# AN ABSTRACT OF THE DISSERTATION OF

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Title: Piscivorous Colonial Waterbirds in the Columbia River Estuary: Demography, Dietary Contaminants, and Management

Abstract approved:

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Caspian terns (*Hydroprogne caspia*) and double-crested cormorants (*Phalacrocorax auritus*) nest in large colonies on East Sand Island in the Columbia River estuary, the largest known colonies for the two species in the world. Both species of piscivorous colonial waterbirds have been identified as predators with a significant impact on the survival of juvenile salmonids (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act. To better understand and address issues related to seabird-fisheries interactions in the Columbia River estuary, I conducted studies related to the ecology, conservation, and management of these two species of piscivorous waterbirds.

I evaluated the demographics and inter-colony movements of Caspian terns belonging to the Pacific Coast metapopulation, with special emphasis on two breeding colonies, one on East Sand Island in the Columbia River estuary and the other on Crescent Island in the mid-Columbia River, based on re-sightings of color-banded individuals. Apparent annual adult survival at both colonies was high, and age at first reproduction was greater than previously reported for the species. Colony site philopatry of breeding adults at both colonies was high; however, some individuals prospected for breeding colonies over much of the Pacific Coast region and moved to

other colonies over distances of up to 3,000 km. Some terns from the large colony in the Columbia River estuary responded quickly to the availability of new colony sites as distant as 550 km from the estuary, and established successful breeding colonies within less than a year of the new sites becoming available. The Caspian tern colony on East Sand Island appears to be an important source colony for a number of smaller, less productive colonies distributed over an extensive area from the Salton Sea, California to the Copper River Delta, Alaska, an area with limited and ephemeral nesting opportunities.

Environmental contaminants have been a conservation concern for wildlife in the Columbia River estuary, especially species that consume fish and are therefore likely to bioaccumulate persistent organic pollutants. I measured and compared levels of polychlorinated biphenyls (PCBs) in eggs and chicks of Caspian terns and double-crested cormorants, as well as their primary prey fish types, at colonies on East Sand Island and farther up-river. Based on differences in tern and cormorant diet composition at the various study colonies, higher PCB levels in eggs and chicks were associated with diets dominated by resident freshwater and estuarine fishes. PCB levels in prey fish were positively correlated with lipid content; however, PCB levels in the livers of chicks were negatively correlated with chick fat scores, suggesting that chick fat reserves are a sink for ingested PCBs. Lower PCB levels in terns and cormorants from East Sand Island compared to colonies farther up-river reflected diets with a higher proportion of marine forage fishes at East Sand Island; marine forage

fishes had lower average levels of PCBs than their resident freshwater and estuarine counterparts.

In order to explore non-destructive techniques for managing nesting colonies of double-crested cormorants, I evaluated habitat enhancement and social attraction, two techniques that have proven effective for relocating Caspian tern colonies to sites where impacts on fish stocks of conservation concern would be minimal. Cormorants were attracted to nest and successfully raised young at test plots on East Sand Island and on islands in the estuary with a previous history of cormorant nesting or unsuccessful nesting attempts. On an island with no history of cormorant nesting or prospecting, however, no cormorants were attracted to nest. My results suggest that attraction of nesting cormorants using these techniques is dependent on the previous history of cormorant nesting or nesting attempts, the frequency and intensity of disturbance by potential predators, and the presence of breeding cormorants nearby. While habitat enhancement and social attraction have potential as methods for redistributing nesting cormorants away from areas where fish stocks of concern are highly susceptible to predation, successful establishment of new colonies using these techniques will likely require a focus on sites with a history of cormorant nesting.

Findings from this dissertation raise some concerns over the management of Caspian tern and double-crested cormorant colonies on East Sand Island in order to re-distribute parts of these colonies to alternative sites and mitigate the impact of those piscivorous colonial waterbirds on ESA-listed salmonids. East Sand Island has supported source colonies of piscivorous colonial waterbirds for many smaller

colonies throughout the region and is close to an abundant and relatively uncontaminated food supply. Also, alternative colony sites that can substitute for East Sand Island are not readily apparent, especially for double-crested cormorants. Therefore, management of Caspian tern and double-crested cormorant colonies on East Sand Island to benefit Columbia Basin salmonids needs to proceed cautiously and reversibly because of the implications for the region-wide populations of these piscivorous colonial waterbirds.

# Piscivorous Colonial Waterbirds in the Columbia River Estuary: Demography, Dietary Contaminants, and Management

by
Yasuko Suzuki

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Yasuko Suzuki, Author

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# CONTRIBUTION OF AUTHORS

Dr. Daniel D. Roby contributed to all aspects of each chapter in this dissertation. Dr. Donald E. Lyons provided generous assistance with study design, field work, data analysis, and interpretation of results in chapters 2-4. Ken Collis assisted with study design and logistics in chapters 2 and 4. Dr. Katie M. Dugger provided assistance with study design, data analysis, and interpretation of results in chapter 2. Dr. Jennifer A. Gervais provided assistance with interpretation of results in chapter 2. Dr. Robert M. Suryan contributed to the early stage of study design in chapter 2. Dr. Keith A. Hobson provided training with sample preparation and assistance with interpretation of stable isotope results in chapter 3. S. Kim Nelson contributed to the initial study design for evaluating contaminant levels in chapter 3. Karen N. Courtot assisted with the initial stage of study design and field work in chapter 4.

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# Piscivorous Colonial Waterbirds in the Columbia River Estuary: Demography, Dietary Contaminants, and Management

## CHAPTER 1

## GENERAL INTRODUCTION

Yasuko Suzuki

Populations of anadromous salmonids (*Oncorhynchus* spp.) in the Pacific Northwest region of the U.S., including the Columbia River basin, have declined for over a century mainly because of various human activities (Lichatowich 1999). Consequently, 13 of 20 evolutionarily significant units of Columbia Basin salmonids are now listed as threatened or endangered under the U.S. Endangered Species Act (ESA; Good et al. 2005). Although many of the measures taken to restore salmonid populations have focused on improvement of salmonid survival through modifications to hydropower dams, habitat, hatcheries, and harvest (the "4-Hs" of salmon restoration), predation on juvenile salmonids is also considered to be a limiting factor for salmonid recovery (National Oceanic and Atmospheric Administration 2004). In the past three decades, colonial piscivorous waterbirds have increased dramatically in the Columbia River estuary (Suryan et al. 2004, Adkins et al. 2010), apparently due to several factors: (1) loss of quality nesting habitat elsewhere in the Pacific Northwest, (2) increased anthropogenic nesting habitat, such as dredged material disposal islands, in the estuary (Suryan et al. 2004), and (3) the availability of large numbers of hatchery-reared juvenile salmonids that are released throughout the Columbia River basin and migrate through the estuary during the waterbird nesting season (Collis et al. 2001).

Because of growing concern by fisheries managers over the increasing impacts of avian predation on survival of ESA-listed juvenile salmonids from the Columbia River basin, a study was initiated in 1996 to better understand the magnitude of avian predation on juvenile salmonids in the basin. Research results indicate that the vast majority of smolt losses to avian predators occur in the Columbia River estuary, and that Caspian terns (*Hydroprogne caspia*) and double-crested cormorants (*Phalacrocorax auritus*) consume millions of juvenile salmonids in the estuary each year (Roby et al. 2003, Lyons 2010).

As an initial effort to reduce the magnitude of this conflict, the Caspian tern colony on Rice Island, in the freshwater zone of the Columbia River estuary, was relocated to East Sand Island, in the marine zone of the estuary, between 1999 and 2001 in an attempt to reduce predation on juvenile salmonids (Roby et al. 2002). This was accomplished by creating an attractive alternative colony site for terns using habitat enhancement and social attraction (Kress 1983) on East Sand Island and simultaneously discouraging terns from nesting on Rice Island (Roby et al. 2002). Although the number of juvenile salmonids consumed by Caspian terns was substantially reduced once the entire tern colony on Rice Island was relocated to East Sand Island (Roby et al. 2003), fisheries managers were still concerned about the magnitude of tern predation on juvenile salmonids. Several federal resource management agencies sought to manage the Caspian tern colony on East Sand Island, the largest known breeding colony for the species in the world that supported more than 9,000 breeding pairs. This effort to further reduce losses of juvenile salmonids to Caspian terns in the estuary resulted in a Final Environmental Impact Statement (EIS) that was issued in 2005 (U.S. Fish and Wildlife Service et al. 2005). The Final EIS specified as the preferred alternative the reduction of the tern colony on East Sand Island to about one-third of its current size. The difference, approximately 6,000 breeding pairs, would be encouraged to move to new nesting habitat intentionally provided at sites where ESA-listed salmonids would not be at risk. The Caspian tern management plan described in the Final EIS was implemented starting in 2008 and implementation is ongoing.

The Caspian tern population in the Pacific Coast region has experienced growth and range expansion in the last half century, with larger breeding colonies at fewer sites compared to historical records (Gill and Mewaldt 1983, Wires and Cuthbert 2000, Suryan et al. 2004). Due to the transitory nature of their preferred nesting habitat and frequent shifts among colony locations in response to changing habitat, Caspian terns appear to have lower colony site fidelity than most other seabird species (Gill and Mewaldt 1983, Cuthbert 1988, Wires and Cuthbert 2000, Collins 2006). The Pacific Coast population of Caspian terns was last evaluated during 1981-2000 by Suryan et al. (2004); thus, the current status of the Pacific Coast population has not been assessed since the large colony on Rice Island was completely relocated to East Sand Island.

The interaction between avian piscivores and their prey in estuaries often raises conservation concerns for the predators due to accumulation of environmental contaminants from their food supply. The U. S. Environmental Protection Agency (USEPA) has designated the Columbia River as one of its national priorities for clean-up of environmental contaminants (USEPA 2009). The Columbia River estuary receives chemical contaminants that enter the river system from various sources throughout the basin, which is about the size of France, and numerous contaminants have been reported in sediments, water, and biota in the estuary (Lower Columbia River Estuary Partnership 2007). Contaminant burdens have been a concern for various wildlife populations in the estuary (Buck et al. 2005, Johnson et al. 2007); however, information on contaminant levels in Caspian terns and double-crested cormorants nesting at the very large colonies on East Sand Island are limited. Because such a large proportion of the regional populations of these two species of piscivorous colonial waterbirds nest on East Sand Island in the Columbia River estuary, the risk of high body burdens of persistent organic pollutants needs to be assessed. Caspian terns and double-crested cormorants nesting in the estuary have access to various food sources; in addition to juvenile salmonids, Caspian terns and double-crested cormorants consume large numbers of resident fishes from both freshwater and estuarine areas of the estuary, as well as marine forage fishes from outside the estuary (Collis et al. 2002, Roby et al. 2003). The extent of contaminant accumulation, the sources of ingested contaminants, and the factors that influence contaminant body burden in terns and cormorants nesting at East Sand Island had not been investigated prior to this research.

The colony of double-crested cormorants on East Sand Island is also of increasing concern to fisheries managers because it has grown from about 90 breeding pairs in 1989 to over 13,700 pairs by 2006, and is now the largest known breeding colony for the species in North America (Adkins et al. 2010). The East Sand Island cormorant colony is not only the largest of its kind, but also represents about 40% of the breeding population of double-crested cormorants in western North America. The population of double-crested cormorant in interior/eastern North America has experienced rapid growth and now numbers over a million breeding individuals. Cormorants in this population are now the subject of widespread lethal control because of their impact on fisheries and other natural resources (Wires and Cuthbert 2006). In contrast, the western North America population of double-crested cormorants numbers only about 31,500 breeding pairs (Adkins et al. 2010). If not for the rapid growth of the East Sand Island colony, the western North America population would be approximately stable. The annual consumption of juvenile salmonids by double-crested cormorants nesting on East Sand Island now exceeds that of the Caspian tern colony on East Sand Island (Lyons 2010, Roby et al. 2011). In contrast to Caspian terns, management actions for double-crested cormorants nesting on East Sand Island have not yet been implemented, but federal, state, and tribal resource management agencies have agreed that management to reduce losses of juvenile salmonids to cormorant predation in the Columbia River estuary is warranted. Discussions to explore potential management options as part of the process of preparing an EIS for double-crested cormorant management have only recently been initiated among regional resource management agencies.

To better understand and address multiple issues related to fisheries-piscivorous bird interactions in the Columbia River estuary, I conducted studies on Caspian terns and double-crested cormorants from several perspectives. Chapter 2 focuses on population dynamics of Caspian terns in the Pacific Coast region. I investigated demographics of the species and connectivity among their breeding colonies over an extensive area at a regional scale, which includes the largest colony of the species on East Sand Island in the Columbia River estuary and much smaller colonies scattered throughout the region. Based on the previously documented population growth, range expansion, and shifts in nesting locations, an evaluation of the Pacific Coast population using a large-scale landscape approach in the context of metapopulation analysis appears necessary for a comprehensive understanding of this Caspian tern population. Results from this chapter provide information necessary to understand the current status of the Caspian tern population in the Pacific Coast region, as well as insights into management efforts at the Caspian tern colony on East Sand Island. In order to evaluate demographic parameters and inter-colony movements at a regional scale, Caspian terns were color banded and re-sighted at colonies throughout the range of the metapopulation, but mainly in Washington, Oregon, and northern California, and with particular emphasis on two colonies in the Columbia River basin. In addition, I opportunistically collected data at colonies in Alaska and southern California to investigate the scale of the landscape that Caspian terns utilize for breeding in the Pacific Coast region. Specific objectives of this chapter were to evaluate (1) adult apparent annual survival, re-sighting probabilities, and breeding site philopatry for birds at two colonies in the Columbia River basin; (2) age at first visit to the natal colony and age at first reproduction; (3) distance and direction of natal and breeding dispersal; and (4) movements of individuals from existing colonies to new colony sites.

In Chapter 3, I examined the level of contaminant body burdens and factors influencing contaminant accumulation in Caspian terns and double-crested cormorants nesting at East Sand Island. Polychlorinated biphenyls (PCBs) are one of the legacy contaminants that have been detected in avian piscivores at a number of locations in the Columbia River system (Thomas and Anthony 1999, Elliott et al. 1998, Henny et al. 2008). In this study, I measured PCB levels in eggs and chick livers from Caspian terns and double-crested cormorants, as well as in their primary prey fish from the lower estuary. For comparison purposes, PCB levels in these two avian species and their prey were also measured at other locations where these species nest farther up the Columbia River. Specific objectives of the study were to evaluate PCB levels during different stages of the breeding season and in relation to diet composition, prey sources, lipid content of prey fish, and fat scores of chicks.

Chapter 4 provides information on potential management techniques for nesting double-crested cormorants. The main methods to control cormorants in the U.S. and Canada are hazing and lethal take of adults, destruction of nests, and oiling of eggs to prevent hatching (Wires and Cuthbert 2006). Such destructive control measures at the East Sand Island cormorant colony, however, would have a significant impact on the entire western North America population because such a high proportion of the breeding population nests on East Sand Island. Therefore, studies are warranted to explore potential non-destructive management techniques to reduce the size of the cormorant colony on East Sand Island. To restore seabird colonies and create new ones, habitat enhancement and social attraction techniques have been successfully used (Kress 1983, Roby et al. 2002, Parker et al. 2007, Jones and Kress 2012). In this study, I tested habitat enhancement and social attraction techniques to evaluate whether these techniques are effective tools to attract double-crested cormorants away from the large colony on East Sand Island. Habitat enhancement and social attraction techniques were tested in two stages: (1) on areas of East Sand Island near the existing cormorant colony, but where cormorants had not previously nested and (2) on islands in the Columbia River estuary other than East Sand Island where potential or historical nesting habitat for cormorants was identified, but where birds currently did not nest. In both sets of trials, I evaluated potential factors that may influence successful attraction of breeding double-crested cormorants.

Overall, this dissertation provides valuable information to further our understanding of the demographic and behavioral characteristics of the piscivorous colonial waterbirds that nest on East Sand Island in the Columbia River estuary, as well as their interaction with prey species. The results of my dissertation research will aid in developing management plans for Caspian terns and double-crested cormorants in the Pacific Northwest. I hope this dissertation also contributes to the exploration and evaluation of management and restoration options for ecosystems where piscivorous waterbirds play a key role.

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# CHAPTER 2

# DEMOGRAPHY AND METAPOPULATION DYNAMICS OF CASPIAN TERNS FROM COLONIES IN THE PACIFIC COAST REGION OF NORTH AMERICA

Yasuko Suzuki, Daniel D. Roby, Katie M. Dugger, Jennifer A. Gervais,
Donald E. Lyons, Robert M. Suryan, Ken Collis

## ABSTRACT

We investigated the demographics and inter-colony movements of Caspian terns (*Hydroprogne caspia*) in the Pacific Coast region of North America based on re-sightings of color-banded individuals breeding at a very large colony in the Columbia River estuary and a much smaller colony on the mid-Columbia River. The colony on East Sand Island in the estuary was of particular interest because it is the largest colony for the species in the world, and recent management actions are designed to reduce colony size in an effort to enhance survival of juvenile salmonids (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act. Apparent annual survival of adult Caspian terns nesting in the Columbia River estuary and on the mid-Columbia River was 0.95 and 0.94, respectively, and apparent median age at first reproduction was at least six years and five years post-hatch, respectively. Colony site philopatry of breeding adults at both colonies was high; however, some individuals prospected for breeding colonies over much of the region, from the Salton Sea in southeastern California to the Copper River Delta in south-central Alaska. For some individual terns, dispersal distances between breeding colonies of up to 3,000 km were documented within a single breeding season. The majority of sub-adults visited breeding colonies for several years prior to their first reproductive attempt, suggesting that sub-adults can prospect at multiple colonies prior to nesting. Terns from the large colony in the Columbia River estuary responded quickly to the availability of new colony sites as far as 550 km away and established successful breeding colonies in less than a year. Due to high vagility, delayed onset of reproduction, and high adult annual

survival of Caspian terns in this metapopulation, individuals can prospect and select nest sites over an extensive area and establish a high degree of connectivity among colonies throughout the Pacific Coast region. The Caspian tern colony in the Columbia River estuary appears to be an important source colony for a number of smaller, less productive colonies distributed over a vast area with limited and ephemeral nesting opportunities.

## INTRODUCTION

Caspian tern (*Hydroprogne caspia*) populations in several regions of North America have experienced growth and range expansion in recent decades (Wires and Cuthbert 2000). In the Great Lakes region, the Caspian tern population nearly tripled during the last three decades of the 20th Century (Wires and Cuthbert 2000), including increased numbers of breeding colonies (Morris et al. 2010). The Pacific Coast population of Caspian terns nearly quadrupled and expanded its breeding range during the last four decades of the 20th Century (Gill and Mewaldt 1983, Wires and Cuthbert 2000, Suryan et al. 2004). Based on the most recent published assessment conducted during 1997-2000, the population size of Caspian terns in the Pacific Coast region was approximately 13,000 breeding pairs (Suryan et al. 2004). The most recent available estimates of the population size of the Pacific Coast region, as recent as 2009, were 15,000-16,000 breeding pairs (J. Hoskins, USFWS, unpubl. data). In contrast to Caspian terns in the Great Lakes region, however, Caspian terns breeding in the

Pacific Coast region have aggregated at fewer large colonies compared to the past (Suryan et al. 2004).

Caspian tern nesting habitat consists of sandy substrate on islands free of mammalian nest predators, habitat that is generally ephemeral because of flooding, erosion, human development, or disturbance by mammalian predators at land-bridged colony sites (Cuthbert 1985, Cuthbert and Wires 1999). Caspian terns appear to have lower colony site fidelity than most other seabird species because of the transitory nature of their preferred nesting habitat (Gill and Mewaldt 1983, Cuthbert 1988, Wires and Cuthbert 2000, Collins 2006). In the Pacific Coast region of North America, the documented population growth and range expansion of Caspian terns, as well as frequent shifts among colony sites in response to changing habitats (Collis et al. 2002, Roby et al. 2002), necessitates a large-scale landscape approach to studies of population dynamics. Consequently, a comprehensive understanding of the Pacific Coast metapopulation of Caspian terns requires an investigation of the demographics and connectivity among breeding colonies spread over an extensive area.

The demographic parameters of Caspian terns in the Pacific Coast region were last evaluated by Suryan et al. (2004) using records of band recoveries from dead birds collected during 1981-2000. As of 2009, the Caspian tern colony on East Sand Island in the Columbia River estuary represented over 60% of breeding pairs in the Pacific Coast population (Roby et al. 2010), and this colony is the largest known breeding colony for the species in the world (Suryan et al. 2004). The East Sand Island Caspian tern colony has been a focus of attention by resource managers and the public in the last decade because of interactions between fisheries and this piscivorous colonial waterbird. Fisheries managers have been particularly concerned about the impact of predation by Caspian terns nesting at the East Sand Island colony on survival of juvenile salmonids (*Oncorhynchus* spp.) from throughout the Columbia River basin that are listed under the U.S. Endangered Species Act (ESA; National Oceanic and Atmospheric Administration 2004, 2008). A management plan designed to reduce the impact of Caspian tern predation on survival of juvenile salmonids in the Columbia River estuary was implemented beginning in 2008 and is ongoing (U.S. Fish and Wildlife Service et al. 2005, U.S. Fish and Wildlife Service 2006). The management action was designed to provide alternative nesting habitat for Caspian terns (i.e., artificial islands) at several locations in Oregon and California and concurrently reduce the area of suitable nesting habitat on East Sand Island. Because of the Caspian tern's adaptation to the dynamic availability of suitable nesting habitat, relocation of breeding colonies is a viable management action (Collis et al. 2002, Roby et al. 2002). Therefore, an understanding of the metapopulation dynamics of Caspian terns in the Pacific Coast region is of interest not only for monitoring the current population status of the species, but also to facilitate management where the species comes into conflict with restoration of endangered salmonids.

We investigated the demography and inter-colony movements of Caspian terns in the Pacific Coast metapopulation during 2001-2010, with particular emphasis on two colonies in the Columbia River basin. We color-banded and re-sighted individuals at breeding colonies throughout the breeding range of this population, with intensive banding and re-sighting efforts at two colonies in the Columbia River basin, one in Oregon and the other in Washington. We conducted a less intensive banding and re-sighting effort at other colonies in Washington, Oregon, and northern California, and collected opportunistic records of marked individuals at colonies in Alaska and southern California. Specific aims of this study were to (1) estimate adult apparent annual survival, re-sighting probabilities, and breeding site philopatry for birds at two colonies in the Columbia River basin; (2) assess age at first visit to the natal colony, and age at first reproduction, (3) evaluate distance and direction of natal and breeding dispersal, and (4) summarize movements of individuals from existing colonies to new colony sites.

## METHODS

### Study Area

We collected data on re-sightings of banded Caspian terns at multiple breeding colonies within the Pacific Coast region of the United States during 2001-2010 (Figure 2.1), but most banding and re-sighting effort was at two colonies in the Columbia River basin: East Sand Island and Crescent Island. East Sand Island in the Columbia River estuary (river km 8; 46º15’94”N, 123º58’05”W) was home to a Caspian tern colony that averaged 9,300 breeding pairs during our study period; and there was no significant trend in the size of this breeding colony over this period (Roby et al. 2011). Because management agencies were particularly concerned about the impact of predation by Caspian terns on survival of ESA-listed salmonids from the Columbia River basin, we focused our banding and re-sighting efforts on the East Sand Island colony and on the Crescent Island colony in the mid-Columbia River (river km 509; 46º05’37”N, 118º55’48”W), one of the smaller Caspian tern colonies in the Pacific Coast region. In contrast to the large East Sand Island colony, the Crescent Island colony steadily declined in size from 668 breeding pairs in 2001 to 375 pairs in 2010; this colony was not the object of any management activities. Banding and re-sightings at these two colonies make up the majority of data presented here.

In addition to East Sand Island and Crescent Island, we also banded and/or re-sighted Caspian terns at nine smaller breeding colonies at seven separate locations in Washington, Oregon, and northern California to better understand movements among breeding colonies. These smaller colonies included: Potholes Reservoir (46º59’07”N, 119 º18’36”W) on the Columbia Plateau in central Washington; the Port of Bellingham, Washington (48 º44’49”N, 122º29’19”W); Dungeness Spit, Washington (48º10’35”N, 123º08’43”W); and two colonies in San Francisco Bay, California (37 º53’59”N, 122º21’38”W). Smaller colonies also included four colonies on artificial islands built by the U.S. Army Corps of Engineers at three locations: Summer Lake Wildlife Area, Oregon (42º57’22”N, 120º42’56”W); Crump Lake, Oregon (42º17’17”N, 119 º56’13”W); and Sheepy Lake in Lower Klamath National Wildlife Refuge, on the border between Oregon and California (41º58’38”N, 121º47’59”W). These islands were created to serve as alternative nesting habitat for Caspian terns nesting on East Sand Island and to compensate for the managed reduction in tern nesting habitat in the Columbia River estuary. The largest of the nine smaller colonies consisted of up to approximately 1,500 breeding pairs during our study period (Dungeness Spit and Port of Bellingham colonies); however, the size of most other colonies was much smaller, approximately 500 pairs or less.

We also opportunistically collected data from three peripheral smaller colonies in the Pacific Coast region. These colonies included one in the Copper River Delta of south-central Alaska (60º13’35”N, 145º10’13”W); one in Icy Bay, southeastern Alaska (59º57’18”N, 141º19’52”W); and one in Salton Sea National Wildlife Refuge, southeastern California (33º10’54”N, 115º37’12”W). No Caspian tern breeding colonies in excess of 50 breeding pairs are known for the Pacific Coast region of Canada (Campbell et al. 1997). Data from these three peripheral colonies were summarized and included where appropriate.

## Banding and Re-sighting

We used data from Caspian terns banded during 2001-2009 and re-sighted during 2002-2010 in this study. We captured adult terns on four different breeding colonies (Table 2.1) using doughnut-shaped leg-hold noose-mat traps placed around nests containing eggs during the late incubation period. Adults captured using this method were assumed to be breeding adults in our study. We banded chicks captured prior to fledging on six different colonies, by herding them into a corral constructed of fabric fence material (Table 2.1). Caspian tern adults and chicks were banded with a metal tarsus band issued by the U.S. Geological Survey – Bird Banding Laboratory and several colored plastic (Darvic) tarsus bands.

In the early years of the study, five small, colored plastic leg bands were placed on each bird (two plastic bands and a metal band on one leg and three plastic bands on the other leg) in a unique color combination to identify banding location, year, and individual. This banding system will be referred to hereafter as “five color bands.” However, loss of some of these smaller plastic bands by some individuals that were banded in this manner prevented individual identification when re-sighted. Consequently, we modified our banding methodology beginning in 2005 for adults and 2006 for chicks to preclude further band loss: (1) we switched from reversing the coil direction of the small, colored plastic bands to keeping the original coil direction; (2) we used a thicker field-readable Darvic leg band engraved with a four-digit alphanumeric code to replace the three color bands on one leg; and (3) we sealed all plastic bands with superglue. This modified banding system will be referred to hereafter as “alphanumeric bands.”

In this study, only individuals banded with alphanumeric bands during 2005-2009 were included in analyses involving breeding adults. Because the number of terns banded as chicks with alphanumeric bands during 2006-2009 and returning to the breeding grounds during the study period would be small if terns exhibited delayed onset of reproduction, chicks banded with five color bands during 2001-2005 and re-sighted with a full set of color bands were also included in some summaries. A total of

472 adults and 1,925 chicks were banded with alphanumeric bands, while 2,052 chicks were banded with five color bands (Table 2.1).

Banded individuals were re-sighted using spotting scopes and, occasionally, binoculars on 14 different breeding colonies at 12 separate locations (Table 2.2), usually from observation blinds built near the colonies. We monitored colonies for banded individuals daily or every other day throughout the nesting season, whenever resources permitted. However, only East Sand Island and Crescent Island were monitored intensively within each breeding season and across all years, as some of the smaller colonies were visited less frequently and/or were not monitored for banded terns in all years (Table 2.2). In addition to band identification data, behavioral data (e.g., loafing, incubating, chick-feeding) were collected to assess the breeding status of each banded individual.

### Adult Annual Survival, Encounter, and Movement Rates

A multistate model (Arnason 1973, Schwarz et al. 1993, Lebreton et al. 2003) in Program MARK (White and Burnham 1999) was used to estimate annual apparent survival ($\phi$), re-sighting (p), and movement ($\psi$) probabilities for Caspian terns banded as breeding adults at two colonies in this metapopulation. We only used data from terns banded and re-sighted at either the East Sand Island or the Crescent Island colony, where the most intensive re-sighting effort was invested across the longest time series (2006-2010). In order to estimate movement rates between these two colonies, each individual was assigned a state based on colony location (either

East Sand Island or Crescent Island) during the breeding season. Terns occasionally were seen at both colonies in the same year; however, only one location per year can be used to assign state in the encounter history, so we assigned each individual to a breeding colony based on observed behaviors and the amount of time at each colony. Although we re-sighted some individuals at colonies other than East Sand Island or Crescent Island, re-sighting effort and the number of individuals banded at these sites was not sufficient to include data from these other colonies in this analysis.

