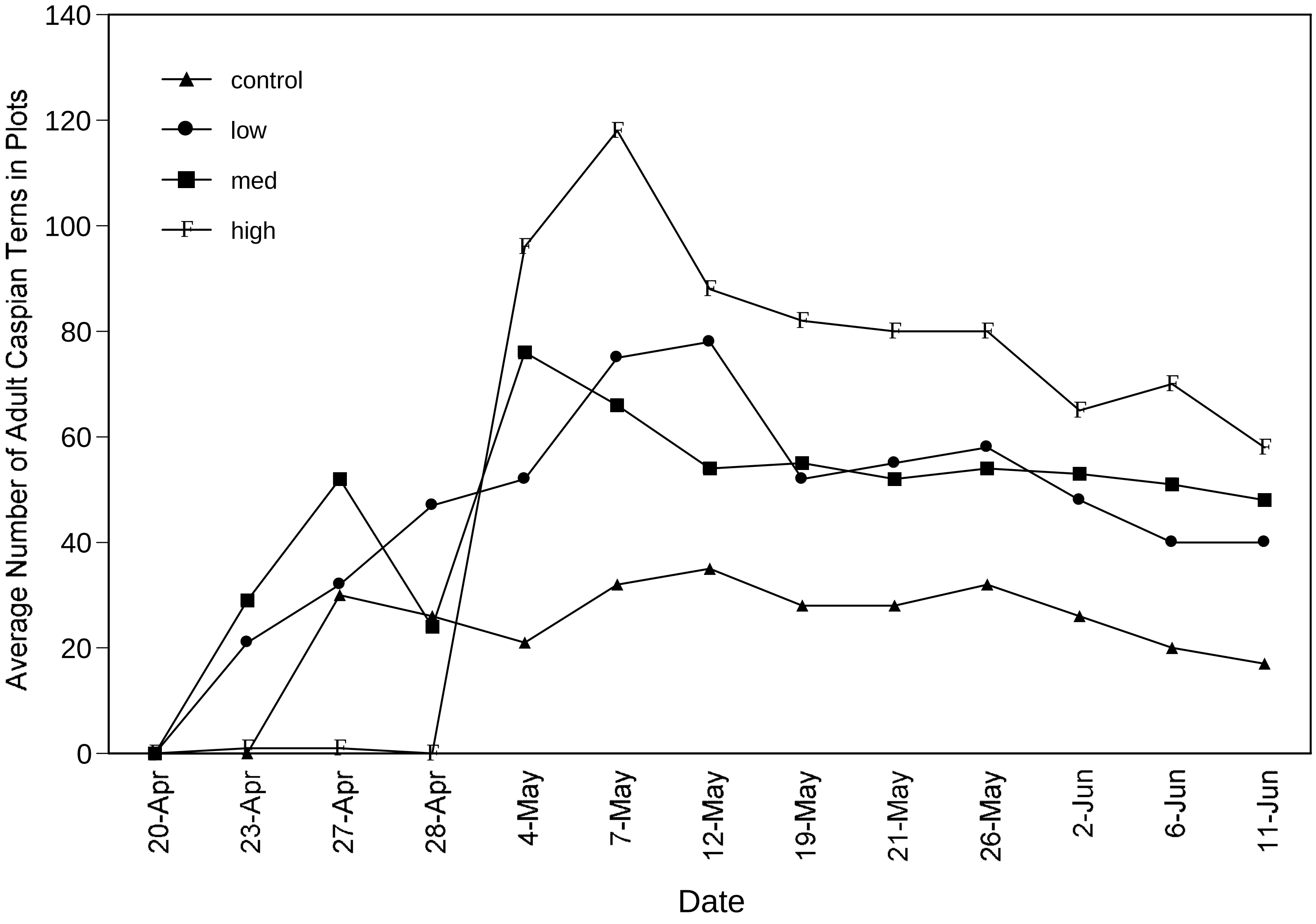


Figure 20. Average attendance by adult Caspian terns on 10 m x 10 m plots within the Rice Island colony, 1998. Transplanted plant densities on plots were either 0/m^2 (control), 0.09/m^2 (low density), 0.36/m^2 (medium density), or 1.0/m^2 (high density).