There were 10 terns from East Sand Island and eight terns from Crescent Island that appeared to permanently emigrate from their original breeding colony because they were re-sighted as breeders or, if breeding was not confirmed, observed spending a considerable amount of time at other colonies. These individuals were coded as “losses on capture” in the encounter history because they were known to leave the two-colony study area encompassed by this particular analysis and were never re-sighted as breeders back at East Sand Island or Crescent Island after their initial emigration (thus their movements were considered “permanent”). This adjustment reduced the potential negative bias in apparent survival rates associated with permanent emigration outside the specific geographic area included in this analysis.

*A priori* models were constructed to evaluate effects of colony and year on all parameters. Additionally, we evaluated whether the overall productivity of the colony (average number of young raised per breeding pair) influenced subsequent movement probability. We hypothesized that annual colony productivity would reflect factors such as predation pressure and food availability, and that productivity during year *i* influenced the rate of emigration to the other colony between year *i* and (*i* + 1). To estimate productivity, we used aerial photography to estimate the number of breeding pairs of Caspian terns at the colony when the colony size was at its peak (late incubation), and the number of surviving young on the colony when most chicks were still too young to fledge from the colony. At the Crescent Island colony, ground counts from a blind adjacent to the colony were combined with counts from aerial photography to improve the accuracy of estimates of colony size and productivity. The range of annual average productivity at the East Sand Island and Crescent Island colonies was 0.37-0.74 and 0.28-0.64, respectively, during 2005-2009 (Figure 2.2).

In order to avoid a large *a priori* model set, we modeled parameters in stages. Re-sighting rates were modeled first, and the best structure was retained as we moved on to model apparent survival rates. The best model for re-sighting rates and apparent survival rates was retained when we modeled movement probabilities. At each stage, the best models were cross-checked against competitive models from a previous stage to be sure that we apportioned variation correctly among parameters and effects. We used Program MARK to generate estimates and model selection results (White et al. 2006). Akaike's Information Criterion (AIC) adjusted for small samples size and over-dispersion (QAICc; if appropriate) was used to select the best model, and evaluate specific covariate effects (Burnham and Anderson 2002). Generally, we selected the best model for inference based on the lowest QAICc, but we also used estimates of regression coefficients (β) and their 95% confidence limits to provide additional information (strength of evidence) for specific effects. Considering the steady colony size decline at Crescent Island during the study period, we predicted that apparent adult survival rate at Crescent Island would be lower than at East Sand Island and/or emigration rate would be higher at Crescent Island compared to East Sand Island.

### Age at First Return to the Natal Colony and Age at First Reproduction

Data from terns banded as chicks at either the East Sand Island or Crescent Island colonies during 2001-2009 and re-sighted during 2002-2010 at their natal colony were used to summarize age when terns were first re-sighted at their natal colony and age when terns were first confirmed breeding at their natal colony. Age at first breeding was primarily based on five color-banded birds only, as we had no alphanumeric-banded age classes older than four years old in 2010. Terns banded with five color bands and those banded with alphanumeric bands were summarized separately because return rates of terns banded with five color bands were most likely underestimated (some terns banded with five color bands were not identifiable due to band loss, while this was not a problem for terns banded with alphanumeric bands). We assumed that re-sighting rates of terns banded with five color bands should not vary across ages due to band loss. If band loss affected re-sighting rates across ages, the bias would be towards younger birds because there was a higher chance that older birds had lost one or more color bands.

Terns that were re-sighted for the first time and/or confirmed breeding for the first time at colonies other than East Sand Island or Crescent Island were excluded from the dataset. We excluded these data because resultant estimates of age at first re-sighting and age at first reproduction would likely be biased high because of the greater chance of failing to detect a banded tern at the time of first visit or first breeding at other colonies where colony visits were less frequent compared to visits to the East Sand Island and Crescent Island colonies. We also excluded data from terns re-sighted for the first time and/or confirmed breeding for the first time at East Sand Island or Crescent Island if the banded individual had been re-sighted and/or confirmed breeding at another colony prior to being re-sighted and/or confirmed breeding on East Sand Island or Crescent Island. Including data from these individuals in the dataset would have resulted in estimates of age at first re-sighting or age at first reproduction that were biased high.

We defined age at first reproduction based on known-age birds that were visually confirmed with eggs or chicks, as compared to birds observed initiating nesting behavior (e.g., copulating, digging nest scrapes), but not actually confirmed to have laid at least one egg within the same breeding season. We made this distinction because we observed terns on breeding colonies that displayed some nesting behavior but apparently never laid eggs, a behavior pattern also observed in other seabird species (Ainley 2002).

Frequencies of age when terns were re-sighted for the first time and confirmed breeding for the first time at their natal colony were not normally distributed; therefore, the median age was used to evaluate age-related patterns in returning to the breeding grounds. When median age was different between colonies, Wilcoxon rank-sum test was used to evaluate if the difference was statistically significant. The analysis was performed using SAS 9.2 (SAS Institute 2009), with $\alpha = 0.05$.

## Distance and Direction of Natal and Breeding Dispersal

Natal and breeding dispersal of Caspian terns banded at East Sand Island and Crescent Island were summarized to investigate patterns of connectivity among breeding colony sites in the metapopulation, particularly direction and distance traveled. In order to evaluate natal dispersal, re-sighting data for terns banded as chicks at the two colonies during 2001-2009 were used. Colony locations where terns were confirmed breeding for the first time were summarized. Terns banded with five color bands and alphanumeric bands were summarized separately as described above.

Re-sighting data for terns banded as breeding adults at East Sand Island and Crescent Island during 2005-2009 were used to summarize breeding dispersal. If a Caspian tern banded at either East Sand Island or Crescent Island was re-sighted at least once at another colony in subsequent seasons, we considered it unfaithful to the colony where it had been banded. If nesting was not confirmed at the alternative colony site, these individuals were likely prospecting for alternative nest sites, because nearest neighbor colonies for either the East Sand Island or Crescent Island colony were more than 100 km distant, greater than the maximum known foraging distance for a breeding bird. Foraging trip distance of breeding Caspian terns from their nest site in the Columbia River estuary averaged less than 30 km (Lyons et al. 2005, Anderson et al. 2007), but foraging trips can extend as far as 80 km (Adrean 2011).

Re-sighting records that may have been from the migration periods or post-breeding dispersal (before May 1 and after approximately July 15 – 31 each year, depending on nesting chronology at a given colony) were excluded.

### Establishment of New Colonies

Here we summarize re-sighting data (return rates) from new Caspian tern colonies that formed on four newly constructed islands: one on Crump Lake in the Warner Valley of south-central Oregon, two at Summer Lake Wildlife Area near Summer Lake, Oregon, and one on Sheepy Lake in Lower Klamath National Wildlife Refuge on the border between Oregon and California. The closest of these islands to East Sand Island is at Summer Lake Wildlife Area, a 445 km straight-line distance, and the farthest of these islands is on Crump Lake, a 550 km straight-line distance. Caspian terns historically nested intermittently on an island on Crump Lake, when the water levels were low and the island was not submerged during the nesting season. The last record of nesting on this historical island (prior to the construction of the new island in 2008), was in 2003, when 71 breeding pairs were recorded. At Summer Lake Wildlife Area, a small colony of Caspian terns had been recorded, but the last record of nesting prior to the construction of the two new islands in 2009 was in 2005, when three pairs nested. Lower Klamath National Wildlife Refuge supported 15-30 breeding pairs of Caspian terns as recently as 1976; however, no Caspian tern nests were recorded since then and prior to the construction of the island on Sheepy Lake in 2010. All banded individuals (with alphanumeric bands) re-sighted during 2008-2010 at the island on Crump Lake, during 2009-2010 at both islands in Summer Lake Wildlife Area, and during 2010 at the island in Lower Klamath NWR were included in the summary, regardless of apparent breeding status. Re-sighting records of individuals that likely migrated through these areas after the nesting season (after approximately July 15 – 31 each year, depending on nesting chronology at a given colony) were excluded from the summary.

All procedures involving the handling of Caspian terns were performed under scientific permits obtained from the Oregon Department of Fish and Wildlife (Salem, OR), the Washington Department of Fish and Wildlife (Olympia, WA), or the California Department of Fish and Game (Sacramento, CA). Marking terns with plastic tarsus bands was performed under auxiliary marking permits obtained from the U.S. Geological Survey - Bird Banding Laboratory (Patuxent, MD). All procedures and methods involving live vertebrate subjects followed protocols approved by the Institutional Animal Care and Use Committee (IACUC) at Oregon State University.

## RESULTS

### Adult Apparent Survival, Re-sighting Rates, and Movement Probabilities

Some over-dispersion in our data was observed (median c-hat = 1.444); thus, model results were adjusted accordingly (i.e., QAICc). There were six competitive models within two ΔQAICc units with consistencies, suggesting there were only weak colony-specific differences in survival, but stronger differences in re-sighting rates for terns banded at East Sand Island compared to those banded at Crescent Island (Table 2.3). Three of the six top models did not include an effect of colony on survival, and in models where colony was included, the 95% confidence limits for the coefficient strongly overlapped zero (Model 3: $\beta = 0.43$, SE = 0.39, 95% CI = -0.33 to 1.20), suggesting colony had a relatively weak effect on survival. Conversely, five of the six top models included the effect of colony on re-sighting rates, with 95% confidence limits not overlapping zero in two of these models, suggesting stronger differences in re-sighting rates between the two colonies (Model 4: $\beta = 0.61$, SE = 0.30, 95% CI = 0.03 to 1.18).

The six competitive models all included the effects of colony and/or annual productivity on movement rates (Table 2.3). Differences in movement rates between colonies were evident in five of the six competitive models, but 95% confidence limits always overlapped zero and in some cases the standard errors of the betas were very poorly estimated, suggesting that while colony differences may be important, we did not have the power to estimate the effect accurately. The effect of productivity on movement rates was strongest in the model without colony effects, and the 95% confidence limits on the beta did not overlap zero and the direction of effects was as predicted, with more movement observed in the year following years with lower annual productivity (Model 4: $\beta = -9.45$, SE = 4.11, 95% CI = -17.50 to -1.40).

Considering the uncertainty in our model selection results, we chose to generate best parameter estimates by model-averaging (Burnham and Anderson 2002).

The model-averaged estimates of all parameters supported our interpretation of model selection results, with no difference in survival estimates for terns from East Sand Island and Crescent Island, but slightly greater support for a difference in estimated re-sighting rates between colonies (Table 2.4). Movement rates were generally very low for East Sand Island terns (<<0.004), but somewhat higher for Crescent Island terns (0.01-0.03), with variation associated with annual productivity (Table 2.4). Overall, site philopatry (1- $\psi$) of breeding adults at both colonies was high (0.97-1.00), but movement was associated with poor reproductive success in the preceding year, as predicted.

### Age at First Return to the Natal Colony and Age at First Reproduction

For tern chicks banded with five color bands, the age when these individuals were first re-sighted at their natal colony was from one to nine years post-hatch; the median age of first re-sighting was five years post-hatch at both colonies (Figure 2.3-A). For tern chicks banded with alphanumeric bands, none were re-sighted at their natal colony one year post-hatch (Figure 2.3-B). Only a few individuals were re-sighted for the first time at their natal colony two years post-hatch, but more individuals were re-sighted for the first time when terns were three or four years post-hatch. Most chicks banded at East Sand Island and subsequently re-sighted there were first seen three years post-hatch, whereas most chicks banded at Crescent Island were first re-sighted there four years post-hatch (Figure 2.3-B).

For tern chicks banded with five color bands, age when individual terns were first confirmed breeding at their natal colony ranged from three to nine years post-hatch, with median age of first reproduction at six years post-hatch for terns banded on East Sand Island and five years post-hatch for terns banded on Crescent Island (Figure 2.4). The median age at first reproduction, however, was not statistically different between the two colonies. For terns banded with alphanumeric bands, only two terns three years post-hatch and one tern four years post-hatch from East Sand Island were confirmed breeding for the first time at their natal colony, whereas none from Crescent Island were confirmed breeding during the study period. In 2010, however, the oldest age class for fledglings banded with alphanumeric bands was only four years post-hatch, so we had limited information on which to base estimates of average age of first reproduction.

Based on data from terns banded with five color bands, 71% of the Caspian terns detected breeding were also detected on their natal colonies at least one year prior to attempting to breed. For these terns that visited their natal colony prior to attempting to breed, the median number of years between the first on-colony re-sighting and first known nesting attempt was two years.

### Distance and Direction of Natal Dispersal

Long-distance natal dispersal from East Sand Island was evident, based on re-sighting data for Caspian terns banded as chicks with five color bands. The colony most distant from East Sand Island where the first reproduction was confirmed for terns banded as chicks was on Gull Island in Icy Bay, west of Yakutat, Alaska (Table 2.5). The Icy Bay colony is approximately 1,900 km (straight-line distance) northwest of East Sand Island. Long distance dispersal from East Sand Island also occurred in a southward direction to the Salton Sea National Wildlife Refuge in southeastern California. The Salton Sea colony is approximately 1,620 km (straight-line distance) from East Sand Island. Natal dispersal from East Sand Island to closer colonies was also observed. Terns banded as chicks at East Sand Island were re-sighted at coastal colonies to the north at the Port of Bellingham, Washington, to the south in San Francisco Bay, inland to colonies on the Columbia Plateau region of Washington (Crescent Island and Potholes Reservoir), and to all three of the sites with newly constructed islands (Crump Lake, Oregon; Summer Lake Wildlife Area, Oregon; Lower Klamath NWR, California). Natal dispersal of terns from Crescent Island was observed for the closest Caspian tern colony at Potholes Reservoir, as well as to other colonies, including the Port of Bellingham and East Sand Island colonies, plus the newly constructed island colony sites at Crump Lake and Lower Klamath NWR.

For terns banded as chicks with alphanumeric bands, three terns from East Sand Island were confirmed breeding for the first time at non-natal colonies: two at the Port of Bellingham colony and one at the Lower Klamath NWR colony. One of the terns banded as a chick at Crescent Island was confirmed breeding for the first time at the non-natal colony on Crump Lake.

## Distance and Direction of Breeding Dispersal

Long-distance movements of Caspian terns banded as breeding adults were confirmed by re-sighting of individuals banded with alphanumeric bands. A tern banded as an adult at the East Sand Island colony was confirmed nesting at a colony on Kokinhenik Bar in the Copper River Delta, Alaska, 2,080 km (straight-line distance) to the northwest of East Sand Island (Table 2.6). This particular Caspian tern nested at the East Sand Island colony during two consecutive years, and then was seen the following season on East Sand Island without confirmation of nesting. The bird was re-sighted at the Copper River Delta colony in the following year and confirmed nesting. In the subsequent breeding season the same tern was re-sighted first at East Sand Island, then in the Copper River Delta, and then back at East Sand Island, all in less than two months. The breeding status of this bird was not confirmed at either colony in that year.

Another Caspian tern banded as an adult at the Brooks Island colony in San Francisco Bay, California was also seen at the Copper River Delta colony during the breeding season (early June). This tern traveled approximately 2,960 km (straight-line distance) from San Francisco Bay to the Copper River Delta in a single breeding season, the breeding season subsequent to when it had been banded. This was the longest dispersal distance between breeding colonies confirmed by our study. The breeding status of this individual was not confirmed at the Copper River Delta colony.

Long-distance movements of Caspian terns banded as breeding adults to colonies in the south were also documented. Four terns banded as adults, three at the East Sand Island colony and one at the Crescent Island colony, were re-sighted at a colony in Salton Sea National Wildlife Refuge in southeastern California, distances of approximately 1,620 km and 1,460 km from East Sand Island and Crescent Island, respectively (Table 2.6, Table 2.7). One of the terns from the East Sand Island colony and the tern from the Crescent Island colony were confirmed nesting at the Salton Sea colony. The banded nesting tern from the East Sand Island colony had at least one season of breeding experience on East Sand Island prior to nesting at the Salton Sea colony the following year. This tern was then re-sighted at the East Sand Island colony later during the same breeding season without confirmation of breeding.

Breeding dispersal to colonies relatively close to East Sand Island and Crescent Island was also observed. Some adult terns banded at East Sand Island were re-sighted at colonies on Dungeness Spit and at the Port of Bellingham, both on the northern coast of Washington (Table 2.6). Dispersal of breeding adults from the Crescent Island colony to the closest colony on Potholes Reservoir and to the colony at East Sand Island was also documented (Table 2.7). Finally, a few breeding adults from the East Sand Island and Crescent Island colonies were re-sighted at some of the newly constructed island colony sites (Table 2.8).

### Movements to New Colony Sites

Caspian terns quickly responded to a new island colony site built on Crump Lake in south-central Oregon, and established a successful breeding colony there within three months of the completion of construction. In the first breeding season after the island was built, the colony numbered 430 breeding pairs of Caspian terns.

Colony size increased to 670 pairs in 2009, and then dropped to 70 pairs in 2010. The significant drop in colony size at Crump Lake in 2010 was apparently due to an unusually cold and late spring and low prey availability, in addition to predation pressure by California gulls (*Larus californicus*). A total of 19 banded Caspian terns from East Sand Island, Crescent Island, and Potholes Reservoir were re-sighted on the Crump Lake tern island during 2008-2010 (Table 2.8); five of them were re-sighted in 2008, during the first breeding season at the new island.

Two islands constructed in Summer Lake Wildlife Area attracted modest numbers of breeding Caspian terns; a total of 15 pairs (more than the most recent record of three pairs in 2005) nested on the two islands during the first breeding season in 2009, followed by 29 pairs in 2010. A total of four terns banded at East Sand Island, Crescent Island, and Crump Lake were re-sighted at the Summer Lake islands during 2009-2010.

The island constructed in 2010 at Lower Klamath NWR attracted and supported 258 breeding pairs during the first breeding season; a total of 18 banded terns from East Sand Island, Crescent Island, and Crump Lake were re-sighted at the Lower Klamath NWR colony. Nine adult terns attracted to the Lower Klamath NWR island from the new Crump Lake colony had been banded in 2009 on the Crump Lake island and were re-sighted at the Lower Klamath colony in the following year. Terns banded as chicks at East Sand Island were re-sighted at all three sites where new islands were constructed, Crump Lake, Summer Lake Wildlife Area, and Lower

Klamath NWR. Terns banded as adults at East Sand Island were also re-sighted at new islands on Crump Lake and at Lower Klamath NWR.

## DISCUSSION

This study revealed that breeding adult Caspian terns at two colonies in the Pacific Coast metapopulation, East Sand Island and Crescent Island, have high annual survival rates and high colony site philopatry. However, long-distance dispersal of terns from their natal colonies and former breeding colonies was documented for some individuals over distances of thousands of kilometers, from the Copper River Delta in south-central Alaska to the Salton Sea in southeastern California. The high vagility, delayed onset of reproduction, and high adult annual survival documented in this study indicate that the connectivity among Caspian tern colonies in this metapopulation is unexpectedly high.

### Life History Traits

The estimated annual adult survival rates of Caspian terns banded as adults at the East Sand Island colony (0.95; 95% CI = 0.92 - 0.97) and the Crescent Island colony (0.94; 95% CI = 0.90 - 0.96) were higher than, but not significantly so, those reported in a previous study (0.91; 95% CI = 0.84 - 0.95; Suryan et al. 2004). Our more recent and more precise estimates of apparent annual adult survival confirm the high adult survival rates for the species in the Pacific Coast region. The decline in size of the Crescent Island tern colony was apparently not due to lower survival rates of adults nesting at this colony compared to adults nesting at the East Sand Island colony. Permanent emigration from East Sand Island and Crescent Island to other colonies could not be measured. Thus, true adult annual survival rate are probably slightly higher than the apparent survival rates observed at these two colonies.

Our estimates of adult annual survival rates for Caspian terns are similar to or greater than that of other tern species where adult survival has been measured. Annual survival rates reported for other tern species include: 0.96 in arctic terns (*Sterna paradisaea*; Devlin et al. 2008), 0.95 in royal terns (*Thalasseus maximus*; Collins and Doherty 2006), 0.91 in common terns (*Sterna hirundo*; Nisbet and Cam 2002), and 0.84 in roseate terns (*Sterna dougallii*; Spendelow et al. 1995).

Our estimate of median age at first reproduction (5-6 years post-hatch) was greater than previously reported (3-4 years post-hatch), which was estimated from recoveries of bands from dead birds found at active colonies, with the assumption that the banded individuals had been breeding at these colonies prior to their death (Ludwig 1942, Gill and Mewaldt 1983). Our estimates also appear to be greater than the age at first reproduction reported in other tern species: 2-4 years in Damara terns (*Sterna balaenarum*; Brady et al. 2011), 2-6 years in common terns (Dittman and Becker 2003), and 3-5 years in roseate terns (Spendelow et al. 2002).

Our data indicate that the majority of sub-adult Caspian terns return to the breeding grounds before they are ready to breed. This suggests that sub-adults can spend several breeding seasons prior to their first nesting attempt prospecting at multiple colonies and gathering performance information from other breeding individuals before making a decision on where to recruit into the breeding population (Dittmann and Becker 2003, Hénaux et al. 2007). Delayed onset of reproduction, as observed in this study, has been associated with higher survival during the first breeding season (Bradley et al. 1989) and high annual adult survival (Ricklefs 1990, Chastel et al. 1995).

## Colony Site Philopatry of Breeding Adults

Our study revealed that colony site philopatry of Caspian terns banded as breeding adults, as estimated from movements between the East Sand Island and Crescent Island colonies, was generally very high, consistent with life-history patterns observed in other seabirds (Inchausti and Weimerskirch 2002, Dugger et al. 2010). Breeding philopatry was higher at the largest colony in the Pacific Coast metapopulation (East Sand Island) compared to a small colony (Crescent Island). This difference may be explained by the conspecific-social attraction hypothesis, whereby the probability of settling at a given colony would depend on whether it is already occupied by the same species (Spendelow et al. 1995, Serrano and Tella 2003). In contrast, lower immigration to large colonies compared to small colonies has also been reported in some seabirds, possibly because of density-dependent competition for nest sites or food resources (Ainley et al. 2004). Personal information (*sensu* Valone and Giraldeau 1993) acquired from years of individual breeding experience and familiarity with nesting habitat has been reported as a factor influencing adults' decisions to either stay or emigrate from their breeding colony (Doligez et al. 2002, Serrano and Tella 2003). This might outweigh conspecific attraction or performance information from other individuals during the adult's decision-making process.

There was evidence that movement rates of breeding adults between the East Sand Island and Crescent Island colonies were influenced by variation in annual productivity at the colony of origin, which agrees with the findings of others (Cam et al. 2004, Catlin et al. 2005, Boulinier et al. 2008). Terns were more likely to emigrate to the other colony after experiencing lower productivity in the previous year. Caspian terns at the Crescent Island colony experienced lower productivity compared to the colony at East Sand Island in some years during the study period, and low food availability has been identified as a factor limiting nesting success for terns nesting at Crescent Island (Roby et al. 2011). The main prey type for terns nesting at Crescent Island is salmonid smolts (Antolos et al. 2005), and smolts often have already migrated past the colony by the late chick-rearing period (Roby et al. 2011). In contrast, the diet of terns nesting at East Sand Island in the Columbia River estuary consists of diverse forage fishes (resident freshwater and estuarine fishes, marine forage fishes, and salmonid smolts; Roby et al. 2002); therefore, even when certain primary prey types becomes scarce, alternative prey types are generally available (Lyons 2010). Additionally, higher rates of gull kleptoparasitism on terns nesting at Crescent Island (mainly by California gulls) compared to East Sand Island have been reported as a factor limiting productivity at Crescent Island (Roby et al. 2011). The steady decline in the size of the Crescent Island tern colony may be due to both decreased replacement of breeders at the colony (i.e., decreased recruitment) and increased emigration to East Sand Island and other smaller colonies, possibly related to poor or variable nesting conditions experienced by breeders at Crescent Island.

The approximate number of breeding adults (marked and unmarked individuals combined) dispersing annually from the East Sand Island colony to the Crescent Island colony and vice versa can be predicted from the product of the average movement probability (across years) times the mean number of breeding adults at each colony during 2006-2010. Based on this calculation, approximately 19 breeding adults (0.001 x 18,600) from the East Sand Island colony would be expected to move to the Crescent Island colony each year and approximately 13 breeding adults (0.014 x 934) from the Crescent Island colony would be expected to move to the East Sand Island colony each year.

The new Caspian tern colonies that recently formed at Crump Lake and in Lower Klamath NWR include hundreds of breeding pairs that recruited to the new colonies during the first nesting season after island construction. These recruits included a number of color-banded breeding adults from both the East Sand Island and Crescent Island colonies (three individuals from each colony). Consequently, it is likely that the movement rates of breeding adults from the East Sand Island and Crescent Island colonies to the new colonies forming on newly constructed tern islands are higher than the movement rates between the East Sand Island and Crescent Island colonies (Cam et al. 2004). Nevertheless, we would expect that the majority of terns recruiting to the new breeding colony sites would be first-time breeders or young breeders, instead of breeding adults recruited from other colonies (Doligez et al. 2002, Serrano and Tella 2003). In order to determine the origin of terns recruiting to new colony sites, it will be necessary to band substantial numbers of fledglings and breeding adults at more breeding colonies and institute a more comprehensive re-sighting program for banded Caspian terns throughout the breeding range of the Pacific Coast metapopulation.

## Long-distance Natal and Breeding Dispersal

Caspian terns in this study exhibited long-distance breeding dispersal, with movement distances up to 3,000 km between breeding colonies within a single breeding season. Northward expansion of the Pacific Coast population into Alaska, resulting in breeding colonies in the Copper River Delta and in Icy Bay, was hypothesized in the 1980s (Gill and Mewaldt 1983, Gibson and Kessel 1992). However, the first breeding records for Caspian terns in Alaska were from the coast of the Bering Sea, where a few pairs nested in 1996 (McCaffery et al. 1997). Subsequently, larger colonies were discovered in 2005 on islands in the Copper River Delta (Lohse et al. 2008) and in Icy Bay (M. Kissling, USFWS, unpublished data). Our findings are the first documentation of dispersal by breeding adults and fledged young from colonies in Oregon and California to new colonies in south-central and southeastern Alaska. The ability of young adult Caspian terns to disperse nearly 2,000 km north from their natal colony is remarkable considering the Icy Bay colony is in the opposite direction from the route followed during fall migration to their wintering grounds in western Mexico (Gill and Mewaldt 1983, Cuthbert and Wires 1999), and particularly given that there were multiple active Caspian tern breeding colonies within 400 km of their natal colony on East Sand Island.

Salton Sea is a major stopover site for Caspian terns migrating to and from more northern colonies, plus islands in Salton Sea National Wildlife Refuge have served as breeding sites (Shuford et al. 2002, Molina 2004). Because the Salton Sea is along the terns' fall migration route to wintering grounds in western Mexico, re-sighting of individuals at the Salton Sea that were banded on more northern colonies is expected. We confirmed, however, an unexpected movement between the nesting colony at the Salton Sea and the colony on East Sand Island. Caspian terns initiate nesting at the Salton Sea as early as January (K. Molina, pers. comm.). Our re-sighting of a banded tern first at the Salton Sea colony and then at the East Sand Island colony later in the same nesting season suggests either a long-distance post-breeding dispersal or that breeding individuals may attempt to sequentially nest in the same breeding season at colonies separated by over 1,600 km.

The long-distance emigration of an experienced breeding adult from the East Sand Island colony to the Copper River Delta colony also demonstrates that some adult Caspian terns prospect for alternative colonies over very large distances and maintain an extraordinary degree of connectivity among far-flung colonies dispersed throughout the Pacific Coast region of North America. While long-distance dispersal from natal colonies has been documented in other seabird species, long-distance dispersal by breeding adults is considered rare (Inchausti and Weimerskirch 2002, Spendelow et al. 2010, Dugger et al. 2010). In Caspian terns, “deserting flights,” defined as a group of nesting terns that abandon a colony because of predation or disturbance and establish a new colony, have been reported in Europe, but only over distances of up to 800 km (Väisänen 1973, Staav 1979, Bergman 1980). To our knowledge, the distance of breeding dispersal documented in our study is unprecedented for seabird species. Cuthbert (1985) reported that most adult Caspian terns that were observed at multiple colonies within a breeding season in the Great Lakes region were either breeders that had failed earlier in the breeding season, breeders exhibiting pre-nesting behavior (e.g., courtship, nest scraping), or non-breeders. Nesting failure caused by disturbance or nest predation might be a major factor causing dispersal in experienced breeding adults (Serrano et al. 2001).

These results also demonstrate that the large breeding colony on East Sand Island, by far the largest in the metapopulation, can serve as a source for breeding colonies more than 2,000 km distant. Re-sighting records of banded individuals, both at their original colony and at distant colonies during a single breeding season, reveals the high vagility of the species and their ability to locate and visit multiple colonies separated by great distances in a short time. Based on movements of these individuals among distant colonies, the degree of large-scale connectivity among Caspian tern colonies appears to be important for understanding the dynamics of the species along the western coast of North America.

### Movements to Newly Created Nesting Habitat

The detection of banded Caspian terns at the newly constructed islands on Crump Lake, Summer Lake Wildlife Area, and Lower Klamath NWR demonstrated that Caspian terns from multiple colonies in the metapopulation could quickly find and colonize new nesting habitat during the first breeding season when it was available. Habitat enhancement and social attraction techniques (decoys and audio playback systems) have been successfully used to establish new tern colonies or relocate part or all of existing tern colonies from one colony site to another (Kress 1983, Lampman et al. 1996, Collis et al. 2002, Roby et al. 2002). Most studies of attempts to establish or relocate tern colonies were for sites relatively close to existing colonies. Our study confirmed that Caspian terns can be quickly attracted to new island nesting habitat from a large source colony 550 km away, and from smaller colonies as distant as 524 km away (the distance between Potholes Reservoir and Crump Lake). Some individuals attracted to the new colonies on the Crump Lake and Summer Lake islands were too young to have had any locational memory of the small historical colonies at these locations. These individuals may have (1) followed others that did have a locational memory of the site, (2) found the site by chance during prospecting, or (3) encountered the site during spring migration. However, the most recent record of nesting by Caspian terns in Lower Klamath NWR was in 1976; therefore, the first explanation is not plausible for the successful colonization of the new island at Lower Klamath NWR.

Caspian terns from the East Sand Island colony were re-sighted at all the new colony sites on Crump Lake, Summer Lake, and Lower Klamath NWR. This suggests that individuals from relatively stable and “attractive” colonies in the metapopulation may nevertheless immigrate to new colony sites, where there is no recent history of nesting. Considering the very large size of the Caspian tern colony at East Sand Island, this one colony appears to be an important source for the establishment of new colonies in the Pacific Coast region of North America.

In conclusion, adult Caspian terns nesting at the large colony on East Sand Island and at a much smaller colony on Crescent Island confirm that Caspian terns in the Pacific Coast population have high annual apparent survival rates and high colony site philopatry. The steady decline in the colony size at Crescent Island, which was associated with lower annual nesting success compared to the East Sand Island colony, was likely because of lower recruitment rates of breeding adults and high emigration rates of breeding adults to other breeding colonies. Some experienced breeding adults and sub-adults from both colonies dispersed and prospected for potential nesting habitat over a vast area, enhancing connectivity among an extensive network of colony sites from the Salton Sea in southeastern California to the Copper River Delta in Alaska. Because of their high vagility, delayed onset of reproduction, and high adult annual survival, Caspian terns from these two colonies can prospect for limited suitable nesting habitat throughout the Pacific Coast region. The large East Sand Island colony in the Columbia River estuary appears to be an important source colony for other potential and existing colony sites, even those thousands of kilometers distant.

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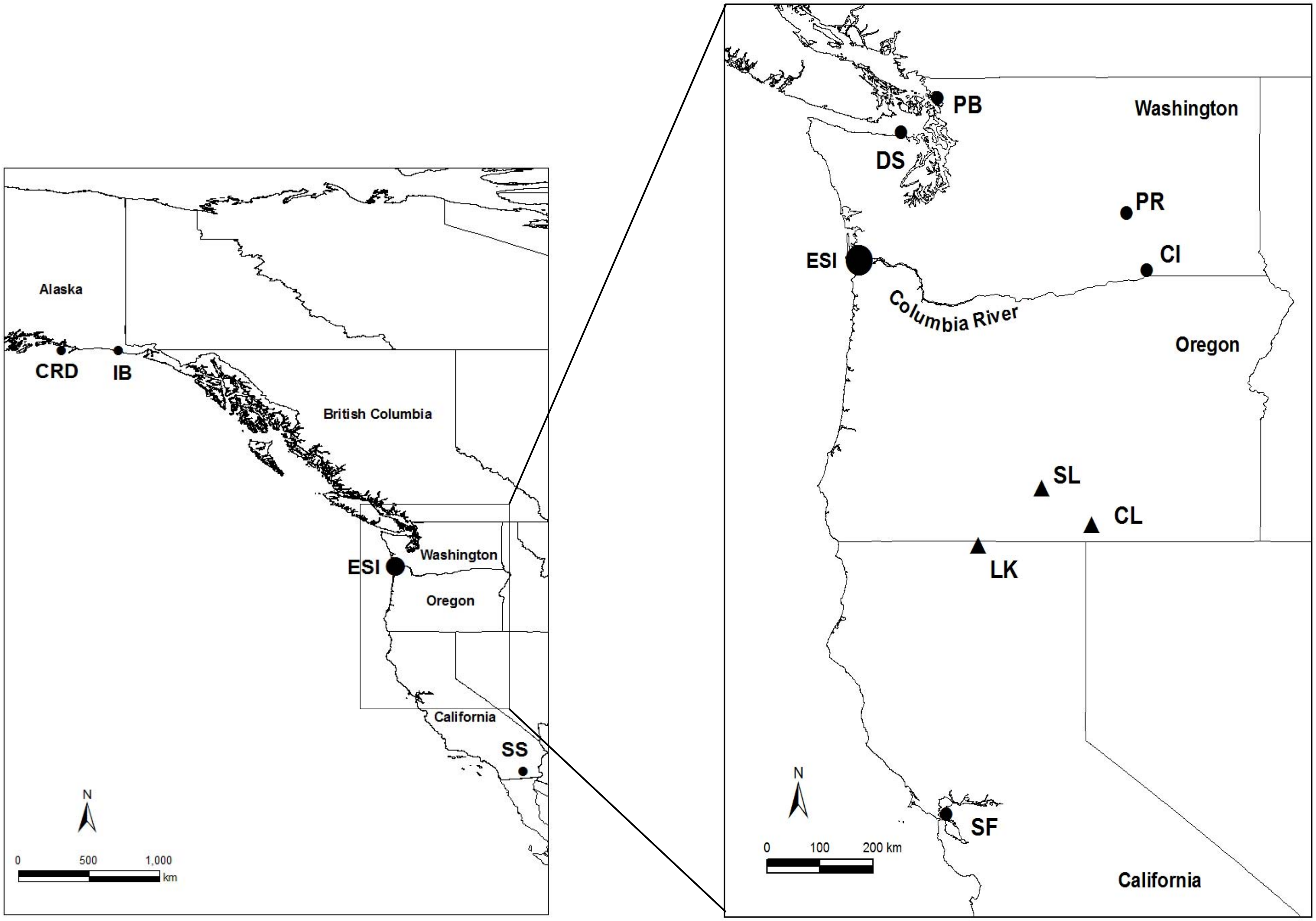
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**Figure 2.1.** Caspian tern breeding colony sites in the Pacific Coast region, USA. East Sand Island (ESI; large dark circle) is the largest colony in the metapopulation. Smaller circles indicate locations of smaller breeding colonies: Copper River Delta (CRD), Alaska; Icy Bay (IB), Alaska; Salton Sea (SS), California; Port of Bellingham (PB), Washington; Dungeness Spit (DS), Washington; San Francisco Bay (SF), California; Potholes Reservoir (PR), Washington; Crescent Island (CI), Washington. Triangles indicate locations where new nesting islands for Caspian terns were constructed: Summer Lake (SL), Oregon; Crump Lake (CL), Oregon; Lower Klamath NWR (LK), California.

**Table 2.1.** Numbers of Caspian tern adults and chicks color-banded in the Pacific Coast region of North America during 2001-2009. Adults during 2005-2009 and chicks during 2006-2009 were banded with a field-readable alphanumeric band, two small colored bands, and a federal metal band. Chicks during 2001-2005 were banded with five small colored bands and a federal metal band (numbers shaded in the table). Banded chicks recovered dead on or near the natal colony were excluded from the dataset.

| Colony/location | Age class | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| East Sand Island, OR | adult | - | - | - | - | 32 | 42 | 56 | 51 | 55 | 236 |
| Crescent Island, WA | adult | - | - | - | - | 57 | 56 | - | - | - | 113 |
| San Francisco Bay, CA | adult | - | - | - | - | - | - | - | 42 | 51 | 93 |
| Crump Lake, OR | adult | - | - | - | - | - | - | - | - | 30 | 30 |
| East Sand Island, OR | chick | 245 | 339 | 390 | 380 | 161 | 202 | 177 | 259 | 197 | 1,515/835 |
| Crescent Island, WA | chick | 61 | 48 | 88 | 201 | 139 | 57 | 190 | 70 | 128 | 537/445 |
| San Francisco Bay, CA | chick | - | - | - | - | - | - | - | 142 | 49 | 191 |
| Potholes Reservoir, WA | chick | - | - | - | - | - | 40 | 115 | - | 112 | 267 |
| Crump Lake, OR | chick | - | - | - | - | - | - | - | 107 | 38 | 145 |
| Copper River Delta, AK | chick | - | - | - | - | - | - | - | - | 42 | 42 |
| Total | | 306 | 387 | 478 | 581 | 89/300 | 397 | 538 | 671 | 702 | 2,052/2,397 |

**Table 2.2.** Colony site locations and years of re-sighting effort for color-banded Caspian terns in the Pacific Coast region of North America during 2002-2010. F = frequent re-sighting (colony visits 3-7 times/week throughout the breeding season), I = infrequent re-sighting (colony visits more than twice during the breeding season), O = opportunistic re-sighting (colony visits once or twice during the breeding season).

| Colony/location | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|
| East Sand Island, OR | F | F | F | F | F | F | F | F | F |
| Crescent Island, WA | F | F | F | F | F | F | F | F | F |
| Port of Bellingham, WA | - | - | - | - | - | - | - | O | I |
| Dungeness Spit, WA | - | - | F | F | - | - | I | I | I |
| San Francisco Bay, CA* | - | F | F | F | - | - | F | F | I |
| Potholes Reservoir, WA | - | - | - | - | - | - | - | - | F |
| Summer Lake, OR** | - | - | - | - | - | - | - | F | F |
| Crump Lake, OR | - | - | - | - | - | - | F | F | F |
| Lower Klamath Lake, CA | - | - | - | - | - | - | - | - | F |
| Copper River Delta, AK | - | - | - | - | - | - | - | O | O |
| Icy Bay, AK | - | - | - | - | - | - | - | - | O |
| Salton Sea, CA | - | - | - | - | - | - | - | - | O |

* Banded individuals were re-sighted at two separate colonies at Brooks Island and at Eden Landing in San Francisco Bay, California.

** Banded individuals were re-sighted at two separate colonies at East Link Impoundment and at Dutchy Lake in Summer Lake Wildlife Area, Oregon.

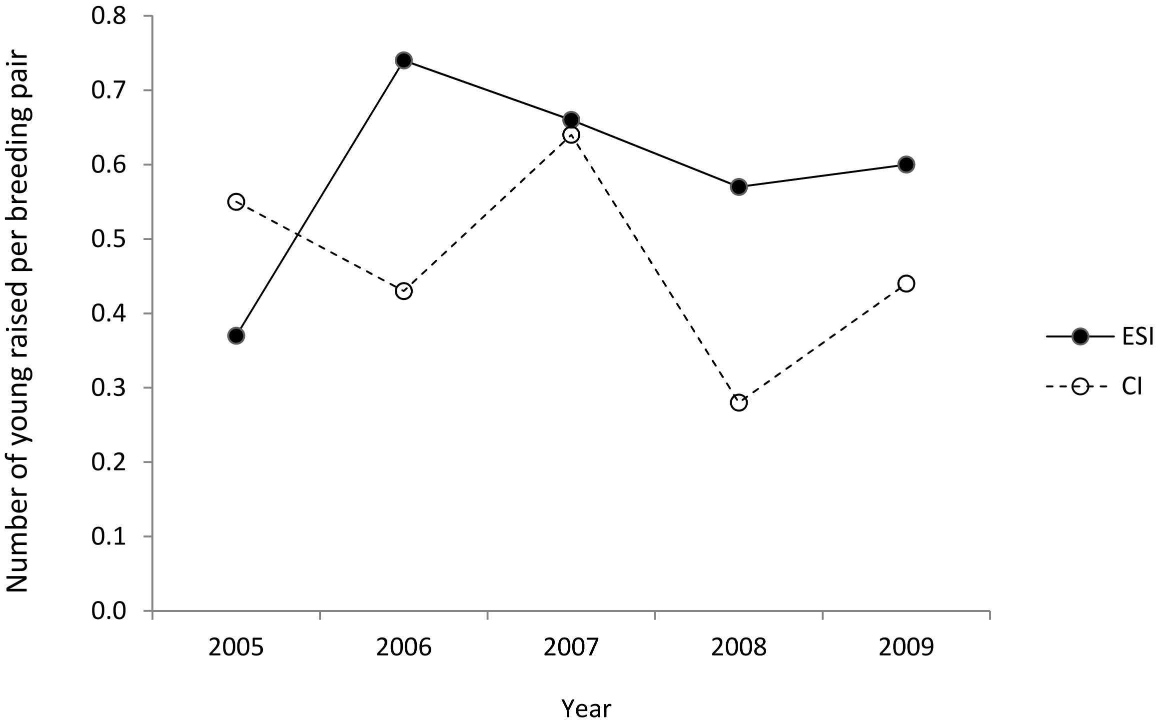

**Figure 2.2.** Annual productivity (average number of young raised per breeding pair) of Caspian terns nesting at East Sand Island (ESI, dark circle) and Crescent Island (CI, open circle) in 2005-2009.

**Table 2.3.** Model selection results for the top 10 models relating apparent survival (ϕ), re-sighting (p), and movement (Ψ) probabilities of Caspian terns banded as breeding adults to the effects of colony (c) (East Sand Island, Oregon or Crescent Island, Washington), year (t), and annual productivity (prod) during 2005 – 2010. Models were ranked according to Akaike's Information Criterion, adjusted for small sample size and over-dispersion ($\hat{c}$ = 1.444; QAICc). Model deviance, number of parameters (*k*), ΔQAICc, and QAICc weights are also included. Additive effects are denoted as "+" and interactive effects as "*". The intercept-only model (.) and global model (c*t) are included for comparison.

| Model number | Model | QAICc | ΔQAICc | QAICc Weights | Model Likelihood | *k* | Deviance |
|---|---|---|---|---|---|---|---|
| 1 | ϕ (.) p (c) Ψ (c) | 702.1861 | 0.0000 | 0.1784 | 1.0000 | 5 | 123.6249 |
| 2 | ϕ (.) p (c) Ψ (c+prod) | 702.8461 | 0.6600 | 0.1283 | 0.7189 | 6 | 122.2598 |
| 3 | ϕ (c) p (c) Ψ (c) | 702.9805 | 0.7944 | 0.1199 | 0.6722 | 6 | 122.3942 |
| 4 | ϕ (.) p (c) Ψ (prod) | 703.5590 | 1.3729 | 0.0898 | 0.5034 | 5 | 124.9978 |
| 5 | ϕ (c) p (.) Ψ (c) | 703.6718 | 1.4857 | 0.0849 | 0.4757 | 5 | 125.1106 |
| 6 | ϕ (c) p (c) Ψ (c+prod) | 703.6784 | 1.4923 | 0.0846 | 0.4742 | 7 | 121.0628 |
| 7 | ϕ (c) p (c) Ψ (prod) | 704.3996 | 2.2135 | 0.0590 | 0.3307 | 6 | 123.8133 |
| 8 | ϕ (c) p (.) Ψ (c+prod) | 704.5781 | 2.3920 | 0.0540 | 0.3024 | 6 | 123.9918 |
| 9 | ϕ (.) p (c) Ψ (c*prod) | 704.8755 | 2.6894 | 0.0465 | 0.2606 | 7 | 122.2598 |
| 10 | ϕ (c) p (.) Ψ (prod) | 705.4365 | 3.2504 | 0.0351 | 0.1969 | 5 | 126.8753 |
| 19 | ϕ (.) p (.) Ψ (.) | 709.5148 | 7.3287 | 0.0046 | 0.0256 | 3 | 134.9912 |
| 35 | ϕ (c*t) p (c*t) Ψ (c*t) | 736.1629 | 33.9768 | 0.0000 | 0.0000 | 28 | 109.9293 |

**Table 2.4.** Model-averaged estimates of survival ($\phi$), re-sighting (p), and movement ($\Psi$) probabilities for Caspian terns banded as breeding adults during 2005-2010 at the East Sand Island (ESI) and Crescent Island (CI) colonies. Annual productivity is expressed as average number of young raised per breeding pair.

| Parameter | Estimate | SE | 95% CI | |
|---|---|---|---|---|
| | | | Lower | Upper |
| $\phi$ (ESI) | 0.9530 | 0.0117 | 0.9241 | 0.9712 |
| $\phi$ (CI) | 0.9401 | 0.0158 | 0.9007 | 0.9645 |
| p (ESI) | 0.9214 | 0.0164 | 0.8826 | 0.9481 |
| p (CI) | 0.8825 | 0.0246 | 0.8250 | 0.9228 |
| $\Psi$ (from ESI to CI: productivity at ESI = 0.37) | 0.0031 | 0.0070 | -0.0106 | 0.0168 |
| $\Psi$ (from ESI to CI: productivity at ESI = 0.74) | 0.0003 | 0.0017 | -0.0031 | 0.0037 |
| $\Psi$ (from ESI to CI: productivity at ESI = 0.66) | 0.0004 | 0.0014 | -0.0023 | 0.0031 |
| $\Psi$ (from ESI to CI: productivity at ESI = 0.57) | 0.0007 | 0.0018 | -0.0030 | 0.0043 |
| $\Psi$ (from ESI to CI: productivity at ESI = 0.60) | 0.0005 | 0.0016 | -0.0026 | 0.0037 |
| $\Psi$ (from CI to ESI: productivity at CI = 0.55) | 0.0096 | 0.0083 | -0.0067 | 0.0258 |
| $\Psi$ (from CI to ESI: productivity at CI = 0.43) | 0.0144 | 0.0090 | 0.0042 | 0.0484 |
| $\Psi$ (from CI to ESI: productivity at CI = 0.64) | 0.0082 | 0.0085 | -0.0086 | 0.0249 |
| $\Psi$ (from CI to ESI: productivity at CI = 0.28) | 0.0256 | 0.0203 | 0.0053 | 0.1148 |
| $\Psi$ (from CI to ESI: productivity at CI = 0.44) | 0.0134 | 0.0083 | 0.0039 | 0.0446 |

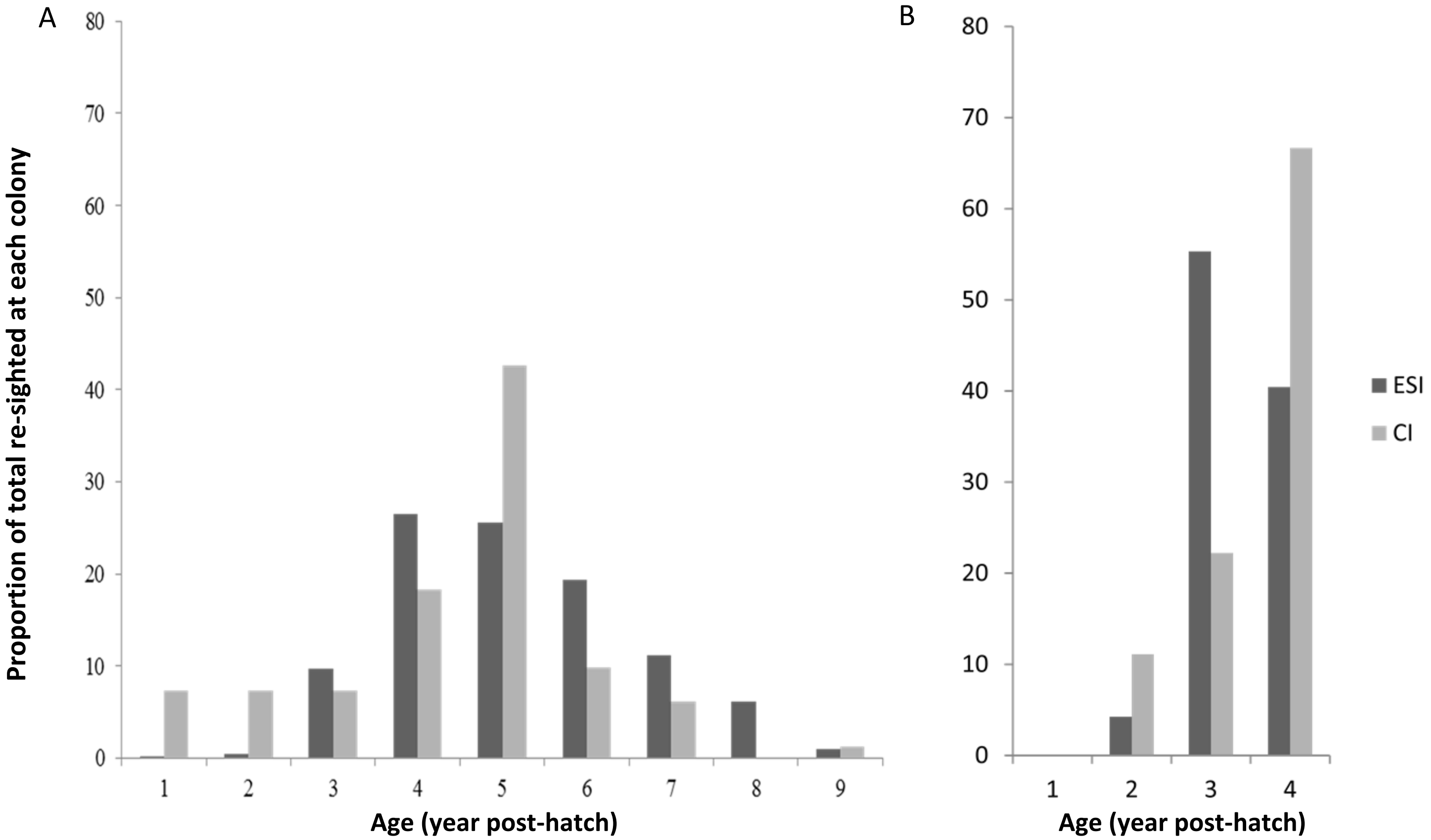

**Figure 2.3.** Age at first known post-fledging visit to the natal colony for Caspian terns in the Pacific Coast region of North America, East Sand Island (ESI) and Crescent Island (CI). Terns banded with five color bands during 2001-2005 (ESI: n = 505, CI: n = 82) and alphanumeric bands during 2006-2009 (ESI: n = 47, CI: n = 9) are shown in figures A and B, respectively.

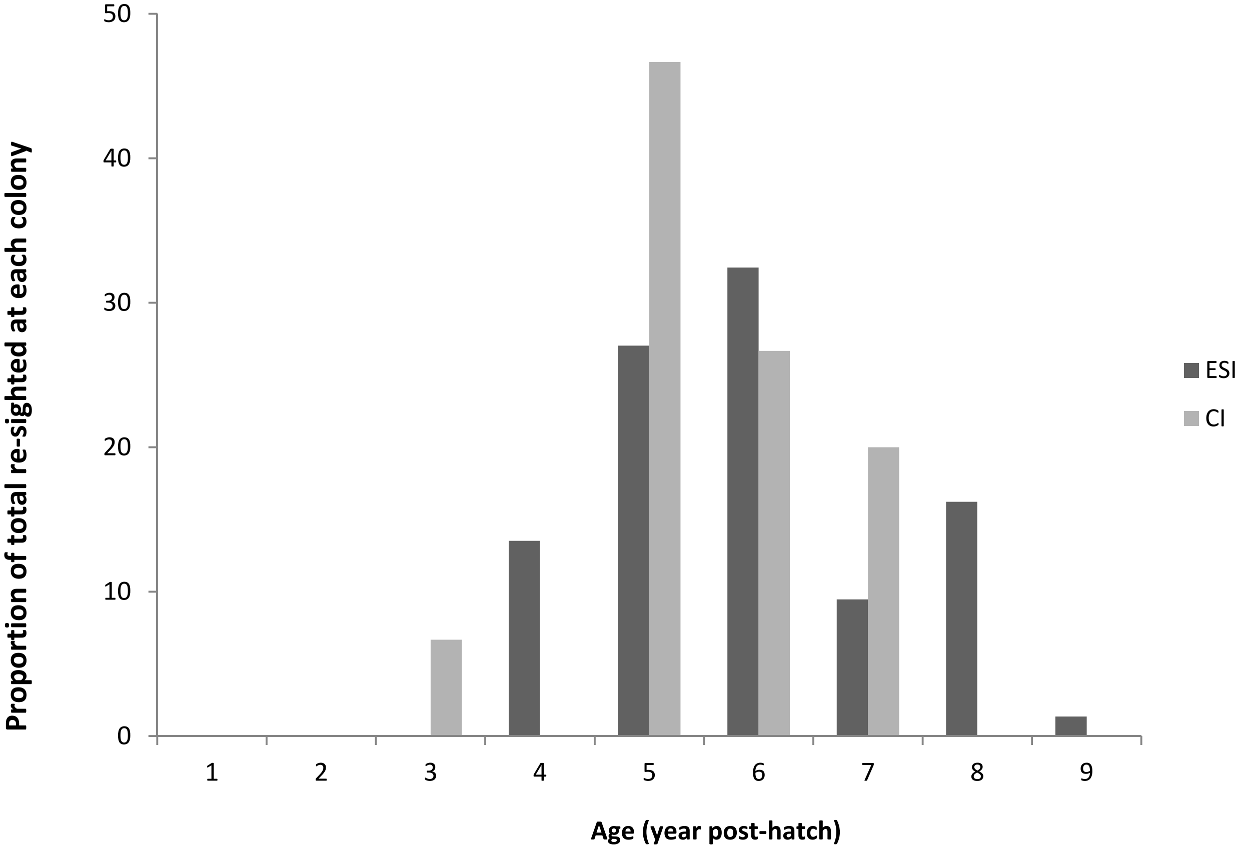

**Figure 2.4.** Age at first reproduction for Caspian terns at their natal colony in the Pacific Coast region of North America, East Sand Island (ESI; n = 74) and Crescent Island (CI; n = 15). Terns were banded with five color bands during 2001-2005.

**Table 2.5.** Caspian terns banded with five color bands as chicks at East Sand Island (ESI, n = 1,515) and Crescent Island (CI, n = 537) during 2001-2005 and confirmed breeding for the first time. Distances between ESI or CI and other colonies are straight-line.

| Colony/location of first confirmed breeding | Distance from natal colony (km) | | Number of terns confirmed breeding for the first time | |
|---|---|---|---|---|
| | ESI | CI | ESI | CI |
| East Sand Island, OR | 0 | 389 | 79 | 4 |
| Crescent Island, WA | 389 | 0 | 1 | 17 |
| Port of Bellingham, WA | 298 | 399 | 4 | 1 |
| Dungeness Spit, WA | 222 | 393 | 0 | 0 |
| San Francisco Bay, CA | 939 | 953 | 1 | 0 |
| Potholes Reservoir, WA | 366 | 103 | 2 | 12 |
| Crump Lake, OR | 551 | 429 | 1 | 2 |
| Summer Lake, OR | 446 | 377 | 1 | 0 |
| Lower Klamath Lake, CA | 507 | 512 | 1 | 1 |
| Copper River Delta, AK | 2,083 | 2,328 | 0 | 0 |
| Icy Bay, AK | 1,905 | 2,136 | 2 | 0 |
| Salton Sea, CA | 1,617 | 1,461 | 1 | 0 |
| Total | | | 93 | 37 |

**Table 2.6.** Caspian terns banded as breeding adults at East Sand Island (ESI) during 2005-2009 (n = 236) and re-sighted at least once at another colony in subsequent breeding seasons. Distances between ESI and other colonies are straight-line.

| Colony where re-sighted | Distance from ESI (km) | Year when re-sighted | | | | | Total |
|---|---|---|---|---|---|---|---|
| | | 2006 | 2007 | 2008 | 2009 | 2010 | |
| Crescent Island, WA | 389 | 0 | 0 | 0 | 0 | 0 | 0 |
| Port of Bellingham, WA | 298 | - | - | - | 0 | 9 | 9 |
| Dungeness Spit, WA | 222 | 0 | 0 | 1 | 1 | 0 | 2 |
| San Francisco Bay, CA | 939 | - | - | 0 | 0 | 0 | 0 |
| Potholes Reservoir, WA | 366 | - | - | - | - | 0 | 0 |
| Crump Lake, OR | 551 | - | - | 1 | 0 | 1 | 2 |
| Summer Lake, OR | 446 | - | - | - | 0 | 0 | 0 |
| Lower Klamath, CA | 507 | - | - | - | - | 1 | 1 |
| Copper River Delta, AK | 2,083 | - | - | 0 | 1 | 0 | 1 |
| Icy Bay, AK | 1,905 | - | - | - | - | 0 | 0 |
| Salton Sea, CA | 1,617 | - | - | - | - | 3 | 3 |
| Total | | 0 | 0 | 2 | 2 | 14 | 18 |

Individuals re-sighted at the same colony for more than one year were counted only in the first year.

**Table 2.7.** Caspian terns banded as breeding adults at Crescent Island (CI) during 2005-2009 (n = 113) and re-sighted at least once at another colony in subsequent breeding seasons. Distances between CI and other colonies are straight-line.

| Colony where re-sighted | Distance from CI (km) | Year when re-sighted | | | | | Total |
|---|---|---|---|---|---|---|---|
| | | 2006 | 2007 | 2008 | 2009 | 2010 | |
| East Sand Island, OR | 389 | 0 | 4 | 0 | 2 | 1 | 7 |
| Port of Bellingham, WA | 399 | - | - | - | 0 | 0 | 0 |
| Dungeness Spit, WA | 393 | - | - | 0 | 0 | 0 | 0 |
| San Francisco Bay, CA | 953 | - | - | 0 | 0 | 0 | 0 |
| Potholes Reservoir, WA | 103 | - | - | - | - | 7 | 7 |
| Crump Lake, OR | 429 | - | - | 3 | 0 | 0 | 3 |
| Summer Lake, OR | 377 | - | - | - | 0 | 0 | 0 |
| Lower Klamath, CA | 512 | - | - | - | - | 0 | 0 |
| Copper River Delta, AK | 2,328 | - | - | 0 | 0 | 0 | 0 |
| Icy Bay, AK | 2,136 | - | - | - | - | 0 | 0 |
| Salton Sea, CA | 1,461 | - | - | - | - | 1 | 1 |
| Total | | 0 | 4 | 3 | 2 | 9 | 18 |

Individuals re-sighted at the same colony for more than one year were counted only in the first year.