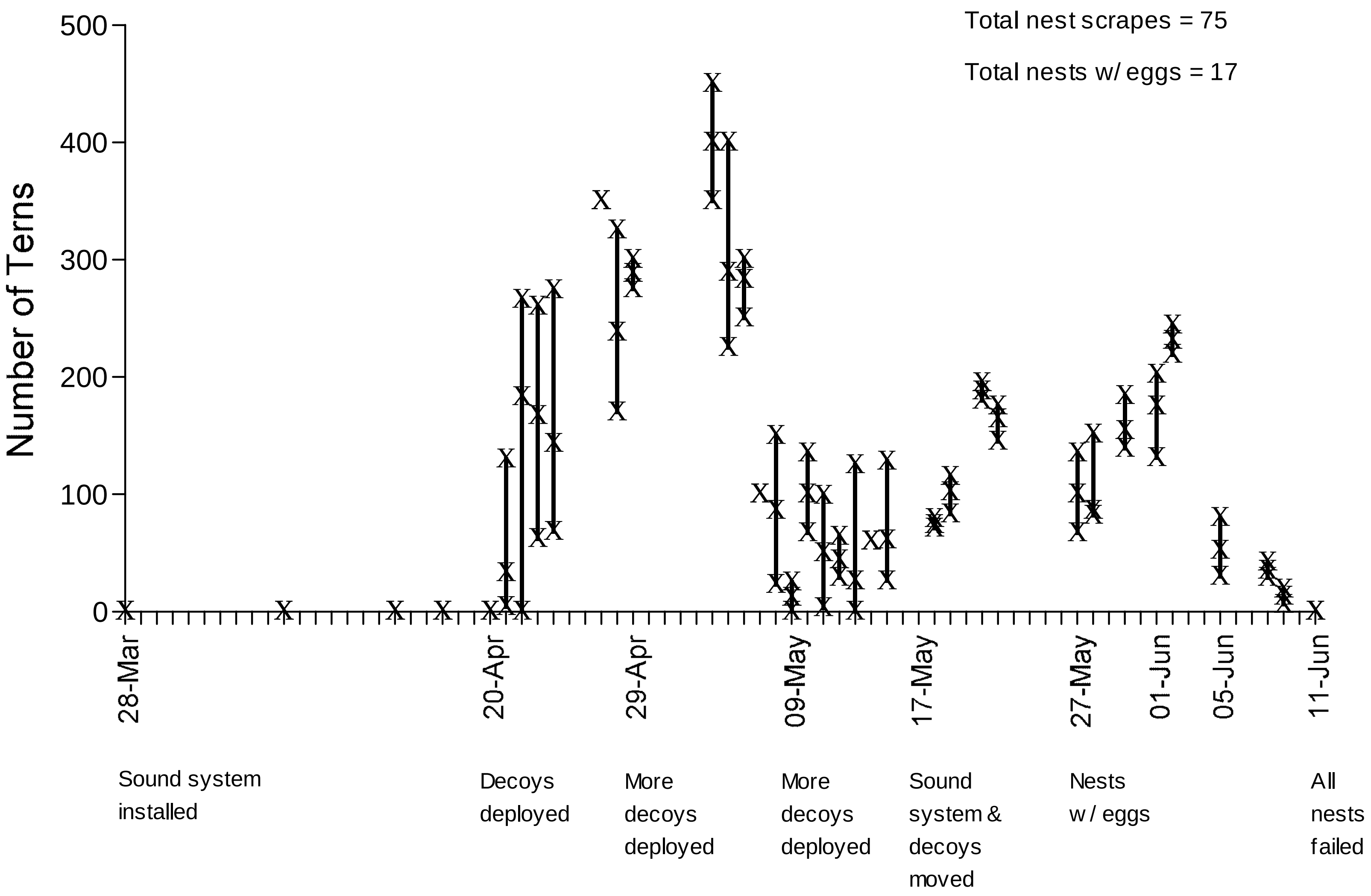


Figure 21. Caspian tern attendance at the experimental colony site at Miller Sands Spit in 1998, 28 March - 11 June. Points on bars represent high, mean, and low counts of adult terns on the colony for a given date.

APPENDICES

Appendix A. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by Caspian terns nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass is 10% greater than for transportation around dams by barge or truck ($M_B > M_T$). Significant positive values for % diff. indicate higher vulnerability of transported smolts to tern predation, as compared to non-transported smolts. Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to tern predation, as compared to transported smolts.

	In-River[1]			On Colony[2]				
$M_B > M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,006	24,211	92.3	49	472	90.6	- 1.7	0.14
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	5,264	2,560	32.7	338	146	30.2	- 2.5	0.24
Wild	320	360	52.9	9	6	40	- 12.9	0.32
1998								
Spring/summer chinook								
Hatchery	5,356	51,118	90.5	105	1,523	93.5	+ 3.0	<0.0001
Wild	817	1,112	57.6	2	11	84.6	+ 27.0	0.05
Steelhead								
Hatchery	2,158	3,077	58.8	316	315	50.0	- 8.8	<0.0001
Wild	854	1,389	61.9	99	63	38.9	- 23.0	<0.0001

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island Caspian tern colony.
[3] N_B = Number of Bonneville Dam bypassed fish in the sample.
[4] N_T = Number of transported fish in the sample.
[5] $\%_T$ = percent of total fish in the sample that were transported.
[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.