**Table 2.8.** Number of color-banded Caspian terns re-sighted at newly constructed islands for Caspian terns at Crump Lake and Summer Lake, Oregon, and at Lower Klamath NWR, California. Some individuals were re-sighted at multiple islands.

| Colony where banded | Age when banded | Total number banded | Location Re-sighted | | | Total |
|---|---|---|---|---|---|---|
| | | | Crump Lake (2008-2010) | Summer Lake (2009, 2010) | Lower Klamath (2010) | |
| East Sand Island, OR | Adult | 236 | 2 | 0 | 1 | 3 |
| | Chick | 835 | 6 | 1 | 4 | 11 |
| Crescent Island, WA | Adult | 113 | 3 | 0 | 0 | 3 |
| | Chick | 445 | 3 | 2 | 4 | 9 |
| Potholes Reservoir, WA | Chick | 267 | 5 | 0 | 0 | 5 |
| Crump Lake, OR | Adult* | 30 | 0 | 1 | 9 | 10 |
| Total | | | 19 | 4 | 18 | 41 |

* Adults were banded at the Crump Lake colony in the second year of the newly formed colony in 2009, and re-sighted on the newly formed colonies either at Summer Lake or Lower Klamath NWR in 2010.

# CHAPTER 3

# FACTORS AFFECTING CONTAMINANT BURDENS IN FISH-EATING BIRDS AND THEIR PREY IN A MAJOR NORTH AMERICAN ESTUARY: PCBs IN THE COLUMBIA RIVER ESTUARY

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S. Kim Nelson, and Donald E. Lyons

## ABSTRACT

Persistent organic pollutants in river estuaries are a potential threat to piscivorous colonial waterbirds that forage and breed in these highly productive habitats. We measured levels of polychlorinated biphenyls (PCBs) in eggs and chicks of two piscivorous waterbird species, Caspian terns (*Hydroprogne caspia*) and double-crested cormorants **(***Phalacrocorax auritus*), that nest in large numbers in the lower Columbia River estuary. For comparison purposes, samples were also collected at colonies in the upper Columbia River estuary and far up-river on the mid-Columbia River, as well as for the primary prey fish types consumed at these colonies. PCB levels in cormorant eggs from a colony in the upper estuary were higher than those of either cormorant or tern eggs from other colonies. PCB levels in cormorant chick livers from the upper estuary, as well as tern chick livers from the mid-Columbia River, were higher than those of either cormorant or tern chick livers from other colonies. Based on differences in cormorant and tern diet composition, as determined by conventional stomach contents analysis, bill load observations, and stable isotope ratios for carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N), higher PCB levels in eggs and chick livers were associated with diets dominated by resident freshwater and estuarine fishes. PCB levels in prey fish were positively correlated with lipid content; however, PCB levels in chick livers were negatively correlated with chick fat scores, suggesting that chick fat reserves are a sink for ingested PCBs. Lower PCB levels in terns and cormorants from colonies near the mouth of the Columbia River, compared to colonies farther up-river, reflected

diets with a higher proportion of marine forage fishes, which had lower average levels of PCBs than freshwater and estuarine resident fish species.

## INTRODUCTION

Estuaries, where fresh and marine waters mix to create biologically productive ecosystems, often receive chemical contaminants from various sources throughout the watershed (Kennish 2002). Potential adverse effects of chemical contaminants in fish and piscivorous avian species have been reported in estuaries in the U.S. and elsewhere (García-Hernández et al. 2001, Connell et al. 2002, Matz and Parsons 2002, Harris et al. 2005, Ackerman et al. 2008). Concentration and accumulation of persistent organic pollutants in river estuaries is a potential threat to large numbers of piscivorous colonial waterbirds that breed and roost in these habitats. In the Columbia River basin, contaminants enter the river system from a variety of point and non-point sources throughout the basin, an area roughly the size of France (670,800 km$^2$). Sources of contaminants include industrial discharge, agricultural run-off, and run-off from urbanized areas. The Water Quality Program Report of the Lower Columbia River described contamination of river water with 20 organic compounds (Fuhrer et al. 1996). Repeated channel dredging operations have been conducted in the lower Columbia River and estuary to allow for large ship traffic to reach the Port of Portland, Oregon, and contaminated sediments may be repeatedly released and re-suspended in the water column, followed by incorporation in biological tissues (U.S. Army Corps of Engineers 2000). The Columbia River has been designated as one of the national priorities for cleanup of contaminated sediments and reducing contaminant concentrations in water and fish by the U.S. Environmental Protection Agency (USEPA) in its Strategic Plan (USEPA 2009a).

The accumulation of polychlorinated biphenyls (PCBs), one of the major classes of persistent organic compounds, has been widely reported in sediments, fish, and waterbirds in estuarine systems (Toschik et al. 2005, Johnson et al. 2007a, Asheley et al. 2009, Herring et al. 2009). Drouillard et al. (2006) demonstrated a spatial gradient in PCB concentrations (higher concentrations down-river compared to up-river) in sediments from the Detroit River, probably due to transport of PCBs from upstream sources by river flow and the accumulation of contaminated sediments deposited downriver. In the Columbia River basin, industrial spills, improper disposal, and other pathways have been identified as sources of PCBs (USEPA 2009b). Studies of avian piscivores in the Columbia River basin have described exposure to PCBs at a number of locations (Thomas and Anthony 1999, Elliott et al. 1998, Henny et al. 2008). Elliot et al. (2000) reported higher levels of PCBs and other persistent organic pollutants in osprey (*Pandion haliaetus*) eggs from the lower Columbia River compared to the upper Columbia River. Anthony et al. (1993) also reported high levels of PCBs and other pollutants in bald eagles (*Haliaeetus leucocephalus*) nesting in the Columbia River estuary, although this species is not entirely piscivorous and also feeds on piscivorous waterbirds. Bald eagle nesting success was lower in the estuary, where levels of contaminants were higher, compared with the upper Columbia River (Buck et al. 2005).

Caspian terns (*Hydroprogne caspia*) and double-crested cormorants (*Phalacrocorax auritus*) are two piscivorous colonial waterbirds that nest in large numbers in the lower Columbia River estuary; the largest known breeding colonies for these two species are currently located on East Sand Island near the mouth of the Columbia River (Suryan et al. 2004, Adkins et al. 2010). Differences in levels of persistent organic contaminants between these two species nesting in the lower Columbia River estuary and factors influencing the accumulation of these contaminants have not been studied. We measured PCB levels in both Caspian terns and double-crested cormorants, as well as in their primary prey fish from the lower estuary. For comparison purposes, PCB levels in these two avian species and their prey were measured at other locations where these species nest farther up the Columbia River. Both eggs and chick livers were collected at different breeding colonies for analysis of PCB levels to investigate the effects of diet composition and stage of the breeding season on PCB burdens in different stretches of the river.

To determine which factors might be contributing to differences in PCB levels between bird species and among colony locations, we evaluated PCB levels in relation to diet composition (based on conventional stomach content analysis for cormorants and bill load observations for terns) and prey sources (determined from stable isotope ratios for carbon and nitrogen). By evaluating stable isotope signatures in the samples of Caspian terns and double-crested cormorants, as well as in their primary prey fish types, prey sources in different bird groups can be inferred. Carbon stable isotope ratios ($\delta^{13}C$) represent a gradient between freshwater and marine environments, whereas nitrogen stable isotope ratios ($\delta^{15}N$) represent trophic levels (Kelly 2000). $\delta^{15}N$ values also represent spatial gradients in rivers (lower $\delta^{15}N$ in upstream). We also evaluated lipid content of prey fish and body condition of chicks (based on fat scores) as potential factors contributing to PCB accumulation.

Results from this study will test the hypotheses that (1) PCB levels of piscivorous waterbirds from the lower estuary are higher than at other breeding colonies farther up the Columbia River and (2) PCB levels would be higher in cormorants compared to terns. We predicted that PCB levels would be higher in Caspian terns and double-crested cormorants nesting in the lower estuary, compared to their counterparts nesting in the upper estuary or the mid-Columbia River, based on the assumption that contaminants from numerous sources throughout the Columbia River basin would become concentrated and accumulate in the estuary. We also predicted that PCB levels would be higher in cormorants compared to terns because cormorants are pursuit-divers that regularly prey on benthic fishes, whereas terns are plunge-divers that can only access prey at or near the surface.

The study will also provide insights into factors contributing to the bioaccumulation of PCBs in piscivorous birds and their prey from the Columbia River basin. The levels of PCBs in terns and cormorants nesting in the lower estuary, and whether levels are high enough to pose a risk of adverse effects, also provides an evaluation of the lower estuary as nesting habitat for such a large proportion of the regional breeding populations for these two species of piscivorous waterbirds.

## METHODS

### Study Area

We collected eggs and chicks of Caspian terns and double-crested cormorants at breeding colonies in the lower Columbia River estuary, the upper Columbia River estuary, and the mid-Columbia River (Figure 3.1). Eggs and chicks collected in the lower estuary were from the very large breeding colonies of Caspian terns and double-crested cormorants on East Sand Island, located 8 km upstream of the mouth of the river. The Caspian tern colony at East Sand Island is currently the largest known breeding colony for the species in the world, consisting of about 9,500 breeding pairs during our study. The double-crested cormorant colony on the same island, which is also the largest known colony for the species, consisted of an average of about 12,000 breeding pairs over the same period.

Cormorant eggs and chicks were also collected from a breeding colony on channel markers adjacent to Miller Sands in the upper part of the Columbia River estuary (referred to hereafter as the “upper estuary”), located 34-40 km upstream from the mouth of the river. The total number of cormorants nesting on eight channel markers near Miller Sands in the upper estuary was approximately 170 breeding pairs during our study. No Caspian terns nested in the upper Columbia River estuary during the study period. On the mid-Columbia River, just below the confluence with the Snake River, Caspian terns and double-crested cormorants nested at Crescent Island and Foundation Island, respectively, in much smaller breeding colonies compared to those on East Sand Island in the lower estuary. During our study, an average of about 450 breeding pairs of Caspian terns nested at Crescent Island, and about 300 breeding pairs of double-crested cormorants nested at Foundation Island. These two islands in the mid-Columbia River are about 9 km apart and approximately 520-530 km upstream from the mouth of the Columbia River.

### Sample Collection

Eggs of Caspian terns and double-crested cormorants were collected during the early part of the incubation period in 2009. Fifteen eggs of each species were collected at each colony, only one egg from each nest, and eggs were collected only from nests containing more than one egg to avoid causing breeding pairs to abandon their nests. Once collected, eggs were kept cool in the field until they were brought back to field stations. At the field stations, eggs were broken open and contents were visually inspected to estimate development stage. All eggs were relatively fresh, apparently within 10 days of the initiation of incubation. Egg contents were homogenized in a blender, divided into separate aliquots for PCB and stable isotope analyses, and stored frozen at -20ºC until analysis. Aliquots of egg homogenates were stored in EPA certified glass jars for PCB analysis and in plastic vials for stable isotope analysis.

Fifteen chicks per bird species per breeding colony were collected between the ages of three and six weeks post-hatch during the 2002 breeding season. Caspian tern chicks were collected after herding them into a pen at the edge of the colony during banding operations; consequently, we were unable to verify that collected chicks were from different nests, although the chance of collecting more than one chick from the same nest was very small. Only one chick per nest was collected from double-crested cormorant nests. Chicks were euthanized with either an overdose of isoflurane or by cervical dislocation. Carcasses were frozen within 3 hours of collection and stored frozen until dissection. Once dissected, whole liver samples were wrapped in aluminum foil, placed in Whirl-Pak bags, and stored frozen at -20ºC until sample preparation for PCB analysis.

Samples consisting of two to four whole breast feathers (contour feathers) were also collected from the same individual chicks for stable isotope analysis. Feathers were collected for stable isotope analysis instead of liver because liver tissue has a high turnover rate and provides information on diet only over the recent past (Hobson and Clark 1992); therefore, stable isotope ratios from liver may not reflect diet over the entire chick development period when PCBs were accumulating in the chick's body. Body condition of chicks was evaluated during dissection based on visual estimation of the amount of subcutaneous adipose tissue. Fat scores of between 1 and 5 (1 = little to no visible fat; 5 = very fat) were assigned to each chick (Table 3.1).

Specimens of the primary types of prey fish consumed by Caspian terns and double-crested cormorants were collected in the Columbia River estuary during 2002-2008 and in the mid-Columbia River during 2007. Primary types of prey fish were selected from among those families of prey fish that comprised at least 10% of either prey biomass or prey items in the diets of Caspian terns and double-crested cormorants in the estuary and the mid-Columbia River, as reported in previous studies (Collis et al. 2002, Antolos et al. 2004, Collis et al. 2006). In the estuary, fish samples were collected within 40 km of East Sand Island, which includes the area where cormorants nest on channel markers near Miller Sands in the upper estuary. In the mid-Columbia River, samples were collected within 60 km of Crescent and Foundation islands.

Fish samples from the estuary and the mid-Columbia River were obtained from six different sources. Samples of primary prey fish types from the estuary were collected in one of three ways: (1) spring Chinook salmon (*Oncorhynchus tshawytscha*) smolts, northern anchovy (*Engraulis mordax*), juvenile Pacific herring (*Clupea pallasi*), and surfperch (*Embiotocidae*) were obtained by lethally collecting adult Caspian terns (whole fish are carried in the bill of terns flying back to the breeding colony); (2) additional surfperch were retrieved from the foreguts of lethally-collected cormorants at East Sand Island; and (3) peamouth (*Mylocheilus caurinus*) were beach-seined in the upper estuary. Samples of primary prey fish types from the mid-Columbia River were also collected in one of three ways: (1) steelhead (*Oncorhynchus mykiss*) smolts were collected at Lower Monumental and Ice Harbor dams on the lower Snake River; (2) spring Chinook smolts were collected at McNary Dam on the mid-Columbia River; and (3) smallmouth bass (*Micropterus dolomieu*) and peamouth were collected from the mid-Columbia River. The fork length of collected fish ranged from 80 mm to 221 mm, within the range of prey sizes utilized by both Caspian terns and double-crested cormorants. Whole fish were placed in Whirl-Pak bags and kept frozen at -20ºC until sample preparation for analysis.

Summaries of the samples collected from birds and fish are presented in Table 3.2 and Table 3.3, respectively.

### PCB Analysis

Samples of bird eggs, chick livers, and fish were analyzed for PCB concentrations at Mississippi State Chemistry Lab (MSCL). At MSCL, five collected specimens per species per location were pooled and homogenized to create three composite samples for chick liver and three composite samples for prey fish types collected during 2000-2003 (anchovy, Pacific herring, and surfperch). For prey fish types collected during 2004-2008 (spring Chinook salmon smolts, steelhead smolts, peamouth, and smallmouth bass), two or three specimens per species per location were pooled to make five composite samples. Three bird eggs were pooled and homogenized at Oregon State University to make five composite samples per species per colony prior to shipping to MSCL for analysis. Pooling samples to make composites and using relatively small numbers of composites for contaminant analyses is a common practice in published studies (Braune et al. 2001, Elliott 2005).

For chick livers and fish collected during 2000-2003, concentrations of 48 PCB congeners were measured. Of these 48, the 19 congeners with the highest concentrations in chick liver samples were selected for analysis in egg and fish samples. The 19 PCB congeners analyzed in this study were 99, 101, 105, 110, 118, 123, 128, 138, 149, 153, 156, 157, 158, 170, 177, 180, 183, 187, and 206. Five of the congeners (105, 118, 123, 156, and 157) are mono-ortho coplanar PCBs, which fall into a group of 12 congeners known to have higher toxicity (dioxin-like toxicity) compared to other congeners. All samples were prepared for PCB analysis (EPA method 3545) and analyzed using capillary gas chromatography (EPA method 3620B) at MSCL. All PCB concentrations presented in this study are expressed on a wet weight basis. Quality control for PCB analysis was assured through duplicate, spike, and % recovery of submitted samples or internal standards. Minimum detection limit was 0.1 ppb. Percent lipid of each sample or composite was also measured at MSCL.

### Diet Composition

The diet composition of Caspian terns and double-crested cormorants was estimated by a combination of non-destructive and destructive sampling methods. Because adult Caspian terns carry fish in their bill to feed their mates and chicks on the breeding colony (referred to hereafter as “bill loads”), the identification of fish to the taxonomic level of family or, whenever possible, to the level of species was conducted by visual observation of bill loads at the nesting colonies. Double-crested cormorants, unlike terns, transport captured fish back to the breeding colony in their foregut. Consequently, cormorants were lethally collected to estimate diet composition based on the foregut contents of adults. Diet samples regurgitated by cormorant chicks during routine handling were also included in some of the diet composition analysis.

The diet composition of Caspian tern chicks was based on the taxonomic composition of bill loads that were delivered to chicks. For cormorants, because adults regurgitate semi-digested fish to chicks, diet composition was estimated from analysis of adult foregut contents during the chick-rearing period and from chick regurgitations. Diet composition was calculated as % of total prey biomass (Collis et al. 2002). For Caspian terns nesting at East Sand Island and Crescent Island, diet composition was based on bill load data collected during the chick-rearing period in 2002 and during the pre-egg laying period in 2009. For double-crested cormorants nesting at East Sand Island, diet composition was based on analyses of adult foregut contents during the 2002 chick-rearing period, and analysis of adult foregut contents during the 2009 pre-egg laying period. Diet composition data for cormorants nesting in the upper Columbia River estuary (Miller Sands channel markers) were not collected during the study period; instead, diet composition data collected during 1997-1998 were used. Diet data for cormorants nesting on Foundation Island were based on foregut contents samples collected during 2005-2010 and pooled because samples of foregut contents were not collected in 2002 and the sample size of foregut contents collected in 2009 was not sufficient to estimate % biomass of prey types in the diet.

### Stable Isotope Analyses

Breast feathers from five to 15 chicks per species per location (the same individuals analyzed for PCBs in liver) were used for analysis of stable isotope ratios in tern and cormorant chicks. The same bird egg and fish samples collected during 2004-2007 and analyzed for PCBs were also analyzed for stable isotopes. Because fish collected during 2000-2003 and analyzed for PCBs were not available for stable isotope analysis, seven specimens per species of northern anchovy, Pacific herring, and surfperch collected during 2007-2008 were analyzed for stable isotopes. Fish samples were either homogenized whole fish or lateral muscle. Fish samples used in this study that consisted solely of lateral muscle were analyzed as part of a separate study of stable isotope ratios in prey fish.

Prior to stable isotope analysis, breast feathers were soaked in and rinsed with 2:1 chloroform:methanol solvent for cleaning and dried under a fume hood. Egg and fish samples were freeze-dried, soaked in 2:1 chloroform:methanol to extract total lipids, dried under a fume hood, and ground into a fine powder using either an analytical mill or a mortar and pestle. Aliquots of each sample were weighed out to 1.0 ± 0.1 mg and loaded into a tin capsule.

Analyses of stable isotope ratios for carbon and nitrogen were performed at the University of Saskatchewan, Saskatoon, Canada. Capsules loaded with sample were combusted using a Eurovector 3000 elemental analyzer, and the resultant $CO_2$ and $N_2$ gases were separated by gas chromatography and introduced into a Nu Horizon triple-collector isotope ratio mass-spectrometer. The abundances of stable isotopes were expressed in delta ($\delta$) notation as the deviation from standards in parts per thousand (‰) according to the equation:

$$\delta X = [(R_{\mathrm{sample}}/R_{\mathrm{standard}})-1] \times 1000,$$

where $X$ is $^{13}C$ or $^{15}N$ and $R$ is the corresponding ratio of $^{13}C/^{12}C$ or $^{15}N/^{14}N$. Standard values were based on the Vienna PeeDee Belemnite for $^{13}C$ and atmospheric $N_2$ for $^{15}N$. Within-run replicate measurements of internal laboratory standards (egg albumen, pugel) indicated measurement errors within 0.1‰ and 0.2 ‰ for $\delta^{13}C$ and $\delta^{15}N$ measurements, respectively.

In order to evaluate prey sources of the piscivorous waterbirds during the pre-egg laying and chick-rearing periods, stable isotope ratios in eggs and chick breast feathers were corrected with discrimination factors so that it was possible to directly compare these values to stable isotope ratios of their respective prey fish types contributing to these tissues. Diet-bird egg discrimination factors ($\Delta\delta^{13}C$: -0.37‰, $\Delta\delta^{15}N$: 1.09‰; Hobson and Becker, unpubl. data on captive common terns) and diet-bird feather discrimination factors ($\Delta\delta^{13}C$: 0.00‰, $\Delta\delta^{15}N$: 4.20‰; Cherel et al. 2005) were applied to data in this study.

## Statistical Analysis

I used ANOVA to compare total PCBs for 19 congeners (hereafter ΣPCB) in eggs from five different bird colonies. I also compared ΣPCB in chick livers from the same five bird colonies, and ΣPCB among several primary prey fish types. Bonferroni adjustments were used to correct for multiple comparisons following ANOVA. For statistical analysis purposes, reported ΣPCB levels that were below minimum detection limits were replaced with a value half the detection limit (0.05 ppb). In an effort to normalize data and to meet assumptions of equal variance, ΣPCB values were log-transformed prior to analysis using the formula log (ΣPCB +1), then back-transformed. ΣPCB levels presented in this study are geometric means.

Stable isotope ratios for carbon and nitrogen in eggs and chick breast feathers from the five bird colonies, and among the prey fish types were evaluated separately using ANOVA, followed by multiple comparisons. Relationships between ΣPCB and % lipid (in fish only) or fat score (in chicks) were analyzed using general linear regression. A t-test was performed when additional comparisons between two sample types were considered appropriate. All statistical analyses were performed using SAS 9.2 (SAS Institute 2009) and $\alpha$ was set at 0.05, except as noted when Bonferroni adjustments were used.

All procedures involving collecting bird eggs, chicks, and fish were performed under scientific collection permits obtained from the U.S. Fish and Wildlife Service (Migratory Bird and Habitat Program, Portland, OR), Oregon Department of Fish and Wildlife (Salem, OR), and Washington Department of Fish and Wildlife (Olympia, WA). All procedures and methods involving live vertebrate subjects followed protocols approved by the Institutional Animal Care and Use Committee at Oregon State University.

## RESULTS

### PCB Body Burdens

There were statistically significant differences in egg ΣPCB levels (hereafter ΣPCB) among the five bird colonies (*F* = 7.84, p = 0.0006, Table 3.4). The highest ΣPCB observed was 1,926 ppb in one of the cormorant egg composites from the upper estuary. The average ΣPCB in cormorant eggs from the upper estuary was higher than that of cormorant eggs from colonies in either the lower estuary (t = -3.25, p = 0.004, α = 0.005 with Bonferroni adjustment; p-values are denoted with * hereafter for the same adjustment) or the mid-Columbia River (t = -4.44, p = 0.0003*). The average ΣPCB in cormorant eggs from the upper estuary was also higher than that of tern eggs from colonies in either the lower estuary (t = -4.29, p = 0.0004*) or the mid-Columbia River (t = -4.90, p < 0.0001*). There was no significant difference in ΣPCB between cormorant eggs and tern eggs from the colonies in the lower estuary or from the colonies on the mid-Columbia River. Within each bird species, ΣPCB was also similar between eggs collected from the lower estuary and those collected from the mid-Columbia River.

ΣPCB in chick livers differed significantly among the five bird colonies (*F* = 38.61, p < 0.0001, Table 3.5). The highest ΣPCB observed in chick livers was 178 ppb in one of the liver composites from Caspian tern chicks on the mid-Columbia River. Average ΣPCB for Caspian tern chick livers was significantly higher at the colony on the mid-Columbia River than at the colony in the lower Columbia River estuary (t = 9.55, p < 0.0001*). ΣPCB for cormorant chick livers was higher at the colony in the upper estuary compared to the colony on the mid-Columbia River (t = -4.54, p = 0.0011*) or the colony in the lower estuary (t = -7.87, p < 0.0001*). In the lower Columbia River estuary, ΣPCB in chick livers was similar between terns and cormorants. At the colonies on the mid-Columbia River, however, ΣPCB for tern chick livers was significantly higher than for cormorant chick livers (t = 5.81, p = 0.0002*). The ΣPCB for cormorant chick livers from the colony in the upper estuary was not different from that of terns from the colony on the mid-Columbia River.

The origin (wild or hatchery) of steelhead and spring Chinook smolts was confirmed by (1) the presence of adipose fins (removed in hatchery-reared smolts), (2) external condition (poor condition in hatchery-reared smolts), and (3) distinct differences in stable isotope signatures, before salmon smolt samples were analyzed for PCBs. None of the 19 PCB congeners measured as part of this study were detected in any of the wild steelhead or wild spring Chinook salmon smolts analyzed, while ΣPCB of hatchery-reared salmon smolts ranged from 11 ppb to 36 ppb. Consequently, wild steelhead and wild spring Chinook salmon smolts were excluded from further analyses involving ΣPCB.

The highest ΣPCB observed in fish prey was 155 ppb in one of the peamouth composites from the estuary. Average ΣPCB was significantly different among the nine remaining fish prey types ($F = 5.26$, $p = 0.0004$, Table 3.6). When fish prey types were grouped based on habitat types, freshwater and estuarine resident fish, such as peamouth, smallmouth bass, and surfperch, had higher average ΣPCB than hatchery-reared juvenile salmonids ($t = 5.51$, $p < 0.0001$**, $\alpha = 0.0167$) or marine fish prey types ($t = 6.57$, $p < 0.0001$**). Average ΣPCB of hatchery-reared salmon smolts and marine forage fish were similar. Average ΣPCB of hatchery-reared spring Chinook salmon from the mid-Columbia River and from the estuary were also similar.

## Diet Composition

The diet of Caspian terns and double-crested cormorants nesting at the five study colonies consisted of a variety of fish species (Figure 3.2A-E and Figure 3.3A-E). During the pre-egg laying period, the diet of terns and cormorants nesting in the estuary consisted of a higher percentage of salmonids (including steelhead and spring Chinook salmon; hatchery-reared and wild fish not distinguished) compared to the chick-rearing period. For terns nesting in the lower estuary, the diet during the chick-rearing period consisted more of marine forage fish compared to the pre-egg laying period. For cormorants nesting in the lower and upper estuary, diet during the chick-rearing period included a more diverse array of prey species, including flounder (Pleuronectidae) and sculpins (Cottidae), compared to the pre-egg laying period. Diet composition of terns and cormorants nesting on the mid-Columbia River did not differ substantially between the pre-egg laying period and the chick-rearing period.

The proportion of the diet that consisted of fish with relatively high ΣPCB (peamouth, smallmouth bass, surfperch) was not especially high at those bird colonies with higher ΣPCB in eggs (i.e., cormorants from the upper estuary) or in chick livers (i.e., tern chicks from the mid-Columbia River and cormorant chicks from the upper estuary). During the pre-egg laying period, the majority of fish in the diet of cormorants nesting in the upper estuary were salmonids, a prey type with relatively low ΣPCB. For tern chicks from the mid-Columbia River, peamouth, smallmouth bass, and their close relatives comprised a total of only 13% of the diet. For cormorant chicks, the total percentage of these two fish prey types in the diet was higher at the colony on the mid-Columbia River (37%) than at the colony in the upper estuary (19%).

## Stable Isotope Analyses

$\delta^{15}N$ and $\delta^{13}C$ values in prey fish types were significantly different among the 11 primary prey types ($\delta^{15}N$: $F = 5.84$, $p < 0.0001$; $\delta^{13}C$: $F = 31.21$, $p < 0.0001$). Mean values for $\delta^{15}N$ in prey fish types ranged from 9.5 to 14.3‰, which may suggest that the prey fish types of terns and cormorants analyzed here represent a range of feeding guilds and/or that the range reflected a spatial gradient in $\delta^{15}N$ along the river (Figure 3.4). The highest values for $\delta^{15}N$ in prey fish types were found in smallmouth bass from the mid-Columbia River, while the lowest $\delta^{15}N$ values were in wild spring Chinook salmon collected from the mid-Columbia River. ΣPCB in wild steelhead and wild spring Chinook salmon were below minimum detection limits, and both exhibited lower $\delta^{15}N$ values compared to most other fish prey types. However, other fish prey types did not exhibit the same positive correlation between $\delta^{15}N$ values and ΣPCB.

Marine species (e.g., anchovy, Pacific herring) had higher $\delta^{13}C$ values compared to freshwater species (e.g., peamouth, smallmouth bass) and estuarine species (e.g., surfperch). Hatchery-reared spring Chinook salmon smolts collected in both the mid-Columbia River and in the estuary, plus hatchery-reared steelhead collected from the mid-Columbia River, had similar $\delta^{13}C$ values to that of marine fish prey types. This is likely attributable to the artificial pelleted food fed to hatchery-reared smolts during rearing, which is largely derived from marine fish meal, similar to commercial feed used for farmed salmon (Easton et al. 2002). $\delta^{13}C$ values in wild steelhead and wild spring Chinook salmon were more similar to that of freshwater and estuarine species than that of marine species and hatchery-reared salmonids. Based on

$\delta^{15}N$ and $\delta^{13}C$ values in fish, the primary prey types of terns and cormorants in the Columbia River can be categorized into three distinct groups: (1) freshwater and estuarine resident species, (2) wild juvenile salmonids, and (3) marine species and hatchery-reared juvenile salmonids. Prey types with higher ΣPCB were all in the group consisting of freshwater and estuarine resident species.

For Caspian tern and cormorant eggs, the difference in $\delta^{15}N$ values among the five bird colonies was significant ($F = 5.68$, $p = 0.0005$), although the range of mean $\delta^{15}N$ values among the colonies was within 1‰ (Figure 3.5). Among cormorant colonies, egg $\delta^{15}N$ values were the lowest in the upper estuary, where egg ΣPCB was the highest among the five colonies.

$\delta^{13}C$ values in tern and cormorant eggs were also significantly different among the five colonies ($F = 25.27$, $p < 0.0001$). $\delta^{13}C$ values in cormorant eggs from the upper estuary colony were lower than at all other bird colonies. In general, carbon and nitrogen stable isotope signatures for each bird species were similar between the lower estuary and mid-Columbia River colonies. The combination of high egg ΣPCB and $\delta^{13}C$ and $\delta^{15}N$ values in cormorant eggs from the upper estuary suggests that the high ΣPCB level was associated with diet dominated by resident freshwater and estuarine fish during the pre-egg laying period.

Overall $\delta^{15}N$ values were lower in chick breast feathers compared to eggs (Figure 3.6). There were significant differences in $\delta^{15}N$ values of chick breast feathers among the five bird colonies ($F = 14.05$, $p < 0.0001$), and the range of mean $\delta^{15}N$ in chick feathers (2.6‰) was greater than in eggs. $\delta^{15}N$ values in chick breast feathers from the Caspian tern colony on the mid-Columbia River, the bird species/colony group with higher ΣPCB in chick liver, was similar to other groups, except cormorants nesting in the same area, which had lower $\delta^{15}N$ values ($t = 5.51$, $p < 0.0001$, $\alpha = 0.005$). $\delta^{15}N$ values in chick breast feathers from cormorants in the upper estuary, the other bird group with higher chick liver ΣPCB, were not significantly higher compared to other groups.

$\delta^{13}C$ values in chick breast feathers were significantly different among bird colonies ($F = 36.03$, $p < 0.0001$). While $\delta^{13}C$ values in eggs for each species were similar between colonies in the lower estuary and the mid-Columbia River, $\delta^{13}C$ values in chick breast feathers were not, suggesting a dietary shift between the pre-egg laying and chick-rearing periods in some bird groups. $\delta^{13}C$ values in breast feathers from Caspian tern chicks at the mid-Columbia River colony were similar to that of eggs whereas $\delta^{13}C$ values in breast feathers from Caspian tern chicks in the estuary were significantly higher ($t = 9.71$, $p < 0.0001$) compared to tern eggs. Cormorant chick feathers from the mid-Columbia River, in contrast, had significantly lower $\delta^{13}C$ values compared to that of eggs ($F = -3.98$, $p = 0.0009$), whereas cormorant chick feathers from the lower estuary had similar $\delta^{13}C$ values to cormorant eggs. $\delta^{13}C$ values in cormorant feathers from the upper estuary colony were the lowest, as were $\delta^{13}C$ values in eggs. The combination of $\delta^{13}C$ and $\delta^{15}N$ values in chick feathers suggests that most of the diet of cormorant chicks nesting at the upper estuary colony consisted of resident freshwater and estuarine fish.

### Lipid Content of Fish and Fat Scores of Chicks

There was a positive correlation between ΣPCB in prey fish types and average lipid content of those fish types (Figure 3.7). The average lipid content of prey fish types that were analyzed for PCBs ranged from 0.9% to 5.7%. The prey fish type with the highest average lipid content was peamouth from the estuary and the fish with the lowest lipid content was wild spring Chinook from the mid-Columbia River. ΣPCB for wild steelhead and wild spring Chinook salmon were below minimum detection limits, and the lipid content of wild steelhead was lower than their hatchery-reared counterparts ($t = -3.46$, $p = 0.0221$), while the lipid content of wild and hatchery-reared spring Chinook was similar.

There was a negative correlation between ΣPCB in chick livers and chick fat scores (Figure 3.8). Fat scores were highest for Caspian tern chicks raised at the colony in the lower estuary and lowest for tern chicks raised at the colony on the mid-Columbia River; cormorant chicks had intermediate fat scores. Tern chicks from the mid-Columbia River and cormorant chicks from the upper estuary, the chicks from colonies that had the higher liver ΣPCB, tended to have low fat scores.

## DISCUSSION

### Differences in PCB Body Burdens

Contrary to our prediction, Caspian terns and double-crested cormorants from the large nesting colonies in the lower Columbia River estuary did not have higher PCB levels in eggs or chicks compared with those from colonies farther up-river. The expected differences in PCB levels between the two bird species were also not observed; cormorants did not have higher PCB levels in eggs or chicks compared to terns nesting nearby. PCB levels in cormorant eggs and chicks from the upper Columbia River estuary, however, were higher than those from either the lower estuary or the mid-Columbia River. Buck et al. (2005) reported higher persistent organic contaminants and lower productivity in bald eagles near the mouth of the Columbia River compared to eagles nesting farther up-river. In our study, PCB concentrations in eggs and chicks of terns and cormorants indicated that in the Columbia River estuary, PCB levels in piscivorous waterbirds are variable among colonies, perhaps reflecting differences in foraging areas and predominant prey types.

Environmental contaminants in fish from the Columbia River have been reported in previous studies (Fresh et al. 2005, Hinck et al. 2006). In our study, freshwater and estuarine resident species had higher PCB levels compared to hatchery-reared salmonids and marine fish species, and especially compared to wild salmonids. These findings suggest that PCBs in fish are derived from residues in the freshwater and estuarine portions of the mainstem. Feed used to raise salmonids in hatcheries contains PCBs and other contaminants (LCREP 2007); however, other studies have indicated that elevated contaminant levels in hatchery-reared salmonids were due more to the relatively high lipid content of hatchery-reared fish, instead of high concentrations of contaminants in feed used at hatcheries (Johnson et al. 2007a, 2007b). PCB levels below minimum detection limits were found in wild juvenile salmonids, both steelhead and spring Chinook. This is likely attributable to lower PCB levels in tributaries compared to the mainstem Columbia River, as well as compared to the diet provided at hatcheries. These findings indicate that wild steelhead and spring Chinook smolts are not a major source of PCB accumulation in piscivorous birds from the Columbia Basin.

Previous studies have reported that nutrient allocation to eggs in some bird species is mainly from exogenous sources, rather than from endogenous reserves deposited on the wintering grounds; thus, contaminants detected in eggs in those species are likely derived from prey consumed near the breeding colony (Hobson et al. 1997 [Caspian terns, double-crested cormorants], Elliot et al. 2007 [ospreys], Bond and Diamond 2010 [arctic terns, *Sterna paradisaea*]). The distance between the two cormorant study colonies in the Columbia River estuary was approximately 30 km. Thus, it is unlikely that cormorants breeding at these two colonies use distinct wintering grounds with different PCB exposure levels that would then be reflected in different PCB levels in eggs. Higher ΣPCB in cormorant eggs from the upper estuary was likely derived from elevated PCB levels in resident freshwater prey fish types captured locally. Caspian tern eggs have a higher lipid content compared to double-crested cormorant eggs because terns develop more precocially than cormorants (Robbins 1993). This indicates that cormorant eggs contained higher levels of PCBs than tern eggs, when expressed on a lipid mass basis.

Surprisingly low proportions of freshwater and estuarine resident fish were observed in the diets of bird colonies with high PCB levels (cormorant eggs and chicks in the upper estuary and tern chicks in the mid-Columbia River), based on conventional diet analysis methods. These findings indicate that differences in diet composition among the five bird colonies, evaluated using bill loads and stomach contents, cannot by themselves explain among-colony differences in PCB levels of eggs or chick livers.

## Factors Contributing to PCB Accumulation

### *Prey Sources*

The combination of carbon and nitrogen stable isotope ratios provided useful information to evaluate differences in PCB levels in piscivorous birds and their prey fish. Stable isotope ratios in prey fish distinguished the three major fish groups, including 1) resident freshwater and estuarine species, 2) marine species and hatchery-reared salmonids, and 3) wild salmonids. These distinct groups of primary prey fish types and $\delta^{13}C$ and $\delta^{15}N$ values in bird egg and chick breast feathers enabled us to infer diet differences among bird groups.

The terns and cormorants in this study had access to different prey resources (freshwater, estuarine, marine, artificial sources), and carbon and nitrogen stable isotope ratios provided some insight into variation in PCB levels. The shift in diet composition between pre-egg laying and chick-rearing was also reflected in the shift in $\delta^{13}C$ and $\delta^{15}N$ values, although not necessarily evident based on conventional diet analysis methods (e.g., cormorants from the mid-Columbia River). This demonstrates the benefits of using both conventional diet analysis methods and stable isotope ratios to evaluate variation in PCB levels of piscivorous birds.

### *Lipid Content of Fish and Fat Scores of Chicks*

Lipid content explained part of the variability in PCB levels among fish, which was expected because of the lipophilic nature of PCBs. Smallmouth bass had higher PCB levels than other fish, except peamouth from the estuary, although bass did not have high lipid content. This suggests that feeding guild or size of prey species may contribute to differences in PCB levels among fish. The high $\delta^{15}N$ values in smallmouth bass supports this interpretation.

Lipophilic compounds, such as PCBs and DDT, are known to be sequestered in fat deposits (Henriksen et al. 1996). When animals lose body fat, PCBs are mobilized and redistributed to other organs, such as brain and liver (Henriksen et al. 1996, Missildine et al. 2005). Weinburg and Shore (2004) reported that PCB concentrations in liver were higher in individuals with lower fat reserves in three different bird species. The negative relationship between PCB concentrations in chick liver and chick fat score is likely explained by the redistribution mechanism of PCBs from fat deposits to liver.

## Risk of Adverse Effects from PCB Accumulation

ΣPCB in eggs of Caspian terns and double-crested cormorants from the Columbia River did not exceed the lowest observable adverse effect level (LOAEL;

4,200 ppb for Caspian tern eggs and 3,500 ppb for double-crested cormorant eggs), which was estimated based on embryo mortality in these two species from the Great Lakes (Tillitt et al. 1992, Yamashita et al. 1992). ΣPCB in all cormorant eggs from the upper estuary and some cormorant eggs from the lower estuary and the mid-Columbia River exceeded the no observable adverse effect levels (NOAEL = LOAEL x $10^{-1}$) reported by Giesy et al. (1994). ΣPCB in all tern eggs were below the NOAEL.

Comparable studies of PCB levels in chick livers of piscivorous birds are scarce; however, Guruge et al. (2000) reported PCB accumulations in nestling and juvenile great cormorants (*P. carbo*) from Japan. Three of the congeners with dioxin-like effects were analyzed both in the present study and in the study by Guruge et al. (2000). The lowest total of these congeners in great cormorant livers collected from colonies in Tokyo, Japan, where cormorants potentially experienced adverse effects of PCB contamination, was three-fold higher than the highest total of these three congeners observed in the livers of double-crested cormorant chicks from the upper estuary colony. Similarly, ΣPCB in chick livers from Forster's terns (*Sterna forsteri*) from San Francisco Bay were an order of magnitude higher than ΣPCB in chick livers of Caspian tern chicks from the mid-Columbia River (Herring et al. 2010). PCB levels in San Francisco Bay are considered near or above the threshold for adverse effects in wildlife (Davis et al. 2007). Although PCB levels in chick livers of Caspian terns and double-crested cormorants from the Columbia River were lower than those in other contaminated systems, the possibility of negative effects from PCBs on young piscivorous birds cannot be excluded, considering the potential for cumulative adverse effects from PCBs and other contaminants in the Columbia River.

Newell et al. (1987) estimated that a PCB burden of 110 ppb, based on fish from the Niagara River and from laboratory studies, would cause no observable adverse effect to piscivorous birds. One of the composite samples of peamouth collected in the Columbia River estuary exceeded this threshold level. In order to better understand the extent of negative effects from PCB exposure in Caspian terns and double-crested cormorants from the Columbia River, further research will be necessary to evaluate performance of breeding colonies, such as colony size and productivity, in relation to burdens of PCBs and other chemical contaminants.

In conclusion, our study indicates that higher PCB levels in Caspian terns and double-crested cormorants nesting at certain colonies on the Columbia River were attributable to consumption of freshwater and estuarine resident fish species. For chicks, size of fat reserves appeared to be an important factor explaining variation in PCB levels in liver. Lower PCB levels in terns and cormorants from colonies near the mouth of the Columbia River compared to those from colonies farther up-river reflected diets with a higher proportion of marine forage fishes, which had lower average levels of PCBs than freshwater and estuarine resident fish species. When the availability of forage fish to piscivorous birds is low in the estuary, PCBs and other lipophilic contaminants are likely to be mobilized from fat deposits to vital organs. If freshwater prey species with higher contaminant levels predominate in tern and cormorant diets (e.g., during poor ocean conditions and lower availability of marine forage fish), this could cause elevated levels of contaminants in piscivorous bird species breeding at colonies in the lower estuary.

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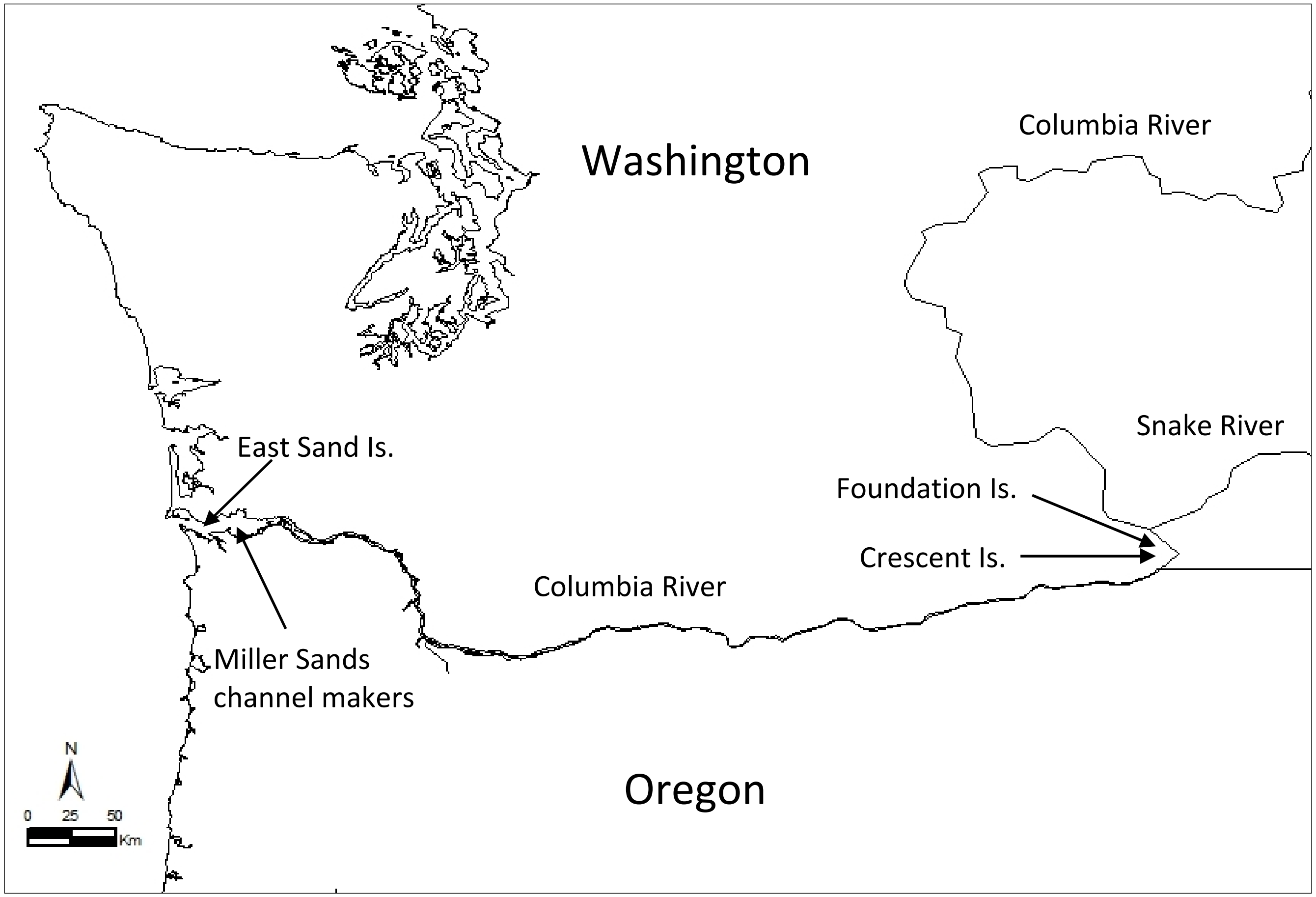

**Figure 3.1.** Study sites in the Columbia River Basin. East Sand Island and Miller Sands channel markers are located in the lower and upper part of the Columbia River estuary, respectively. Foundation and Crescent islands are located on the mid-Columbia River just below the confluence with the Snake River.

**Table 3.1.** Descriptions of chick fat scores. A fat score was assigned to each collected Caspian tern and double-crested cormorant chick based on the amount of visible subcutaneous fat after making an incision through the skin over the breast and abdominal areas and deflecting the skin away from the body.

| Fat score | Description |
|---|---|
| 1 | Little to no subcutaneous fat observed upon opening the carcass. All feather shafts visible, and no areas within the carcass have concentrations of fat. Any fat present is firmly attached to the bird’s skin, and difficult to remove. |
| 2 | Very little fat observed upon opening the carcass, with no concentrations of fat attached to the skin. A thin layer of fat is present between feather shafts, but remains firmly attached to the skin. Very small amounts of fat may be visible at the base of thighs and breast. |
| 3 | Small concentrations of fat visible in areas surrounding the breast and thighs of the bird. Some fat present and attached to the bird’s skin surrounding feather shafts, but all shafts are still visible and not obscured by fat. |
| 4 | A thin layer of fat present in the area formerly covering the breast, abdomen, and thighs. Fat concentrations are observed at the base of breast and thighs, and some fat remains attached to breast after opening the carcass. Some feather shafts are obscured by a layer of fat, which is loosely attached to skin. |
| 5 | A continuous layer of subcutaneous fat over the area formerly covering the breast and abdomen so as to obscure the tips of feather shafts through the skin. Fat concentrated in many areas, and can be easily removed. |

**Table 3.2.** Summary of bird sample matrix and size for PCB and stable isotope analyses.

| Colony location | Species | Year | Matrix for PCB analysis | n (pools) for PCB analysis | Matrix for stable isotope analysis | n for stable isotope analysis |
|---|---|---|---|---|---|---|
| East Sand Island | Caspian tern | 2002 | Liver | 15 (3) | Breast feathers | 15 |
| East Sand Island | Double-crested cormorant | 2002 | Liver | 15 (3) | Breast feathers | 15 |
| Miller Sands channel markers | Double-crested cormorant | 2002 | Liver | 15 (3) | Breast feathers | 5 |
| Crescent Island | Caspian tern | 2002 | Liver | 15 (3) | Breast feathers | 15 |
| Foundation Island | Double-crested cormorant | 2002 | Liver | 15 (3) | Breast feathers | 8 |
| East Sand Island | Caspian tern | 2009 | Egg | 15 (5) | Egg | 15 |
| East Sand Island | Double-crested cormorant | 2009 | Egg | 15 (5) | Egg | 15 |
| Miller Sands channel markers | Double-crested cormorant | 2009 | Egg | 15 (5) | Egg | 15 |
| Crescent Island | Caspian tern | 2009 | Egg | 15 (5) | Egg | 15 |
| Foundation Island | Double-crested cormorant | 2009 | Egg | 15 (5) | Egg | 15 |

**Table 3.3.** Summary of prey fish sample matrix and size for PCB and stable isotope analyses. All samples were collected from the Columbia River.

| Sampling location | Species | Year | Matrix for PCB analysis | n (pools) for PCB analysis | Matrix for stable isotope analysis | n for stable isotope analysis | Sampling year for stable isotope analysis | Adipose fin clipped* | Sampling method |
|---|---|---|---|---|---|---|---|---|---|
| Lower estuary | Anchovy | 2003 | Whole fish | 15 (3) | Lateral muscle | 7 | 2008 | N/A | Bill load |
| Lower estuary | Herring | 2002-2003 | Whole fish | 15 (3) | Lateral muscle | 7 | 2007-2008 | N/A | Bill load |
| Lower estuary | Surfperch | 2002-2003 | Whole fish | 11 (3) | Lateral muscle | 7 | 2008 | N/A | Bill load, foregut content |
| Lower estuary | Spring Chinook | 2004-2007 | Whole fish | 14(5) | Whole fish | 14 | 2004-2007 | Yes | Bill load |
| Upper estuary | Peamouth | 2006 | Whole fish | 15 (5) | Lateral muscle | 13 | 2006 | N/A | Beach sening[d] |
| Mid-river | Spring Chinook | 2007 | Whole fish | 15 (5) | Whole fish | 15 | 2007 | Yes | Dam[b] |
| Mid-river | Spring Chinook | 2007 | Whole fish | 5 (5) | Lateral muscle | 15 | 2007 | No | Dam[b] |
| Mid-river | Steelhead | 2007 | Whole fish | 15 (5) | Whole fish | 15 | 2007 | Yes | Dams[a] |
| Mid-river | Steelhead | 2007 | Whole fish | 5 (5) | Whole fish | 15 | 2007 | No | Dams[a] |
| Mid-river | Smallmouth bass | 2007 | Whole fish | 15 (5) | Whole fish | 15 | 2007 | N/A | Electrofishing[c] |
| Mid-river | Peamouth | 2007 | Whole fish | 15 (5) | Whole fish | 15 | 2007 | N/A | Electrofishing[c] |

* Steelhead and Spring Chinook samples with clipped adipose fins were assumed raised in a hatchery.

Fish samples collected by: a = U.S. Army Corps of Engineers, b = Pacific Northwest National Laboratory, c = Oregon Department of Fish and Wildlife, d = National Oceanic and Atmospheric Administration.

**Table 3.4.** ΣPCB (wet weight, ppb) in Caspian tern and double-crested cormorant eggs. Means are geometric means. Different letters represent significant differences.

| Location | Species | Mean | Range | Significant difference |
|---|---|---|---|---|
| East Sand Island | Caspian tern | 254.1 | 228.4-285.5 | b |
| East Sand Island | Double-crested cormorant | 353.0 | 279.7-450.5 | b |
| Miller Sands channel markers | Double-crested cormorant | 987.4 | 683.8-1926.1 | a |
| Crescent Island | Caspian tern | 209.4 | 174.6-313.5 | b |
| Foundation Island | Double-crested cormorant | 241.7 | 104.2-883.0 | b |

**Table 3.5.** ΣPCB (wet weight, ppb) in chick livers of Caspian terns and double-crested cormorants. Means are geometric means. Different letters represent significant differences.

| Location | Species | Mean | Range | Significant difference |
|---|---|---|---|---|
| East Sand Island | Caspian tern | 17.1 | 11.4-25.4 | c |
| East Sand Island | Double-crested cormorant | 18.8 | 13.7-25.1 | b, c |
| Miller Sands channel markers | Double-crested cormorant | 100.6 | 95.2-111.6 | a |
| Crescent Island | Caspian tern | 131.0 | 108.6-178.2 | a |
| Foundation Island | Double-crested cormorant | 38.5 | 34.1-45.1 | b |

**Table 3.6.** ΣPCB (wet weight, ppb) in the main prey fish types of Caspian terns and double-crested cormorants. Means are geometric means. Different letters represent significant differences.

| Location | Species | Mean | Range | Significant difference |
|---|---|---|---|---|
| Lower estuary | Anchovy | 11.4 | 6.9-15.7 | b, c |
| Lower estuary | Herring | 6.2 | 5.3-7.6 | c |
| Lower estuary | Surfperch | 28.9 | 21.5-42.8 | a, b |
| Lower estuary | Spring Chinook | 13.7 | 10.7-20.8 | b, c |
| Upper estuary | Peamouth | 60.8 | 32.4-154.7 | a |
| Mid-river | Spring Chinook | 14.2 | 10.7-17.5 | b, c |
| Mid-river | Steelhead | 16.5 | 12.0-35.6 | b, c |
| Mid-river | Smallmouth bass | 31.0 | 20.1-69.4 | a, b |
| Mid-river | Peamouth | 25.9 | 22.2-29.0 | b |

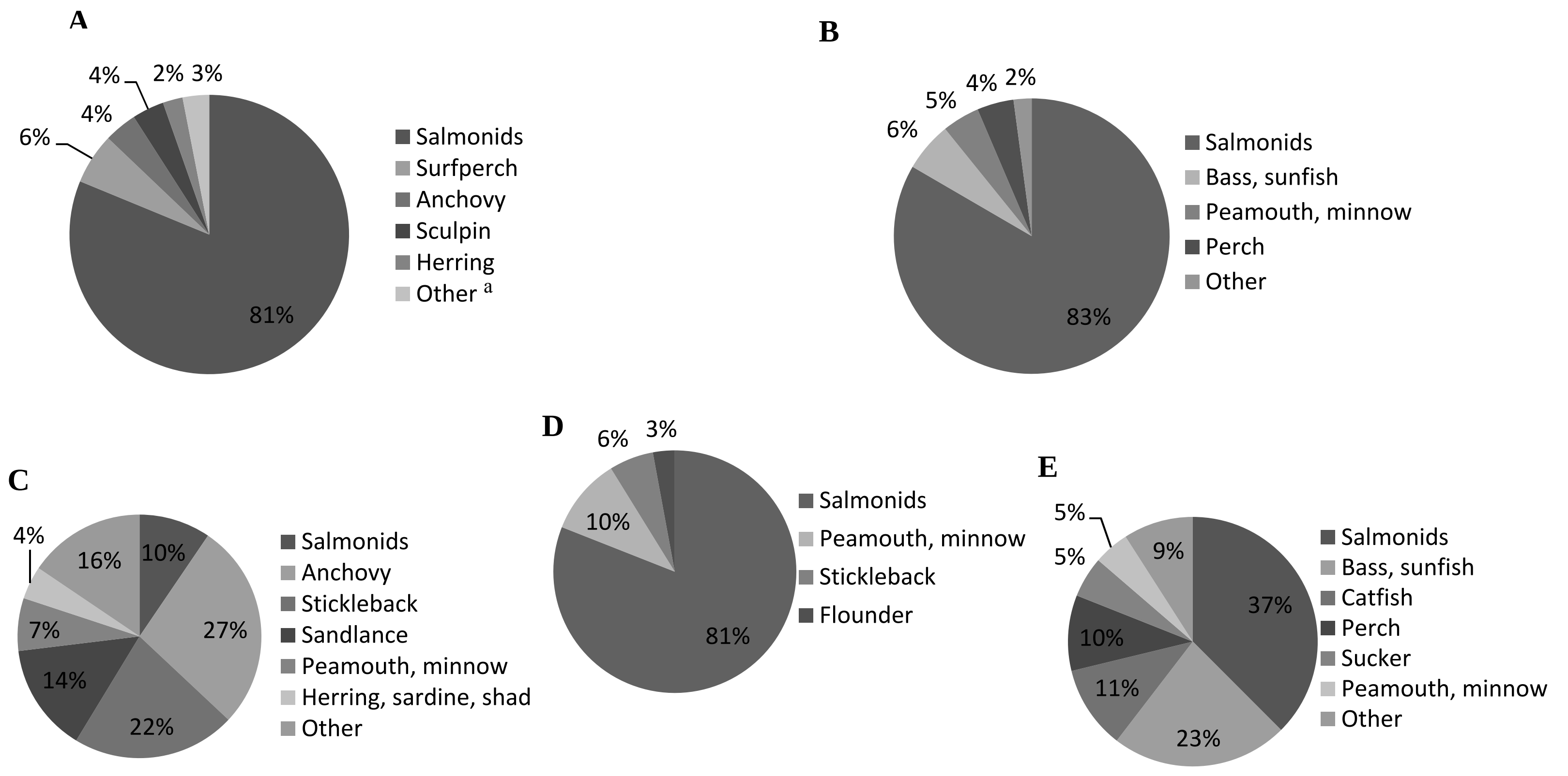

**Figure 3.2.** Diet composition during the pre-egg laying period of Caspian tern adults nesting on East Sand Island (A, n = 395) and Crescent Island (B, n = 455), and double-crested cormorant adults nesting on East Sand Island (C, n = 42), Miller Sands channel markers (D, n = 34), and Foundation Island (E, n = 69).