Appendix B. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by Caspian terns nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass is 10% less than for transportation around dams by barge or truck ($M_B < M_T$). Significant positive values for % diff. indicate higher vulnerability of transported smolts to tern predation, as compared to non-transported smolts. Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to tern predation, as compared to transported smolts.

	In-River[1]			On-Colony[2]				
$M_B < M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,229	21,790	90.7	49	472	90.6	- 0.1	0.92
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	5,849	2,304	28.2	338	146	30.2	+ 2.0	0.37
Wild	356	324	47.6	9	6	40	- 7.6	0.56
1998								
Spring/summer chinook								
Hatchery	5,951	46,006	88.5	105	1,523	93.5	+ 5.0	<0.0001
Wild	908	1,008	52.6	2	11	84.6	+ 32.0	0.02
Steelhead								
Hatchery	2,398	2,769	53.6	316	315	50.0	- 3.6	0.08
Wild	949	1,250	56.8	99	63	38.9	- 17.9	<0.0001

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.
[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island Caspian tern colony.
[3] N_B = Number of Bonneville Dam bypassed fish in the sample.
[4] N_T = Number of transported fish in the sample.
[5] $\%_T$ = percent of total fish in the sample that were transported.
[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.

Appendix C. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by double-crested cormorants nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass is 10% greater than for transportation around dams by barge or truck ($M_B > M_T$). Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to cormorant predation, as compared to transported smolts.

	In-River[1]			On-Colony[2]				
$M_B > M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,012	25,450	92.7	42	289	87.3	- 5.4	0.0002
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	5,424	2,957	35.3	161	60	27.1	- 8.2	0.01
Wild	314	369	54.0	16	12	42.9	- 11.1	0.24
1998								
Spring/summer chinook								
Hatchery	5,389	30,831	85.1	46	165	78.2	- 6.9	0.005
Wild	806	841	51.1	7	7	50.0	- 1.1	0.94
Steelhead								
Hatchery	2,313	3,146	57.6	100	68	40.5	- 17.1	<0.0001
Wild	905	1,216	57.3	26	23	46.9	- 10.4	0.15

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.

[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island cormorant colony.

[3] N_B = Number of Bonneville Dam bypassed fish in the sample.

[4] N_T = Number of transported fish in the sample.

[5] $\%_T$ = percent of total fish in the sample that were transported.

[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.

Appendix D. Relative vulnerability of PIT-tagged transported vs. non-transported juvenile salmonids to predation by double-crested cormorants nesting on Rice Island in 1997 and 1998, as indicated by smolt PIT tag recoveries. This analysis assumes that the direct mortality associated with Bonneville Dam bypass is 10% less than for transportation around dams by barge or truck ($M_B < M_T$). Significant negative values for % diff. indicate higher vulnerability of non-transported smolts to cormorant predation, as compared to transported smolts.

	In-River[1]			On-Colony[2]				
$M_B < M_T$	N_B[3]	N_T[4]	$\%_T$[5]	N_B[3]	N_T[4]	$\%_T$[5]	% diff[6]	*P*
1997								
Spring/summer chinook								
Hatchery	2,236	22,905	91.1	42	289	87.3	- 3.8	0.02
Wild	-	-	-	-	-	-	-	-
Steelhead								
Hatchery	6,027	2,661	30.6	161	60	27.1	- 3.5	0.27
Wild	349	332	48.7	16	12	42.9	- 5.8	0.54
1998								
Spring/summer chinook								
Hatchery	5,988	27,748	82.2	46	165	78.2	- 4.0	0.12
Wild	896	757	45.8	7	7	50.0	+ 4.2	0.75
Steelhead								
Hatchery	2,570	2,831	52.4	100	68	40.5	- 11.9	0.002
Wild	1,006	1,094	52.1	26	23	46.9	- 5.2	0.48

[1] "In-river" refers to PIT tags detected at Bonneville Dam and PIT-tagged, transported smolts that were released below Bonneville Dam.

[2] "On-colony" refers to PIT tags from the "in-river" sample that were subsequently detected on the Rice Island cormorant colony.

[3] N_B = Number of Bonneville Dam bypassed fish in the sample.

[4] N_T = Number of transported fish in the sample.

[5] $\%_T$ = percent of total fish in the sample that were transported.

[6] %diff = $\%_T$ on-colony - $\%_T$ in-river.