[a] Other includes unidentified non-salmonids.

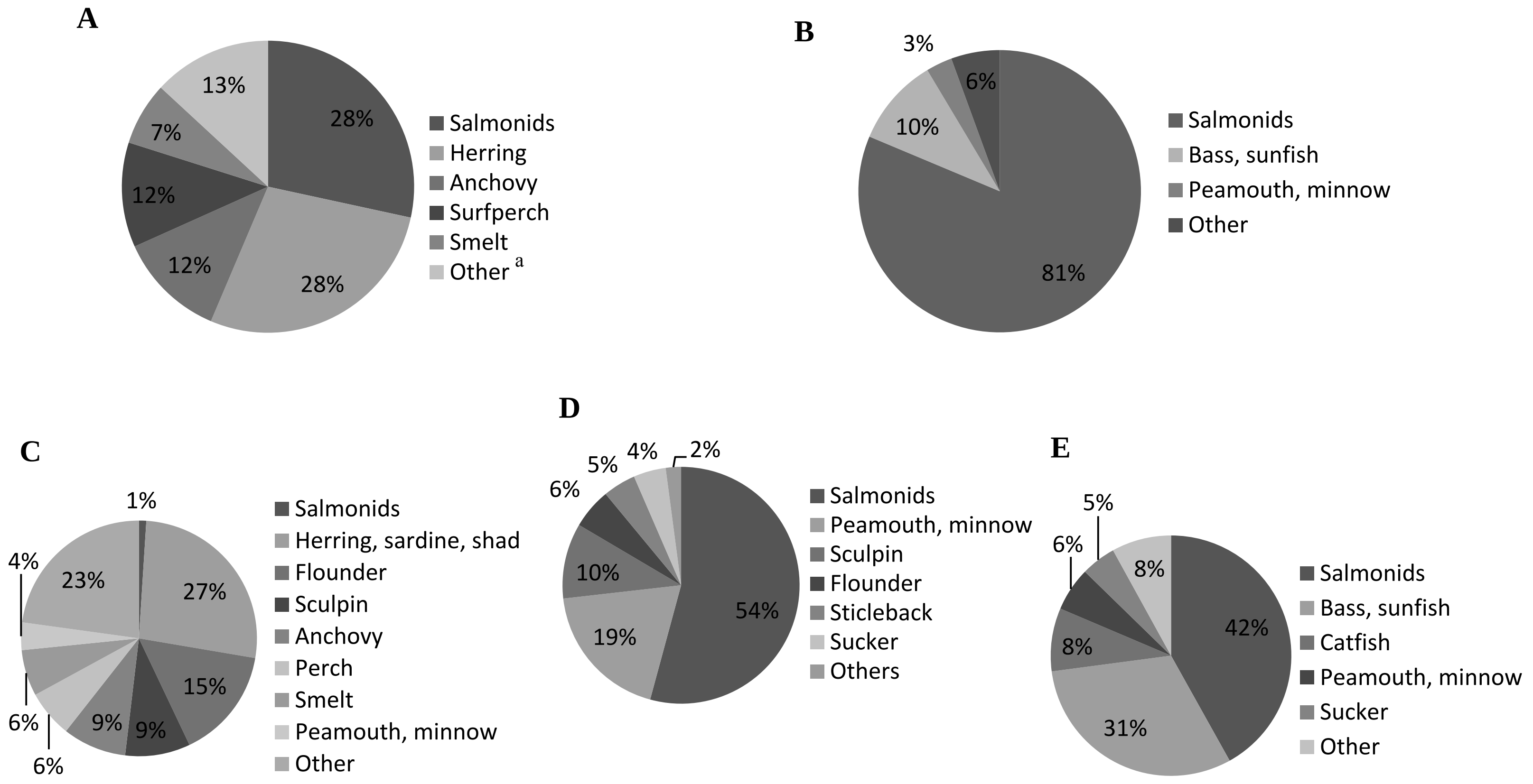

**Figure 3.3.** Diet composition of Caspian tern chicks at colonies on East Sand Island (A, n = 1294) and Crescent Island (B, n = 575), and double-crested cormorant chicks at colonies on East Sand Island (C, n = 65), Miller Sands channel markers (D, n = 96), and Foundation Island (E, n = 74).

[a] Other includes unidentified non-salmonids.

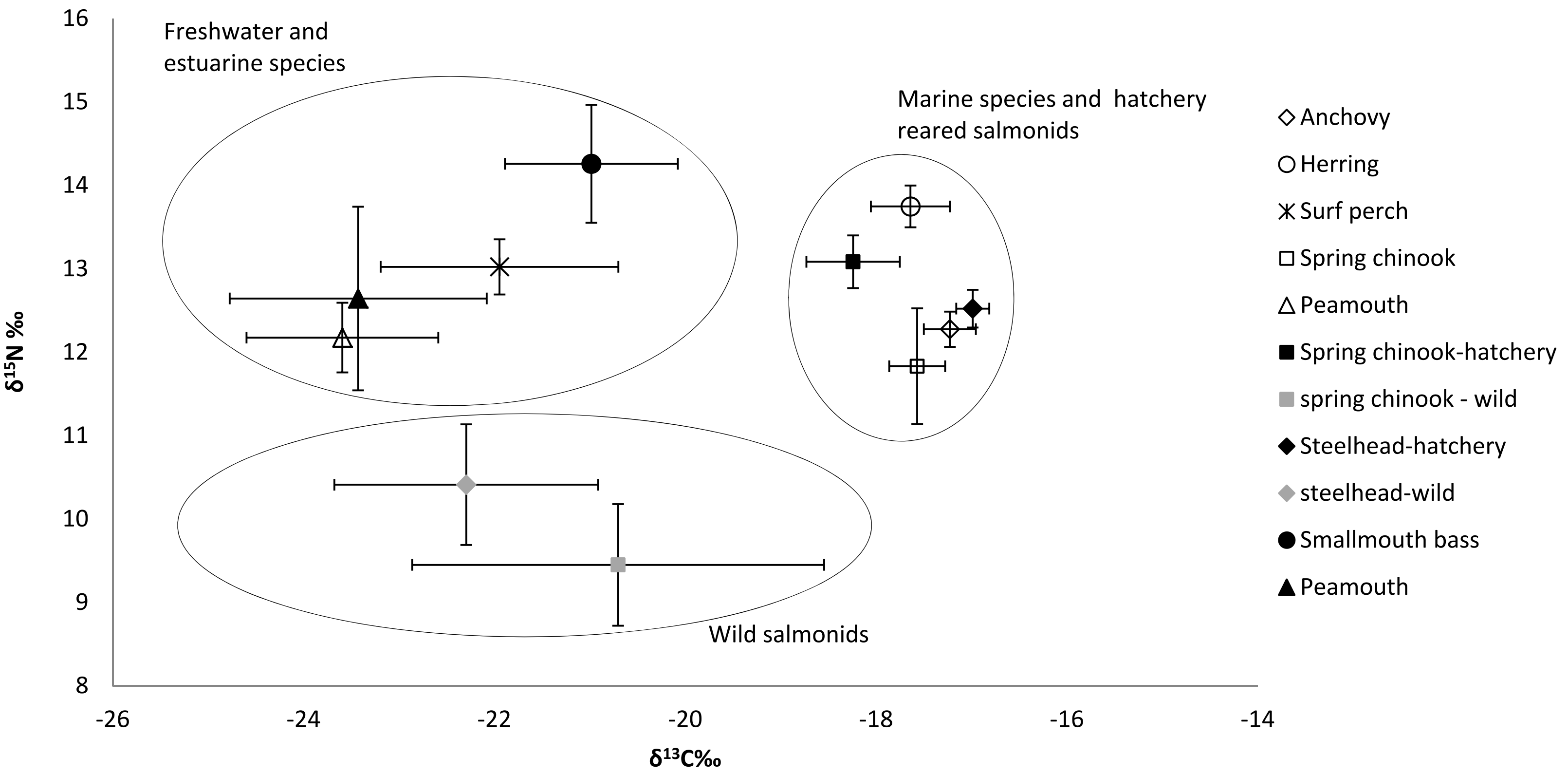

**Figure 3.4.** Stable isotope ratios for carbon (C) and nitrogen (N) in the main prey fish types of Caspian terns and double-crested cormorants. Error bars are 95% confidence intervals. Open and filled symbols represent fish samples from the Columbia River estuary and from the mid-Columbia River, respectively.

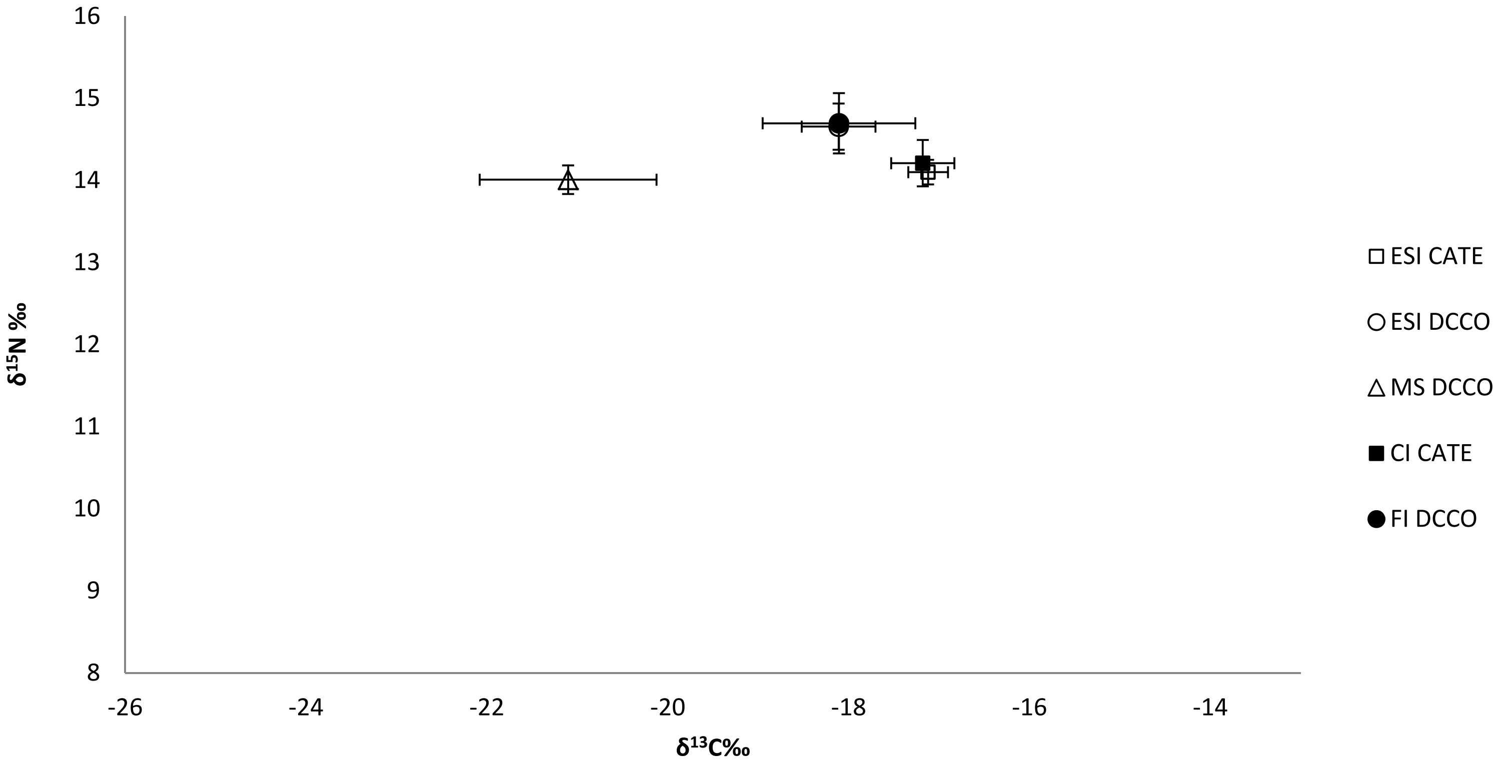

**Figure 3.5.** Stable isotope ratios for carbon (C) and nitrogen (N) in Caspian tern (CATE) and double-crested cormorant (DCCO) eggs. Error bars are 95% confidence intervals. Open and filled symbols represent bird samples from the Columbia River estuary (ESI and MS) and from the mid-Columbia River (CI and FI), respectively. Carbon and nitrogen stable isotope ratios were adjusted with diet-bird egg discrimination factors.

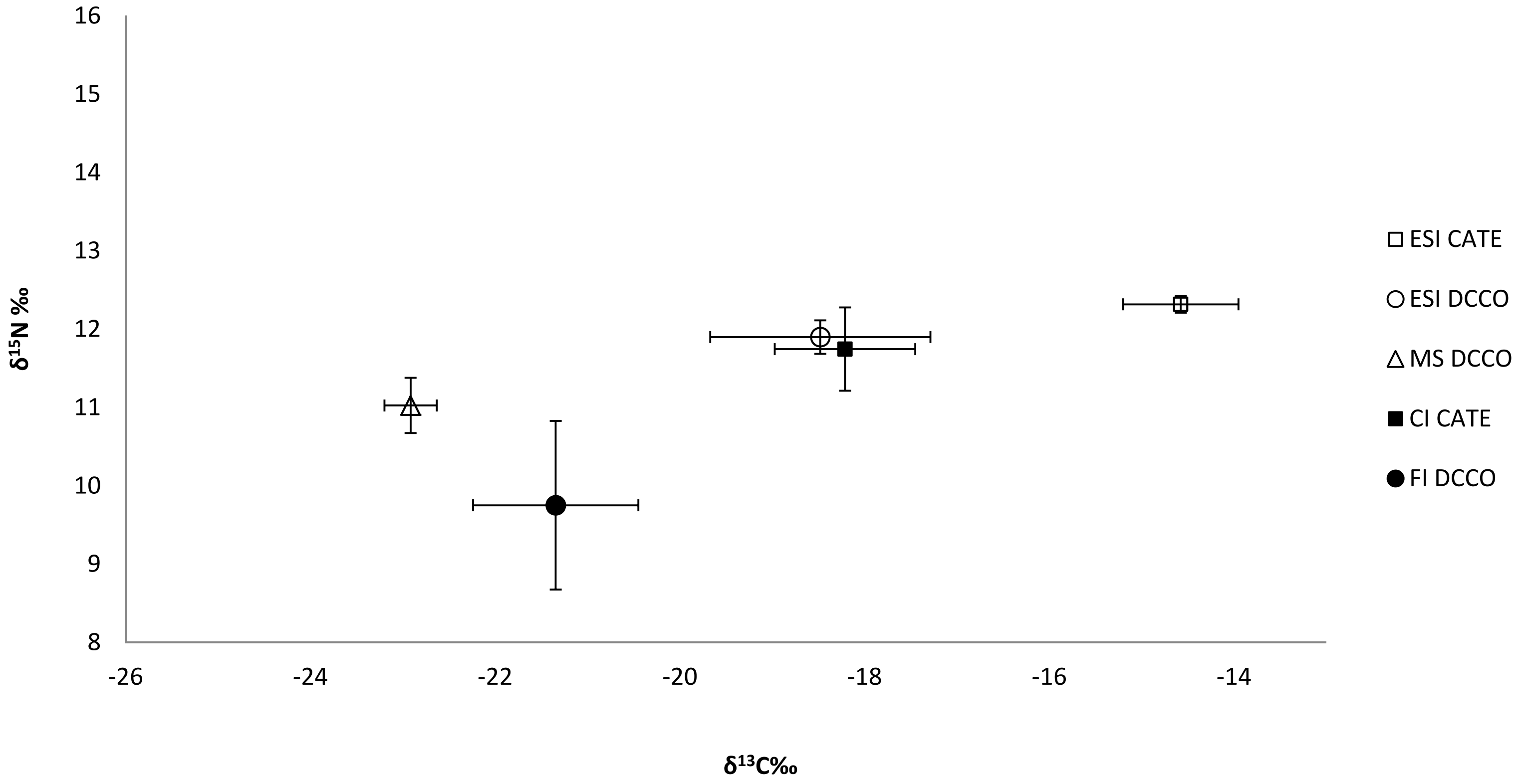

**Figure 3.6.** Stable isotope ratios for carbon (C) and nitrogen (N) in breast feathers from Caspian tern (CATE) and double-crested cormorant (DCCO) chicks. Error bars are 95% confidence intervals. Open and filled symbols represent bird samples from the Columbia River estuary (ESI and MS) and from the mid-Columbia River (CI and FI), respectively. Carbon and nitrogen stable isotope ratios were adjusted with diet-bird feather discrimination factors.

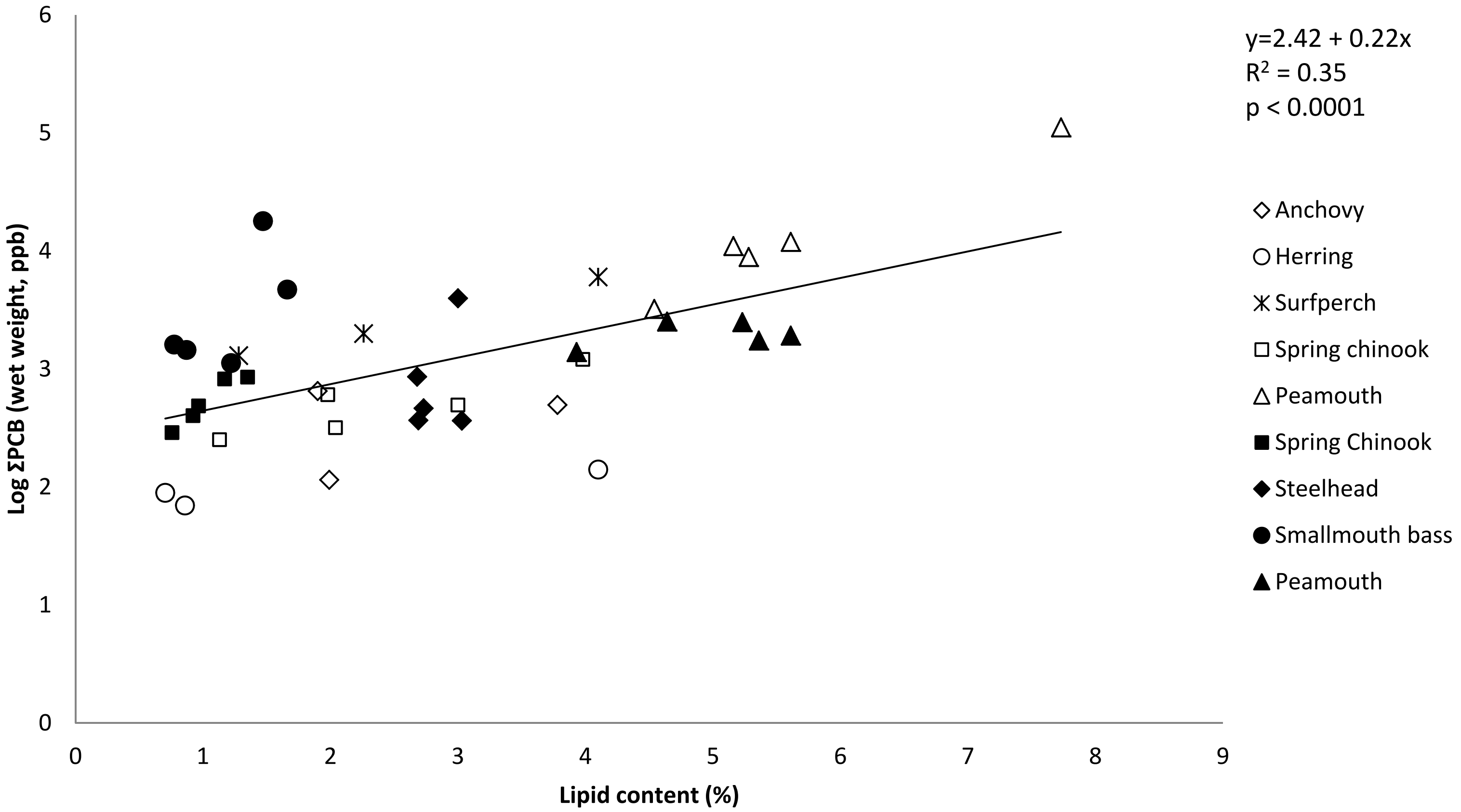

**Figure 3.7.** Relationship between log PCB concentration and % lipid content of the main prey fish types for Caspian terns and double-crested cormorants nesting on the Columbia River. Open and filled symbols represent fish from the Columbia River estuary and from the mid-Columbia River, respectively. Steelhead and spring Chinook salmon were hatchery-reared.

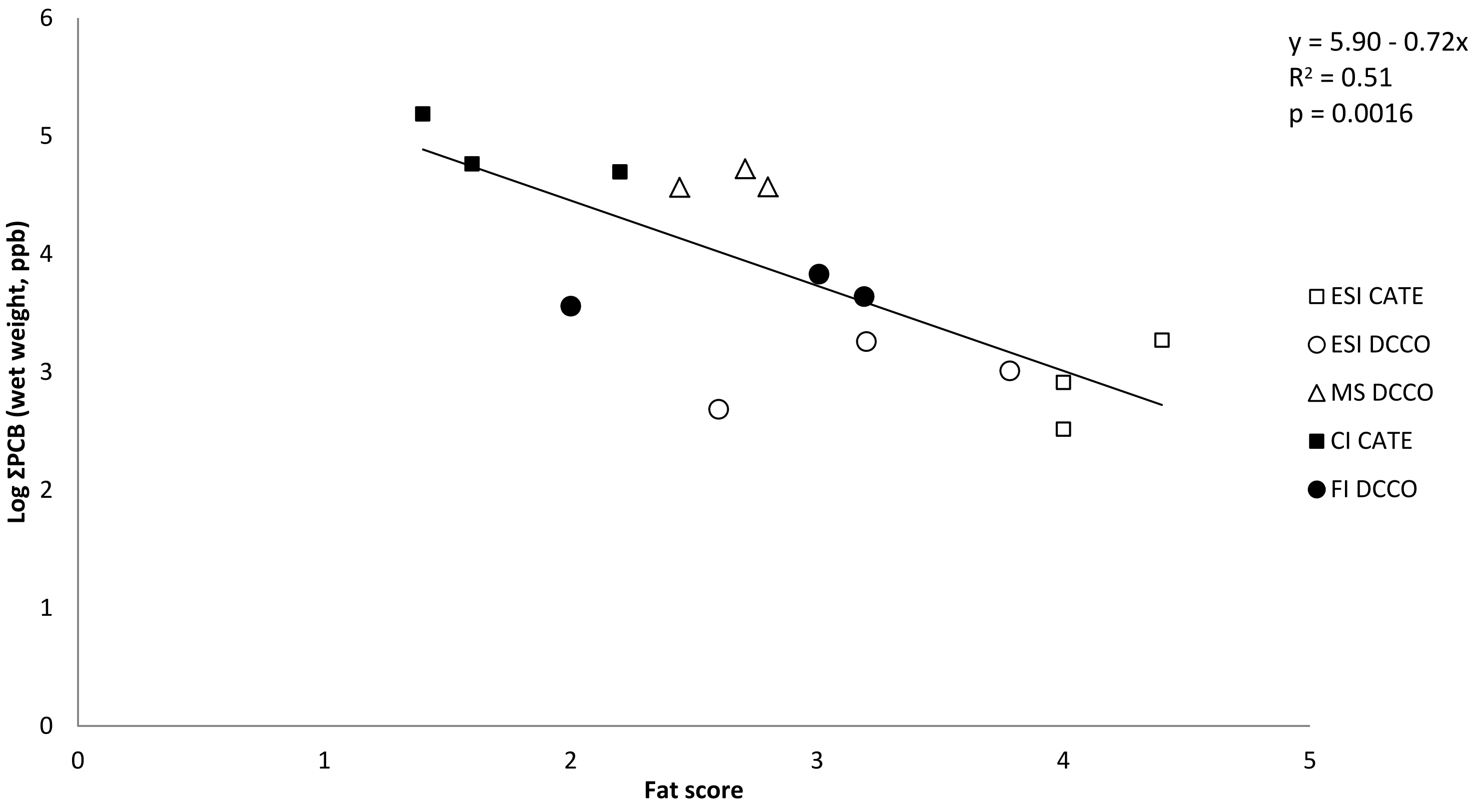

**Figure 3.8.** Relationship between log PCB concentration in liver and the fat score of Caspian tern (CATE) and double-crested cormorants (DCCO) chicks. Open and filled symbols represent chicks from the Columbia River estuary (ESI and MS) and from the mid-Columbia River (CI and FI), respectively.

# CHAPTER 4

# DEVELOPING NON-DESTRUCTIVE TECHNIQUES FOR MANAGING CONFLICTS BETWEEN FISHERIES AND DOUBLE-CRESTED CORMORANT NESTING COLONIES

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Karen N. Courtot, and Ken Collis

## ABSTRACT

Fisheries managers are increasingly concerned about the impact of cormorant (*Phalacrocorax* spp.) predation on fish stocks of commercial or conservation concern. Options for reducing the size of the large double-crested cormorant (*P. auritus*) breeding colony on East Sand Island near the mouth of the Columbia River to enhance survival of juvenile salmonids (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act are currently under consideration by federal, state, and tribal resource management agencies. We evaluated habitat enhancement and social attraction as potential non-destructive techniques for managing nesting colonies of cormorants. First, we tested habitat enhancement (tires containing nest material) and social attraction (decoys and audio playback systems) on plots adjacent to the East Sand Island cormorant colony. Cormorants quickly colonized these plots, where they had not previously nested, and successfully raised young. Second, cormorants were attracted to nest and raised young at similar plots on two islands ca. 25 km from East Sand Island; one island had a previous history of cormorant nesting and the other of cormorant prospecting and an unsuccessful nesting attempt. On a third island with no history of cormorant nesting or nesting attempts, however, no cormorants were attracted to nest. Our results suggest that attraction of nesting cormorants using these techniques is influenced by (1) previous history of cormorant nesting or nesting attempts, (2) frequency and intensity of disturbance by potential predators, and (3) presence of breeding cormorants nearby. While habitat enhancement and social

attraction have potential as techniques to redistribute nesting cormorants away from areas where fish stocks of concern are highly susceptible to predation, successful establishment of new colonies using these techniques will likely require a focus on sites with a history of cormorant nesting.

## INTRODUCTION

Negative interactions between cormorants (*Phalacrocorax* spp.) and fisheries have been a growing concern in many parts of the U.S. and Canada (Krohn et al. 1995, Weseloh et al. 1995, Wires et al. 2001, Dorr et al. 2004), as well as in other nations (Carss and Ekins 2002, Naruse and Sugawa 2002, Cowx 2003). In order to reduce such conflicts involving double-crested cormorants (*P. auritus*) in the U.S., Depredation Permits were issued by the U.S. Fish and Wildlife Service (USFWS) starting in 1986, followed by a Depredation Order (USFWS 1998; 50 CFR 21.47), and then an Environmental Impact Statement (USFWS 2003) for a Public Resource Depredation Order. The main methods used to control double-crested cormorants in the U.S. and Canada are hazing and lethal control of adults, nest destruction, and egg destruction through oiling (Hatch and Weseloh 1999, Wires and Cuthbert 2006).

In the Columbia River basin, fisheries managers are increasingly concerned about the impact of avian predation on the survival of juvenile anadromous salmonids listed under the U.S. Endangered Species Act (ESA). A variety of piscivorous colonial waterbirds, including double-crested cormorants, have been identified as the source of significant mortality to smolts out-migrating from the basin (National Oceanic and Atmospheric Administration 2004). In particular, a breeding colony of double-crested cormorants on East Sand Island in the Columbia River estuary has increased dramatically in recent decades, from approximately 90 breeding pairs in 1989 to more than 13,000 pairs in 2010 and 2011. The double-crested cormorant colony on East Sand Island is now the largest known breeding colony for the species in western North America (Adkins et al. 2010; Roby et al. 2011; D. Roby et al., unpubl. data). Estimates of the number of juvenile salmonids consumed annually by cormorants nesting at this colony in 2010 and 2011 were approximately 20 million smolts, or approximately one-sixth of all the juvenile salmonids that survive out-migration to the Columbia River estuary (Roby et al. 2011; D. Roby et al., unpubl. data).

The Caspian tern (*Hydroprogne caspia*) is another species of piscivorous colonial waterbird that nests in large numbers on East Sand Island, and this colony has been the subject of management since 2008 to reduce its impact on survival of juvenile salmonids in the Columbia River estuary (USFWS et al. 2005, USFWS 2006). Annual consumption of juvenile salmonids by Caspian terns nesting on East Sand Island averaged 5.4 million during 2001-2010 (Lyons 2010), far less than recent estimates of smolt consumption by cormorants nesting on East Sand Island. Management of Caspian terns in the Columbia River estuary was first implemented in 1999, when efforts were initiated to test whether terns could be relocated from the colony on Rice Island, a dredged material disposal island in the upper estuary, to East Sand Island near the mouth of the river (Roby et al. 2002). The goal of relocating the colony was to increase the availability of marine forage fishes as an alternative food source for nesting Caspian terns, and thereby reduce their reliance on juvenile salmonids as prey. The methods used to accomplish colony relocation were habitat enhancement and social attraction on East Sand Island, coupled with dissuasion through habitat manipulation on Rice Island (Roby et al. 2002). Despite the successful relocation of the tern colony and a more than 50% reduction in annual consumption of juvenile salmonids, further management efforts were initiated in 2008 to reduce the size of the Caspian tern colony on East Sand Island (ca. 9,500 breeding pairs) to one-third its initial size (USFWS et al. 2005, USFWS 2006). In contrast, management actions for double-crested cormorants nesting on East Sand Island have not yet been selected and implemented, despite agreement among federal, state, and tribal resource management agencies that management is warranted to reduce the impact of East Sand Island double-crested cormorants on recovery of ESA-listed stocks of salmonids.

The double-crested cormorant population in western North America is a distinct management unit, and the size of the population is estimated to be less than 10% that of the interior/eastern North America population of the species (Adkins et al. 2010). The East Sand Island colony supports approximately 40% of the breeding pairs belonging to the western North America population. The population of double-crested cormorants in interior/eastern North America erupted throughout much of its breeding and wintering range, reached a population size of 300,000-500,000 breeding pairs, and is now the subject of widespread lethal control for its impact on fisheries and other resources. The western North America population, however, numbers only approximately 31,500 breeding pairs, and average annual population growth rate has been about 3% (Adkins et al. 2010). If not for the rapid growth of the East Sand Island colony, the western population of double-crested cormorants would be approximately stable. Consequently, the impact to the western population of destructive control measures at the East Sand Island cormorant colony would be proportionately much greater than lethal control at any of the breeding colonies in interior/eastern North America.

The Public Resource Depredation Order that was implemented to limit the impact of the double-crested cormorant population in interior/eastern North America does not include the range of the western population, and no federal action to control the western population has been implemented. Consequently, the western population of double-crested cormorants remains protected under the Migratory Bird Treaty Act, and federal and state permits are required for lethal take. Given the protected status of double-crested cormorants nesting on East Sand Island, and that fisheries managers have determined that the impact of cormorant predation on ESA-listed juvenile salmonids in the Columbia River estuary warrants management, studies to explore potential nondestructive management approaches are necessary.

Habitat enhancement and social attraction techniques to encourage seabirds to nest at suitable colony sites have been successfully used for restoration of breeding colonies of a variety of seabird species (Kress 1983, Jones and Kress 2012). Management of Caspian terns in the Columbia River estuary to reduce their impact on the survival of juvenile salmonids has relied primarily on these restoration techniques

(Roby et al. 2002, 2010). In the present study, our objective was to test whether habitat enhancement and social attraction techniques could be used to attract nesting double-crested cormorants to alternative colony sites and away from the East Sand Island colony. If these techniques proved successful, then they could be employed to redistribute some or all of the double-crested cormorants nesting at the East Sand Island colony to colony sites where the cormorants' impact on ESA-listed fish would be much less. We sought to test habitat enhancement and social attraction techniques at plots in three different settings: (1) in areas of East Sand Island where cormorants had not previously nested; (2) on other islands in the Columbia River estuary where cormorants had a history of successful nesting or unsuccessful nesting attempts; and (3) on an island in the Columbia River estuary that appeared suitable for cormorant nesting, but where cormorant nesting had not previously been reported. At East Sand Island, we evaluated potential factors that influence attraction of prospecting adult double-crested cormorants to plots of new nesting habitat. We also estimated nesting success (the average number of young raised per breeding pair) in plots on East Sand Island and on other islands in the estuary to evaluate whether plots where breeding habitat had been enhanced and social attraction techniques had been employed to attract nesting double-crested cormorants would provide suitable alternative nesting habitat.

## METHODS

## Study Area

We evaluated techniques to enhance nesting habitat and to socially attract nesting double-crested cormorants by creating plots adjacent to the cormorant colony on East Sand Island during 2004-2007. The double-crested cormorants that nest on East Sand Island build their nests almost entirely on the ground, with the exception of a few pairs that build their nests in low trees or shrubs. The vast majority of cormorants at this colony nest on artificial rocky revetment, patches of accumulated driftwood and other floating debris, or on patches of vegetation such as beach/dune grass. In order to evaluate whether double-crested cormorants can be attracted to potential colony sites at islands other than East Sand Island, test plots using habitat enhancement and social attraction were also created at three different locations within the Columbia River estuary: (1) a small rock island at the mouth of Trestle Bay, 5 km south of East Sand Island (in 2005); (2) the downstream end of Rice Island, 26 km up-river from East Sand Island (in 2006); and (3) the downstream end of Miller Sands Spit, 30 km up-river from East Sand Island (in 2004-2007; Figure 4.1). Our intent was to test the feasibility of habitat enhancement and social attraction techniques for establishing new breeding colonies of double-crested cormorants, not to establish permanent colonies at the three locations.

Double-crested cormorants were known to have nested on old, abandoned railroad trestles at Trestle Bay in the 1980s and early 1990s (Carter et al. 1995); however, there is no record of cormorants nesting on the anthropogenic rocky islet at the mouth of Trestle Bay where a test plot was set up. On Rice Island, double-crested cormorants formerly nested on the ground near the downstream end of this dredged material disposal island, but had not nested since 2003, three years before a test plot was set up near the site of the previous colony. The cormorant colony on Rice Island was once much larger, with over 1,100 breeding pairs counted in 1997. Unlike Rice Island, there was no prior history of successful nesting by double-crested cormorants on Miller Sands Spit, another dredged material disposal island, although 10 pairs of double-crested cormorants attempted to nest on the ground at the downstream end of the island in 2001. All of those nests were abandoned prior to egg hatching.

## Cormorant Habitat Enhancement and Social Attraction

### *East Sand Island Test Plots*

We created two test plots each in 2004 and 2005 in the interior of East Sand Island and adjacent to the existing cormorant colony to evaluate whether habitat enhancement and social attraction techniques would induce cormorants to nest in areas where cormorants had not previously nested. Twelve double-crested cormorant decoys (Mad River Decoys, Waitsfield, Vermont, USA) in sitting and incubating postures and two speakers broadcasting vocalizations recorded on a double-crested cormorant breeding colony were deployed in each plot to test social attraction techniques. Vocalizations of double-crested cormorants were digitally recorded at the East Sand Island colony (Alaska's Spirit Speaks, Fairbanks, Alaska, USA) and broadcasted using solar-charged sound systems (Murremaid Music Boxes, South Bristol, Maine, USA).

During the 2004 breeding season, two types of habitat enhancement techniques were tested. A 41-$m^2$ plot was set up using pieces of driftwood that were moved to the plot to create structure similar to natural habitat used by nesting double-crested cormorants elsewhere on the island. This driftwood plot was filled with small woody debris to supply abundant nest-building material for prospecting cormorants. A few dozen old cormorant nests from previous breeding seasons were also added to the plot. The other test plot in 2004 was created with a square array of 49 old truck tires laid out in a 99-$m^2$ area. The center of each tire was filled with sand, and an old cormorant nest used in previous years was placed in the center of each tire. The driftwood plot and the tire plot were approximately 20 m apart and separated by a gully and sparse cover of herbaceous vegetation. The preparation of these two test plots was completed prior to the breeding season. The habitat enhancement materials and social attraction in the test plots were removed before the following breeding season to evaluate whether nesting cormorants would be faithful to the same area in the subsequent year, despite the lack of social attraction and habitat enhancement.

During the 2005 breeding season, two wooden platforms measuring 5 m x 5 m and elevated approximately 0.7 m above ground level were constructed in two different areas of the East Sand Island colony where cormorants had not previously nested. The platforms were constructed to evaluate whether cormorants could be induced to nest on artificial structures. Thirty-six old truck and car tires filled with sand and old cormorant nests were placed on each platform. The distance between the platforms was approximately 30 m and separated by a small gully and sparse herbaceous vegetation. In both years, nesting activities and numbers of active cormorant nests on the two test plots were monitored from a nearby observation blind, from the onset of nest building (April) through chick-rearing (end of July).

Prior to the 2006 breeding season, we built four additional test plots in the cormorant colony at East Sand Island, one plot on either side of the two platforms built in 2005, in order to create two groups of three plots, or a total of six test plots. The distance between plots within a group ranged from 3.0 to 7.6 m, and the two groups were about 30 m apart. These same six plots were also used during the 2007 breeding season. We employed three different treatments, two plots per treatment, in each of the two years to evaluate cormorant preferences for habitat enhancement and social attraction (Table 4.1). The three different treatments were designed to evaluate whether cormorants prefer plots with social attraction (decoys and audio playback systems) over plots without such attraction. The treatments were also designed to assess whether cormorants prefer wooden platforms elevated above ground level over plots created on the ground. Each plot within a group of plots was haphazardly assigned to one of the three treatments. The two new platforms built in 2006 were identical in dimensions to the two original platforms built in 2005. Plots laid out on the ground were the same dimensions as the wooden platforms. The three plots in the two groups of plots were as identical as we could make them in an effort to replicate each plot treatment. Each test plot was filled with a 6 x 6 array of 36 car and truck tires filled with either sand and old cormorant nests or sand and fine woody debris that was suitable as nest material. Twelve cormorant decoys and one or two speakers broadcasting recorded cormorant vocalizations were placed in each of the four plots that were assigned to the social attraction treatment.

In 2006, we also evaluated whether old cormorant nests (used in previous years) were more attractive to adult cormorants prospecting for nest sites in test plots compared to fine woody debris that was suitable as nest material. In three of the six plots, 18 tires in each plot were haphazardly selected to receive old cormorant nests, and the rest of the tires were filled with fine woody debris collected from the shoreline of the island. All tires in the other three plots were filled with fine woody debris, but no old cormorant nests. Nesting activities and numbers of active cormorant nests were monitored from a nearby elevated observation blind from April through July of each year.

### *Nesting Success on East Sand Island Test Plots*

The average number of young produced per breeding pair was estimated to assess nesting success in each test plot on East Sand Island during 2004-2007. In order to evaluate whether cormorants nesting in the test plots produced more or less young compared to cormorants nesting elsewhere in the East Sand Island colony, we also monitored nests in control plots (n = 20-65/control plot) delineated in unmanipulated habitat in three different areas of the colony. Nesting success was estimated based on the average number of nestlings alive at 28 days post-hatch per active nest; cormorant chicks in ground nests at East Sand Island were capable of leaving their nests after 28 days. Nesting success was compared between test and control plots in each year during 2004-2007 using t-tests. All statistical analyses were performed using SAS 9.2 (SAS Institute 2009), and α was set at 0.05.

### *Test Plots on Other Islands in the Columbia River Estuary*

<u>Island with recent cormorant nesting history (Rice Island)</u> - In April 2006, we created a test plot at the downstream end of Rice Island, near where double-crested cormorants had previously nested, most recently in 2003. A total of 36 old tires, 40 decoys, and four speakers broadcasting recordings of cormorant vocalizations were placed in a 4.0 m x 4.3 m plot. Each tire was filled with fine woody debris to simulate nesting material. Numbers of cormorants, nesting activities, and sources of disturbance to cormorants on or near the plot were monitored from a nearby observation blind from May through July. An average of 13 hours of observation was recorded during each week. Disturbances to cormorants in or near the plot caused by predators and human activities were recorded during observation hours. Any event that caused a flight response by cormorants was counted as one disturbance event. The plan was to remove the test plot after the 2006 breeding season, regardless of whether cormorants attempted to nest there or not. If the plot was used by nesting cormorants in 2006, removal of the habitat enhancement and social attraction after the 2006 breeding season would assess whether cormorants would nest at the same site in subsequent years without habitat enhancement and social attraction.

Island with no prior history of successful nesting (Miller Sands Spit) - We created a test plot in April 2004 at the downstream end of Miller Sands Spit, where a few double-crested cormorants had previously attempted to nest in 2001. The plot was similar to the driftwood plot created adjacent to the cormorant colony on East Sand Island; driftwood was gathered into a 10 m x 8 m plot, and the plot was filled with fine woody debris suitable as nest material that was collected from the shoreline of the island. A total of 62 decoys and two speakers broadcasting cormorant vocalizations were placed in the plot. In 2005, we created a smaller driftwood plot (8 m x 5 m) with 24 decoys and two speakers in the same area of the island, but with 25 old tires filled with fine woody debris to simulate nesting material. In the subsequent two years (2006 and 2007), we repeated the test at the same site on the island using larger numbers of decoys (40), tires (36), and speakers (4) placed in a smaller plot (4.5 m x 4.5 m).

Because there was no observation blind on this island, we monitored the presence of cormorants on the test plot, plus any nesting activities on the plot, during boat-based and aerial surveys conducted 1-3 times per week from April through July, with occasional land-based surveys at considerable distance from the plot to ensure that any potential nesting cormorants were not disturbed. In addition to the routine surveys, we monitored the plot and adjacent areas of Miller Sands Spit from Rice Island, located across the river channel and approximately 1 km from Miller Sands Spit, for the presence of cormorants and potential causes of disturbance to nesting cormorants, averaging 11 hours of observation each week from June through July in 2006.

<u>Island with no prior history of nesting (rocky islet at mouth of Trestle Bay)</u> - A test plot was created on top of a small rocky islet, measuring approximately 10 m x 20 m in size, in April 2005. A total of 26 decoys, 24 old car and truck tires, and two speakers broadcasting cormorant vocalizations were secured on large rocks. The center of each tire was filled with fine woody debris to simulate cormorant nesting material. Land- and boat-based surveys were conducted once or twice weekly from April to early July to monitor the number of cormorants, potential nesting activities, and the presence of potential disturbance to nesting cormorants (i.e., predators and humans).

### *Nesting Success at Plots on Other Islands in the Columbia River Estuary*

At test plots on islands in the Columbia River estuary other than East Sand Island, we based nesting success on whether nestling presence was visually confirmed during either land- or boat-based surveys. We conducted a single on-the-ground survey at each test plot during the chick-rearing period to count nest structures and numbers of nestlings. In order to minimize gull (*Larus* spp.) predation on cormorant eggs and nestlings while adult cormorants were away from their nests because of our presence at the plots, each on-the-ground survey was conducted at night. Each on-the-ground count of nests and chicks was conducted when we estimated the oldest chicks were about 28 days old. When nesting chronology was highly asynchronous within a plot, the single on-the-ground survey of nests and nestlings was postponed in an attempt to maximize the number of chicks old enough to be included in an estimate of nesting success. In these cases, we set up a fence made of fabric around the plot in order to catch and count any older chicks that could move away from their nests. Nests with eggs or chicks less than two weeks old were excluded from the estimates of nesting success because the fate of eggs and young chicks were unpredictable at such early stages of nesting.

## RESULTS

### Habitat Enhancement and Social Attraction on East Sand Island

#### *Attracting Cormorants to Nest in New Areas Adjacent to the Colony*

In 2004 and 2005, double-crested cormorants were attracted to both test plots and successfully raised young to fledging age on each plot in both years, regardless of the method of habitat enhancement (driftwood accumulation vs. old tires vs. raised platforms with tire arrays). The first observations of cormorants and the initiation of nesting behavior on the plots were concurrent with when early nesters first settled on other sections of the colony. The timing of first observations of cormorants and the initiation of nesting behaviors were also synchronous between plots within a year, the driftwood plot and the tire plot in 2004 and the two platform plots in 2005. The nesting density of cormorants on each test plot was similar to or greater than colony-wide nesting densities (0.7-1.2 nests/$m^2$ during 2004-2007, Table 4.2). After habitat enhancement (driftwood or tires) and social attraction were removed from the two plots after the 2004 nesting season, cormorants did not nest in these two areas in 2005 or in the two subsequent years of the study.

### *Factors Influencing Successful Attraction*

The first observation of cormorants on plots subject to different treatments was fairly synchronous in both 2006 and 2007. In 2006, the first prospecting cormorant was observed on a plot consisting of a platform without decoys or speakers (treatment B, Table 4.1). In 2007, the first prospecting cormorant was observed on a plot consisting of a platform with decoys and speakers (treatment F). In 2006, prospecting cormorants were first observed on all six test plots within 36 min of the arrival of the first cormorant at one of the plots, and in 2007 within just 6 min. In 2006, cormorant nest initiation (egg-laying) was observed earliest and the number of active nests was highest in treatment A (decoys and speakers on the ground) among the three treatments. In 2007, however, the timing of nest initiation was highly synchronous among treatments and the number of active nests was similar among the three treatments (Table 4.2).

Prospecting cormorants did not appear to favor old cormorant nests over fine woody debris in any of the plots where the two types of nest materials were offered to test for a preference. The first prospecting cormorants observed in each of the three plots where both types of nest materials were offered inspected tires filled with both types of nesting material and some immediately started courtship displays, regardless of the type of nesting material in the tire.

### *Nesting Success*

The mean nesting success in test plots at East Sand Island during 2004-2007 ranged from 1.9 to 2.9 young raised per active nest. There was no significant difference in mean nesting success between test and control plots within a year, except in 2005 when mean nesting success was greater in the two test plots compared to the control plots ($t = 3.7$, $p = 0.0003$; Figure 4.2).

## Habitat Enhancement and Social Attraction on Other Islands in the Columbia River Estuary

### *Island with a Recent History of Cormorant Nesting*

Double-crested cormorants were quickly attracted to the test plot on Rice Island and fledged chicks in the first year. The first observation of prospecting cormorants on the Rice Island test plot occurred only one day after the completion of plot preparations. On that day, cormorants were also observed engaged in courtship displays on the test plot. A total of 30 pairs of cormorants nested within the plot and five additional pairs nested immediately adjacent to the plot. Based on a single on-the-ground, nocturnal nest and chick count at the plot (the observation blind near the plot did not provide a clear vantage of nest contents), the best estimate of nesting success for cormorants that nested in or adjacent to the plot was 2.6 young raised per active nest (older chicks were approximately 28 days post-hatch).

Bald eagles (*Haliaeetus leucocephalus*) caused disturbances to double-crested cormorants nesting on the Rice Island test plot or roosting in the immediate vicinity at a rate of 0.1 disturbance events/daylight hour (total observation time was approximately 87 daylight hours). Up to five bald eagles were observed at one time on the beach adjacent to the test plot. Although recreational boaters were frequently observed in the vicinity of Rice Island, no boats were observed close enough to the plot to visibly disturb cormorants nesting on the plot. During the subsequent nesting season, after the habitat enhancement and social attraction had been removed from the plot, double-crested cormorants did not attempt to re-nest at the site, or anywhere else on Rice Island.

### *Island with No Prior History of Successful Cormorant Nesting*

In contrast to the results from the test plot on Rice Island, the first successful nesting by double-crested cormorants at the test plot on Miller Sands Spit did not occur until the third year of the trial. Cormorants were observed congregated on the beach immediately adjacent to the test plot on several occasions, and also in the upland area near the plot on one occasion during the first year of deploying the plot; however, there was no evidence that cormorants attempted to nest on the plot during the first year. The first confirmation of cormorant nesting attempts in the test plot on Miller Sands Spit was recorded during the second year, when cormorants were observed carrying nest material to the plot 24 days after completion of plot preparations. Subsequently, a total of 21 partially or completely built cormorant nests and six cormorant eggs in four different nests were confirmed both within and immediately adjacent to the test plot. All of these cormorant nests failed prior to eggs hatching, however, presumably due to egg predation by glaucous-winged/western gulls (*L. glaucescens/occidentalis*), which nested in the vicinity of the plot. During disturbance events, when breeding cormorants leave nests unattended, the nest contents are highly susceptible to predation by gulls. Incubating cormorants leave their clutches unattended due to a variety of disturbance factors, including bald eagles, recreational boaters, and researchers (Adkins et al. 2010).

During the third year of deploying a test plot on Miller Sands Spit, double-crested cormorants successfully nested and fledged chicks for the first time on Miller Sands Spit, and did so again in the fourth year. Prospecting cormorants were first observed on the test plot 26 days and 28 days after completion of plot preparations in the third and fourth year, respectively, of the trial. Based on a single on-the-ground nocturnal nest and chick count, a total of 41 breeding pairs nested in the plot or immediately adjacent to the plot in the third year, with an average of 2.2 young raised per breeding pair (oldest chicks were approximately 28 days post-hatch). We counted 90 active nests in and around the test plot in the fourth year of the trial, with an average of 1.7 young raised per breeding pair (oldest chicks were approximately 40 days post-hatch).

During routine boat-based and aerial surveys in all years and extensive monitoring of the Miller Sands Spit test plot conducted from Rice Island in the third year, bald eagles and recreational boaters were both observed in the immediate vicinity of the plot. Eagles disturbed nesting cormorants in the plot and roosting cormorants on the beach below the plot at a similar rate to that measured at the Rice

Island test plot (ca. 0.1 disturbance events/daylight hour; total observation time for the Miller Sands Spit plot ca. 79 daylight hours). Recreational boaters were frequently observed in the area and on multiple occasions were seen driving along the shore within 15 m of the beach immediately below the test plot, causing cormorants roosting on the beach to flush and presumably disturbing prospecting cormorants on the plot as well.

### *Island with No Prior History of Cormorant Nesting*

No double-crested cormorants were observed on or in the immediate vicinity of the rocky islet at the mouth of Trestle Bay during the 2005 nesting season, when habitat enhancement and social attraction were deployed on the islet. Cormorants were seen in the Trestle Bay area during all surveys in 2005 (n = 16) except one; however, the majority of cormorants observed in the area were in sub-adult plumage. The highest number of cormorants recorded during a survey of the Trestle Bay area was 52. Bald eagles and/or recreational boaters were present in the Trestle Bay area during most surveys. Up to four eagles were observed in the bay on one occasion.

## DISCUSSION

Tests conducted as part of this study demonstrated that habitat enhancement and social attraction techniques can attract double-crested cormorants to nest at sites where they do not currently nest. Cormorants were enticed to nest in areas where they had not previously nested, adjacent to a large existing colony. A combination of habitat enhancement and social attraction were also used to successfully attract breeding cormorants that fledged young at a location that had been abandoned for two breeding seasons, and to establish a breeding colony that successfully fledged young where the only previous nesting attempts had failed. To our knowledge, our study represents the first case where double-crested cormorants, or any other cormorant species, have been successfully attracted to nest and raise young at sites where habitat enhancement and social attraction techniques were specifically employed for that purpose.

## Tests Adjacent to a Large Colony

The tests at East Sand Island demonstrated that habitat enhancement and social attraction techniques can create attractive nesting habitat for double-crested cormorants in areas where cormorants had not previously nested, on an island where a large nesting colony already existed. Cormorant nest initiation in the test plots was simultaneous with nest initiation in other sections of the colony where cormorants tended to initiate nesting early in the breeding season. This indicates that habitat enhancement and social attraction provided a set of cues that prospecting adult cormorants found as attractive as the cues present in nesting habitat that had been used during the previous nesting season. The simultaneous occupancy by cormorants of both the driftwood plot and the tire plot in the first year of the study, and of the newly built platforms in the second year of the study, indicates that double-crested cormorants can readily adapt to nesting on artificial structures. The similar cormorant nesting densities on the test plots compared to unmunipulated habitat of the colony also supports the interpretation that the habitat enhancement and social attraction techniques created nesting habitat that was attractive to cormorants breeding at the colony. The absence of any cormorant nesting attempts in former plots where habitat enhancement and social attraction had been removed suggests that double-crested cormorants avoid nesting on bare ground that lacks structure to build nests on. This result is of management interest because it suggests a potential technique for dissuading cormorants from nesting in locations where other natural resources are negatively affected: remove or modify the structure that supports nesting cormorants. Removing structure, such as piles of driftwood, in natural nesting habitat can potentially be used as a dissuasion technique for ground-nesting cormorants.

### *Factors Influencing the Success of Social Attraction*

Differences in the timing of the first prospecting adult cormorants on different treatment plots were minor, contrary to our expectations. In 2006, we expected that cormorants would be more attracted to and initiate nest building earlier on plots with treatment C (social attraction, raised platform) compared to plots with other treatments. Instead, the first observations of cormorants were on plots with treatment B (no social attraction, raised platform). This result could have been due to the nesting history on that platform in the previous year. Once cormorants started settling in, however, they appeared to favor plots with treatment A (social attraction, on ground), as indicated by the earlier colonization and higher number of nesting pairs compared to the plots in the other treatments.

In 2007, cormorants did not show a strong preference among the three treatments, probably because all plots regardless of treatment already had a history of cormorant nesting during the 2006 breeding season. This may explain the similarities in timing of nest initiation and number of active nests per plot among the three treatments. We did observe, however, some cormorants landing near test plots without social attraction that walked by without showing any interests in the plots, and instead headed directly towards a plot with decoys and playback speakers and immediately started exploring that plot. This suggests that decoys and/or vocalizations of cormorants combined with habitat enhancement are more effective in attracting nesting cormorants than just habitat enhancement alone.

The size of the East Sand Island colony steadily increased from 12,480 breeding pairs in 2004 to 13,770 breeding pairs in 2007 (Roby et al. 2008). The increasing colony size during the study period might have influenced the successful attraction of cormorants to test plots created in areas where cormorants had not previously nested, adjacent to the existing colony.

Prior to 2006, only old cormorant nests were used in test plots on East Sand Island, whereas fine woody debris was used instead on the test plots at Miller Sands Spit and the rocky islet at Trestle Bay. We were uncertain whether substituting fine woody debris as nesting material would be less attractive to cormorants than plots with old cormorant nests. Observations of cormorants prospecting at both types of nests and not seeming to distinguish between old cormorant nests and fine woody debris in plots at East Sand Island, combined with the results of successfully attracting cormorants to nest on test plots with no old cormorant nests (Rice Island and Miller Sands Spit) indicated that nest sites containing just fine woody debris can be effective habitat enhancement for double-crested cormorants.

### *Nesting Success*

Similar nesting success between test and control plots on the East Sand Island colony suggests that cormorants did not experience substantial differences in the quality of nesting habitat between plot types.

## Attracting Cormorants Away from a Large Colony

Habitat enhancement and social attraction techniques have been used for restoration of waterbird colonies since the late 1970s (Kress 1983), and many studies of social attraction have been conducted on avian species since then (reviews by Ahlering et al. 2010, Jones and Kress 2012). In cormorants, habitat enhancement and social attraction have been used to attempt to attract tree-nesting double-crested cormorants to nest on the ground (Feldmann 2011) and to restore a colony of Brandt's cormorants (*P. penicillatus*) as part of a restoration project for nesting common murres (*Uria aalge*; McChesney et al. 2004, 2005). In both studies, however, social attraction techniques did not succeed in inducing cormorants to nest at the intended locations.

In this study, the response of double-crested cormorants to habitat enhancement and social attraction at three separate islands in the Columbia River estuary where cormorants were not currently nesting varied from an immediate response to no response at all. A key factor that likely had a strong influence on the success of these tests with double-crested cormorants was the previous history of cormorant nesting or nesting attempts on the islands. The island with the most recent history of successful cormorant nesting displayed the most rapid response to habitat enhancement and social attraction, whereas no response whatsoever was observed on the island with no previous history of cormorant nesting or nesting attempts. The establishment of new double-crested cormorant colonies at sites distant from existing colonies using habitat enhancement and social attraction will likely be extremely difficult if there is no recent history of cormorant nesting or nesting attempts at the site. Other factors that likely played a major role in the size and nesting success of new cormorant colonies at social attraction sites were: (1) the frequency and intensity of disturbances by potential predators (e.g., bald eagles and humans), (2) predation pressure by gulls on cormorant eggs and young chicks, and (3) the presence of other breeding cormorants at nearby foraging and roosting areas.

Bald eagles have been observed harassing and depredating adult and juvenile double-crested cormorants at the East Sand Island colony, and the associated disturbance to nesting cormorants has resulted in the loss of large numbers of cormorant eggs to predation by glaucous-winged/western gulls (Adkins et al. 2010). The first cormorant egg laid on the test plot at Rice Island was confirmed when the egg was taken by a gull during a disturbance event caused by a bald eagle. Humans in the vicinity can also prevent cormorants from landing or nesting at sites that are otherwise suitable nesting habitat. Recreational boaters were observed repeatedly near the rocky islet at Trestle Bay and onshore immediately below the test plot on Miller Sands Spit. In contrast, no recreational boaters were seen near the test plot on Rice Island, where cormorants were successfully attracted to nest in the first year of the trial. If the techniques used in this study are employed for management or restoration of double-crested cormorant colonies, careful screening and evaluation of prospective new or restored colony sites appears crucial. Without this assessment, habitat enhancement and social attraction could fail, or might lure cormorants to nest in habitat where nesting success is consistently low (Schlossberg and Ward 2004). If cormorants have never historically nested at a site, or have previously nested but the colony was abandoned, the factors responsible need to be identified and thoroughly evaluated (Kress 1998, Ahlering et al. 2010). Also, choosing a colony location with considerable cormorant use during the nesting season appears to be an important factor for successful colony establishment. Although the number of years that habitat enhancement and social attraction need to be sustained after the establishment of a new colony was not examined in this study, long-term restoration projects of other seabird species used social attraction techniques for at least nine years (Kress and Nettleship 1988, Parker et al. 2007).

During 2007-2009, two additional test plots designed to attract nesting double-crested cormorants were created outside the Columbia River estuary using old tires and fine woody debris as habitat enhancement, plus decoys and audio playback systems as social attraction (Roby et al. 2008, Collis et al. 2009, Roby et al. 2010). One plot was on a floating platform in an impoundment at Fern Ridge Wildlife Area near Eugene, Oregon. Double-crested cormorants use the impoundment for foraging and roosting during winter and early spring, but there is no history of cormorant nesting in the area. The other plot was on a scaffolding platform on Foundation Island in the mid-Columbia River, where ca. 300 pairs of double-crested cormorants nested in trees. The scaffolding platform was 4.3 m above ground level and immediately adjacent to the arboreal cormorant colony. Neither of these efforts at using habitat enhancement and social attraction to either establish a new cormorant colony or expand an existing arboreal colony succeeded during a three-year trial period.

The unsuccessful attempt at attracting cormorants to nest on the test plot at Fern Ridge Wildlife Area was probably due to the lack of a previous history of cormorant nesting in the area, plus the presence of bald eagles in the vicinity of the floating platform. The long distance to a large source colony (approximately 250 km from East Sand Island) might have also been a contributing factor (Jones and Kress 2012) in the failure of habitat enhancement and social attraction to establish a cormorant colony at Fern Ridge Wildlife Area.

The failed attempt on Foundation Island suggests that double-crested cormorants nesting in trees may be reluctant to shift their nesting substrate to something new (artificial structure lower in elevation than nearby trees) when there was ample nesting habitat available in nearby trees.

Social attraction has been successfully used for restoration of breeding colonies for a number of tern species (Burger 1989, Dunlop 1991, Kress 1997). Caspian terns nesting in the Columbia River estuary exhibited a rapid response to habitat enhancement and social attraction techniques on East Sand Island, relocating their breeding colony from Rice Island to East Sand Island in just three breeding seasons (Roby et al. 2002). Also, using similar habitat enhancement and social attraction techniques, part of the East Sand Island tern colony has been relocated to alternative colony sites as far as 550 km from the estuary (Collis et al. 2009, Roby et al. 2010, Roby et al. 2011, Chapter 2). Double-crested cormorants, however, have been generally less responsive to habitat enhancement and social attraction than Caspian terns. Double-crested cormorants may be less likely than Caspian terns to respond to these techniques because they are more neophobic and wary of new nesting habitat than Caspian terns. The sensitivity of nesting double-crested cormorants to disturbance by predators and humans has been documented in this and previous studies (Henny 1989, Carter 1995, Chatwin 2002, Adkins et al. 2010), and cormorants may be more sensitive to these limiting factors for successful attraction than Caspian terns. Choosing locations with a history of cormorant nesting or nesting attempts and with minimal disturbance by humans and other potential predators appears to be important for successful attraction of nesting double-crested cormorants, more so than for Caspian terns.

Maximum foraging distance of double-crested cormorants from their breeding colony, as determined from radio-telemetry of adults nesting on East Sand Island, was

47 km (Anderson et al. 2004). Therefore, alternative colony sites for nesting cormorants that currently pose a significant threat to survival of fish species of conservation concern should be at least 50 km from sites where these fish species are vulnerable to cormorant predation. Post-breeding dispersal of satellite-tagged double-crested cormorants from the East Sand Island colony has been investigated (Courtot et al. in review), and the average maximum distances of northward and southward dispersal were approximately 215 km and 530 km, respectively. This suggests that cormorants from the East Sand Island colony may prospect for nesting sites hundreds of kilometers from the Columbia River estuary. However, whether these techniques for restoring or establishing new cormorant colonies can be effective at sites far from a source colony and with no history of cormorant nesting or nesting attempts remains questionable.

Habitat enhancement and social attraction techniques are potential applications in the effort to manage and restore breeding colonies of double-crested cormorants. In particular, if dispersing double-crested cormorants from an existing colony is part of a management plan, attracting displaced cormorants to specific alternative colony sites using these techniques deserves consideration as a means to minimize recruitment of breeding cormorants to other colony sites of management concern. In order to successfully induce double-crested cormorants to nest at new colony sites using these techniques, however, thorough assessment of prospective colony sites is a crucial first step. Long-term monitoring of incipient colonies is also critical for evaluating those factors that may influence the establishment and persistence of new cormorant breeding colonies.

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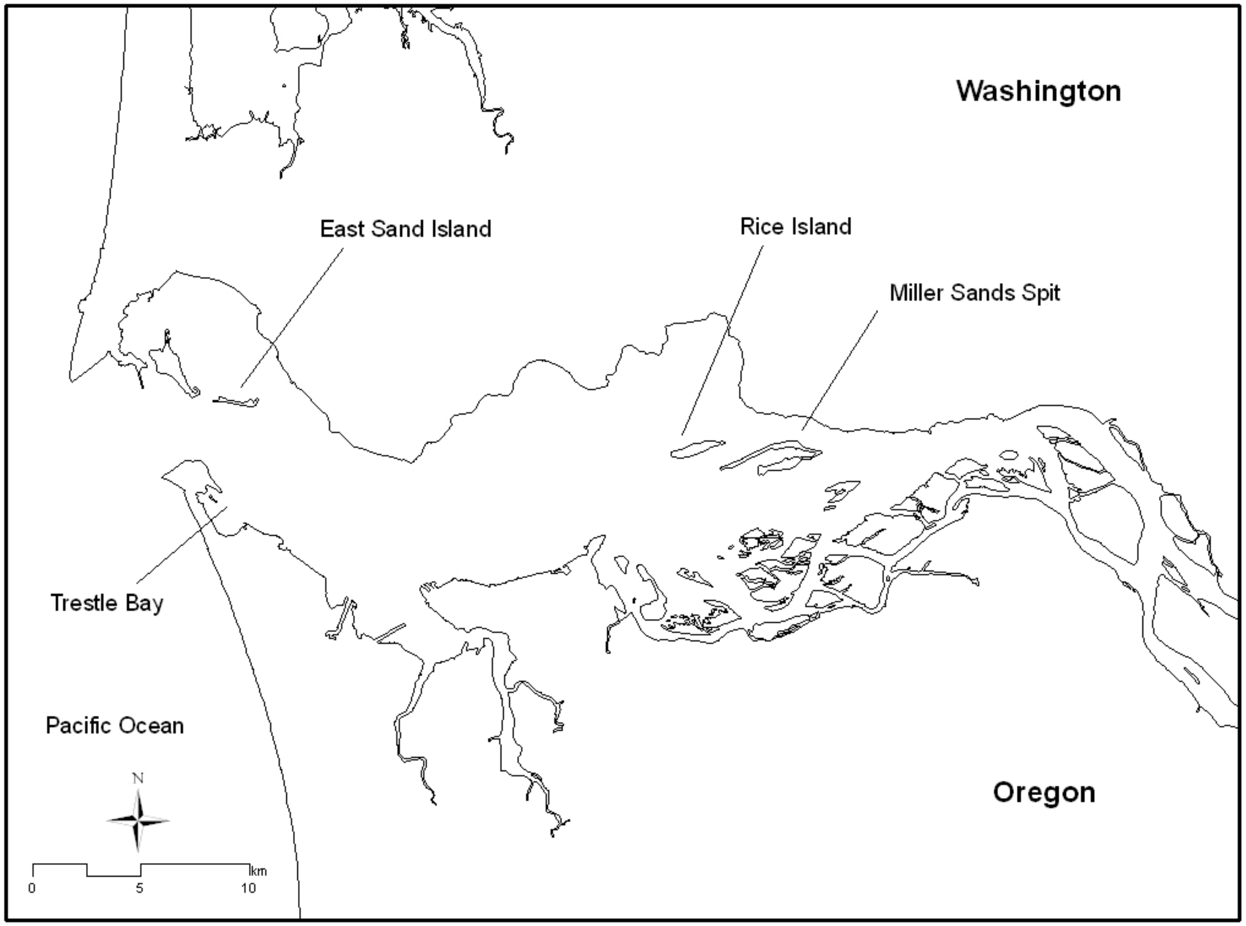

**Figure 4.1.** Map of the Columbia River estuary showing the location of islands where test plots for habitat enhancement and social attraction techniques for double-crested cormorants were created.

**Table 4.1.** Habitat enhancement and social attraction treatments on plots adjacent to the double-crested cormorant colony on East Sand Island in 2006 and 2007. Two of the six plots were designated for one of each of the three treatments in each year.

| Year | Treatment | Nesting substrate | Decoys and sound systems? | Previous nesting history? |
|---|---|---|---|---|
| 2006 | A | Tires filled with nest material on the ground | Yes | No |
|  | B | Tires filled with nest material on elevated platforms | No | Yes (one year) |
|  | C | Tires filled with nest material on elevated platforms | Yes | No |
| 2007 | D | Tires filled with nest material on the ground | No | Yes (one year) |
|  | E | Tires filled with nest material on elevated platforms | No | Yes (two years) |
|  | F | Tires filled with nest material on elevated platforms | Yes | Yes (one year) |

**Table 4.2.** Number of breeding pairs of double-crested cormorants that nested and nest density in each test plot for habitat enhancement and social attraction on East Sand Island during 2004-2007. Colony-wide nest densities for each year are presented for reference.

| Year | Plot/treatment | Area ($m^2$) | Number of breeding pairs | Nest density (active nests/$m^2$) | Colony-wide nest density (active nests/$m^2$) |
|---|---|---|---|---|---|
| 2004 | Driftwood | 41 | 94 | 2.3 | 0.7 |
| | Tires on ground | 99 | 162 | 1.6 | |
| 2005 | Tires on platform 1 | 25 | 29 | 1.2 | 1.2 |
| | Tires on platform 2 | 25 | 33 | 1.3 | |
| 2006 | A-1 | 25 | 37 | 1.5 | 1.1 |
| | A-2 | 25 | 39 | 1.6 | |
| | B-1 | 25 | 32 | 1.3 | |
| | B-2 | 25 | 30 | 1.2 | |
| | C-1 | 25 | 31 | 1.2 | |
| | C-2 | 25 | 32 | 1.3 | |
| 2007 | D-1 | 25 | 34 | 1.4 | 1.2 |
| | D-2 | 25 | 34 | 1.4 | |
| | E-1 | 25 | 34 | 1.4 | |
| | E-2 | 25 | 33 | 1.3 | |
| | F-1 | 25 | 34 | 1.4 | |
| | F-2 | 25 | 33 | 1.3 | |

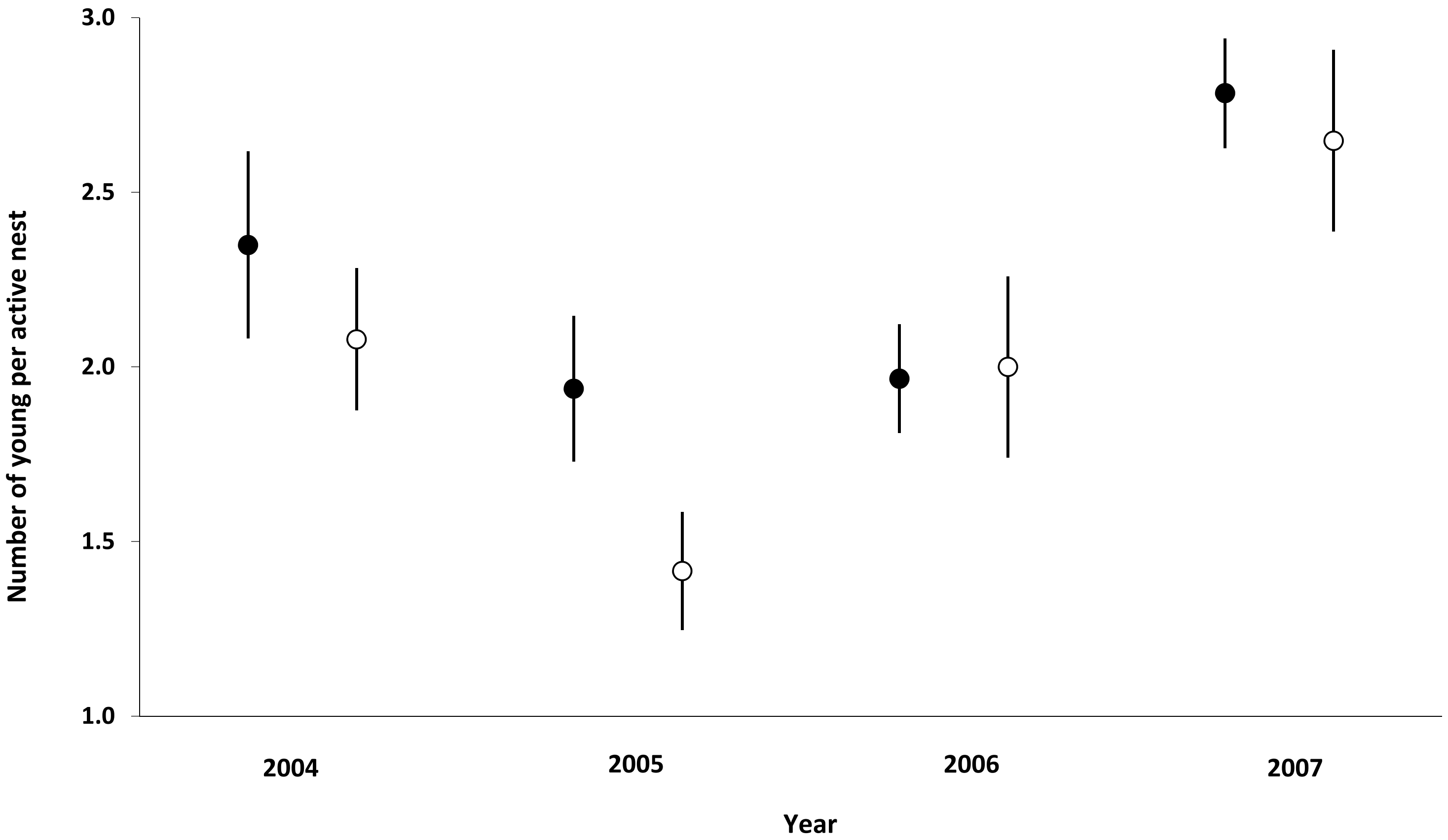

**Figure 4.2.** Nesting success of double-crested cormorants in test plots and control plots at East Sand Island during 2004-2007. Dark circles and open circles represent test and control plots, respectively. Error bars represent 95% confidence intervals.

# CHAPTER 5

# SYNOPSIS AND CONCLUSIONS

Yasuko Suzuki

This dissertation evaluated several aspects of the breeding ecology of two species of piscivorous colonial waterbirds, Caspian terns (*Hydroprogne caspia*) and double-crested cormorants (*Phalacrocorax auritus*), which nest in large numbers on East Sand Island in the Columbia River estuary. The primary motivation for this research is the impact of predation by these two species on fisheries in the Columbia River estuary, in particular out-migrating anadromous salmonids from throughout the Columbia River basin. More than half of the 20 evolutionarily significant units of salmonids (*Oncorhynchus* spp.) in the Columbia River basin are now listed as threatened or endangered under the U.S. Endangered Species Act (ESA; Good et al. 2005), due to population declines caused mainly by various human activities (Lichatowich 1999). Numbers of colonial piscivorous waterbirds nesting in the Columbia River estuary have increased dramatically over the past three decades; the sizes of the Caspian tern and double-crested cormorant colonies on East Sand Island have reached more than 9,500 and 13,000 breeding pairs, respectively, and these colonies are the largest known in North America for both species (Suryan et al. 2004, Adkins et al. 2010, Roby et al. 2011).

Avian predation on juvenile salmonids is considered a limiting factor for the recovery of Columbia Basin salmonids (National Oceanic and Atmospheric Administration 2004). Management actions to reduce the size of the Caspian tern colony on East Sand Island and disperse them to new nesting habitat provided at sites where ESA-listed salmonids would not be at risk (U.S. Fish and Wildlife Service et al. 2005, U.S. Fish and Wildlife Service 2006) were implemented starting in 2008 and are ongoing. Management actions to reduce the numbers of double-crested cormorants nesting on East Sand Island have not yet been implemented; however, management agencies have agreed that management of the double-crested cormorant colony on East Sand Island is warranted. To further our understanding of these two piscivorous colonial waterbirds and address multiple issues related to fisheries-piscivorous waterbird interactions in the Columbia River estuary, I conducted studies on Caspian terns and double-crested cormorants, with an emphasis on the demographic and behavioral characteristics of these two species nesting on East Sand Island.

I investigated the demographic characteristics and dispersal patterns of Caspian terns, with emphasis on individuals nesting at two colonies in the Pacific Coast region: the East Sand Island colony, which is the largest for the species in the world, and the Crescent Island colony, a much smaller colony on the mid-Columbia River in eastern Washington State. My study to better understand the current status of the Pacific Coast metapopulation was based on re-sightings of color-banded individuals. Breeding adult Caspian terns from these two colonies experienced high apparent annual survival (0.94 – 0.95), and sub-adults exhibited delayed onset of reproduction (median age at first reproduction of 5-6 years post-hatch). Colony philopatry by breeding adults at these two breeding colonies was high; however, dispersal of breeding adults to distant colonies was also observed. The spatial scale of the landscape used by some individual breeding adults was very extensive, from the Copper River Delta in south-central Alaska to the Salton Sea in southeastern California. Dispersal distances by breeding adults of up to 3,000 km between colonies within a single breeding season demonstrated the high vagility of Caspian terns in this population. The high connectivity amongst an extensive network of colony sites, due to dispersal of both experienced adults and sub-adults, reflects the species' adaptation to the dynamic availability of limited suitable nesting habitat. Observations of banded individuals from East Sand Island at a number of smaller, less productive colonies throughout the region suggest that the East Sand Island colony is an importance source colony for sustaining these smaller colonies.

Caspian terns from East Sand Island and other colonies responded quickly to the availability of new colony sites and established successful new breeding colonies in less than a year because of their great vagility and the high connectivity among colonies over a vast area. The managed reduction in nesting habitat for the East Sand Island colony, however, could also result in dispersal to colony sites other than those especially designed and built for their use, including sites where fish species of conservation concern may be negatively affected. My study and previous studies indicate that movement rates of breeding adults between colonies are influenced by annual productivity at the colony of origin (Catlin et al. 2005, Boulinier et al. 2008). Previous studies also demonstrated that sub-adults will readily leave their natal colony to prospect for nest sites at other colonies, especially when the habitat at the natal colony is comparatively poor (Suryan and Irons 2001, Kildaw et al. 2005). Management efforts to provide and maintain high quality nesting habitat that supports high annual productivity at new colony sites appear to be critical for minimizing unintended outcomes involving new tern/fisheries conflicts.

A comprehensive understanding of the current status and trends of the Pacific Coast population of Caspian terns requires a large-scale landscape approach and rigorous analysis methods to develop a reliable population model. In addition to annual apparent survival rates of adults, survival rates from fledging to one year post-hatch, and from one year post-hatch to recruitment into the breeding population need to be investigated. I was only able to estimate movement rates of breeding adults between two breeding colonies, East Sand Island and Crescent Island, in the Columbia River basin; evaluating movement rates among a larger proportion of colonies that comprise the Pacific Coast metapopulation will require more extensive and uniform efforts to band and re-sight individuals. Our study revealed that inter-colony movements by sub-adults and experienced adults occur over a vast area. Thus, the multi-state model used in this study should include more breeding colonies than just East Sand Island and Crescent Island and extend across the full range of the metapopulation from southern California to Alaska in order to obtain a better understanding of the population dynamics of Caspian terns in the Pacific Coast region.

Accumulation of environmental contaminants has been a concern for various species of wildlife in the Columbia River estuary (Buck et al. 2005, Johnson et al. 2007). Breeding colonies of Caspian terns and double-crested cormorants on East Sand Island in the Columbia River estuary represent large proportions of their respective regional populations. I evaluated the extent of polychlorinated biphenyl

(PCB) accumulation, the sources of ingested PCBs, and the factors that influence PCB body burdens in terns and cormorants nesting at East Sand Island. For comparison, PCB levels in these two avian species and their prey were also investigated at other locations farther up the Columbia River where these species nest. PCB levels in cormorant eggs and chick livers were higher for cormorants nesting in the upper part of the Columbia River estuary, 30 km above East Sand Island. PCB levels in chick livers were higher for terns nesting on an island in the mid-Columbia River than for terns nesting on East Sand Island.

Evaluation of cormorant and tern diet composition, as determined by conventional diet study methods and carbon and nitrogen stable isotope analyses, indicated that higher PCB levels in eggs and chick livers were associated with diets dominated by resident freshwater and estuarine fishes, which had higher PCB levels than juvenile salmonids or marine forage fishes. I found a positive correlation between PCB levels in prey fish and their lipid content, which had been expected based on the lipophilic properties of PCBs. A negative correlation between PCB levels in chick livers and the fat scores of chicks suggested that fat reserves of chicks serve as a sink for ingested PCBs. Lower PCB levels in terns and cormorants nesting on East Sand Island, where I had predicted higher PCB levels compared to the same species nesting in other locations, appeared to reflect the higher proportion of marine forage fish in the diet at East Sand Island.

Estuarine systems offer unique opportunities for piscivorous colonial waterbirds to prey on a variety of prey fish types, including freshwater, estuarine, and marine forage fishes. In the case of the Columbia River estuary, juvenile salmonids of both wild and hatchery origin are also potential primary prey types. The significant differences in PCB levels of cormorant eggs between the East Sand Island colony in the lower estuary and the Miller Sands channel markers colony in the upper estuary (only 30 km apart) emphasizes the importance of evaluating contaminant accumulation in piscivorous colonial waterbirds at a local scale in systems where diet composition can vary greatly over short distances.

My study also revealed that accumulation of lipophilic contaminants in the livers of piscivorous waterbirds can be partly explained by their fat reserves (in this study, the fat score of chicks). This suggests the importance of fat depots as a sink for lipophilic contaminants, as well as the potential influence of body condition when samples are collected and the tissue types analyzed for the interpretation of geographical or temporal patterns of contaminant accumulation (Henriksen et al. 1996). Although terns and cormorants nesting at East Sand Island had lower PCB levels in eggs and chick livers than at some other colonies in the Columbia River basin, PCB levels in some cormorant eggs from East Sand Island exceeded the no observable adverse effect level reported by Giesy et al. (1994). All cormorant eggs collected from the upper estuary and some cormorant eggs from the mid-Columbia River also exceeded the no observable adverse effect level. Further monitoring of the levels of PCBs and other contaminants at colonies that revealed higher PCB levels seems prudent. Long-term monitoring of contaminant accumulation in Caspian terns and double-crested cormorants nesting at East Sand Island is also desirable to evaluate whether environmental contaminants pose threats to large proportions of the regional populations of piscivorous waterbirds, especially during those breeding seasons when the diet consists primarily of freshwater and estuarine fishes.

The double-crested cormorant colony on East Sand Island represents approximately 40% of the breeding pairs belonging to the western North America population. Therefore, destructive control measures that have been used to reduce numbers of double-crested cormorants at breeding colonies in interior/eastern North America (hazing and lethal control of adults, nest destruction, and egg destruction through oiling; Hatch and Weseloh 1999, Wires and Cuthbert 2006) would have a disproportionately large impact on the western North American population, if such methods were applied to the East Sand Island colony. In order to explore non-destructive management methods, I tested habitat enhancement and social attraction techniques (Kress 1983, Roby et al. 2002, Jones and Kress 2012) to evaluate whether such methods are suitable for attracting double-crested cormorants to nest at sites outside the Columbia River estuary.

Trials conducted on plots adjacent to the cormorant colony on East Sand Island, where cormorants had not previously nested, demonstrated that plots with habitat enhancement and social attraction were colonized quickly by cormorants that subsequently raised young to fledging age. When similar test plots were placed on two islands in the estuary approximately 25 km from East Sand Island, one with a history of cormorant nesting and the other with a history of one unsuccessful nesting attempt, cormorants were attracted to nest and young were successfully raised on both plots. In contrast, no cormorants were attracted to a third island where there had been no history of nesting or nesting attempts. Thus, a previous history of cormorant nesting or at least nesting attempts appears to be an important factor influencing the effectiveness of these techniques for attracting breeding cormorants. I also identified other factors that may influence successful attraction of nesting cormorants, including: (1) the presence of breeding cormorants nearby; (2) the presence of potential predators; and (3) gull predation pressure on cormorant eggs and chicks.

My study documented important behavioral differences between double-crested cormorants and Caspian terns in response to habitat enhancement and social attraction techniques for establishing new breeding colonies. Caspian terns responded rapidly to these techniques when the entire breeding colony was relocated within the Columbia River estuary (Roby et al. 2002) and when some terns from the colony were redistributed to alternative colony sites outside the estuary (see Chapter 2). Double-crested cormorants were less responsive, however, to these techniques compared to Caspian terns, and appeared warier of unfamiliar settings and more sensitive to disturbance caused by humans and other potential predators. Therefore, identifying historical nesting sites of double-crested cormorants and efforts to limit disturbance by humans and other predators appear to be necessary steps for successful attraction of breeding cormorants and establishment of new colonies using habitat enhancement and social attraction techniques.

In this study, we tested social attraction (presence of conspecifics) using decoys and vocalizations of adult cormorants. However, performance-based information (i.e., reproductive success of other individuals) could assist birds in identifying high-quality breeding sites. If individuals tend to initiate nesting at a site in the year following visiting the colony when many adults were raising young, this may be a more important factor in decisions on nesting habitat selection than social attraction *per se* (Boulinier et al. 1996, Danchin et al. 1998, Doligez et al. 2002, Boulinier et al. 2008). This mechanism for nesting habitat selection has also been reported in great cormorants (*P. carbo*; Schjørring et al. 1999). Boulinier et al. (1996) suggested that the peak of prospecting for nesting habitat occurs when information on reproductive success by others is readily available, usually late in chick-rearing, but before young fledge. Therefore, using chick decoys and chick vocalizations later in the breeding season might enhance social attraction of prospecting cormorants and result in their return to the site in the following breeding season. This approach might be especially worthwhile when attempts to attract cormorants early in the breeding season with adult decoys and vocalizations are not successful.

Based on the results of my study, habitat enhancement and social attraction techniques have some potential as techniques to manage and restore breeding colonies of double-crested cormorants. These techniques appear to deserve consideration especially if double-crested cormorants are dispersed from an existing colony, as has been done with Caspian terns nesting in the Columbia River estuary.

From the perspective of salmon conservation and fisheries management, the large numbers of Caspian terns and double-crested cormorants nesting in the

Columbia River estuary have been seen as a significant obstacle to effective restoration of depleted fish stocks. However, both bird species are also native to the Pacific Northwest region of North America and protected under the Migratory Bird Treaty Act. Redistribution of some of the terns and cormorants nesting on East Sand Island to historical or new nesting sites could benefit the birds, as well as reduce their impact on the recovery of ESA-listed salmonids from the Columbia River basin. The potential benefits to protected bird populations relate to the large proportion of the western North America populations of both Caspian terns and double-crested cormorants that currently concentrate their nesting efforts at one location: East Sand Island. Local threats, such as environmental disasters, infectious diseases, introduced predators, and environmental contaminants, could have a potentially much greater impact on the population as a whole if large proportions of the populations nest at one site.

Management actions designed to redistribute colonial species over a broader geographic area require a comprehensive understanding of the species' ecology. This dissertation focused on the ecology of Caspian terns and double-crested cormorants nesting in the Columbia River estuary from several different perspectives relevant to the management of interactions between these piscivorous colonial waterbirds and fish of conservation concern. The results from this dissertation highlighted that (1) understanding current status and trends of piscivorous colonial waterbird populations requires approaches at large temporal and spatial scales (Chapter 2), (2) evaluating risks to piscivorous waterbird colonies necessitates fine-scale temporal and spatial approaches (Chapter 3), and (3) developing effective conservation and management plans for piscivorous colonial waterbirds requires knowledge of species-specific behavioral responses to environmental conditions (Chapter 4).

The results from this dissertation fill in some important gaps in our knowledge of the demography, susceptibility to environmental contaminants, and behavior of Caspian terns and double-crested cormorants in the Columbia River estuary. My dissertation will assist with informed management planning and decisions for Caspian terns and double-crested cormorants, not only in the Columbia River estuary, but throughout the Pacific Coast region of North America. Findings of this dissertation also raise some concerns over the management of Caspian tern and double-crested cormorant colonies on East Sand Island, to redistribute parts of these colonies to alternative sites, in order to mitigate the impact of those piscivorous colonial waterbirds on ESA-listed salmonids. The Caspian tern colony on East Sand Island has supported a source colony for many smaller, less productive Caspian tern colonies throughout the Pacific Coast region. East Sand Island is also a better location, at least in terms of PCB accumulation in piscivorous colonial waterbirds, because it is closer to an abundant and relatively uncontaminated food supply compared to colonies farther upriver. And finally, using habitat enhancement and social attraction techniques may not be as effective for redistributing double-crested cormorants as they have been for Caspian terns. Alternative colony sites that can substitute for East Sand Island are also not readily apparent, especially for double-crested cormorants.

Therefore, management of Caspian tern and double-crested cormorant colonies on East Sand Island to benefit Columbia Basin salmonids need to proceed cautiously and reversibly because of the implications for the region-wide populations of these two piscivorous colonial waterbirds. An adaptive management framework for reducing the conflicts between piscivorous colonial waterbirds and ESA-listed salmonids is necessary considering the uncertainties and unpredictability of managing the regional populations of piscivorous colonial waterbirds over very large landscape scales.

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