AN ABSTRACT OF THE THESIS OF

Lindsay J. Adrean for the degree of Master of Science in Wildlife Science presented
on June 2, 2011.
Title: Caspian Tern (*Hydroprogne caspia*) Foraging Ecology and Predation on
Juvenile Salmonids in San Francisco Bay, California.

Abstract approved:

_____

Daniel D. Roby

Brooks Island, located in central San Francisco Bay, California, currently

supports the largest breeding colony of Caspian terns (*Hydroprogne caspia*) in the Bay

Area, and is one of several proposed relocation sites for some Caspian terns from the

world's largest colony in the Columbia River estuary of Oregon. Juvenile salmonids

have been identified in the diet of Caspian terns nesting at Brooks Island, so I

investigated whether the colony, at its current or an enhanced size, poses a threat to the

recovery of several runs of salmonids (*Oncorhynchus* spp.) in San Francisco Bay that

are listed under the U.S. Endangered Species Act (ESA). I also examined the foraging

ecology of Brooks Island Caspian terns to 1) determine whether the colony is suitable

for expansion based on availability of forage fish resources, a factor potentially

limiting the size and productivity of the colony, and 2) investigate how Caspian terns

nesting at this colony exploit forage fish resources.

I used a bioenergetics modeling approach, employing estimates of tern energy

requirements and proportions of energy supplied by various prey types, to estimate

consumption of juvenile salmonids by Caspian terns nesting on Brooks Island during

2008 and 2009. Estimated salmonid consumption was 205,000 smolts (95% CI:

175,000 – 245,000 smolts) in 2008 and 167,000 smolts (95% CI: 144,000 – 191,000

smolts) in 2009. Predation rates on ESA-listed Central Valley spring-run Chinook

salmon (*O. tshawytscha*; 0.08%) were lower than those on unlisted fall-run Chinook

salmon (1.0%). Average per capita predation rates on juvenile salmonids by Brooks

Island Caspian terns (2008: 126 fish; 2009: 123 fish) were less than half those of

Caspian terns nesting in the Columbia River estuary. If the current downward trend in

the number of Caspian terns nesting on Brooks Island continues until the colony is no

longer extant, the resulting declines in predation on salmonids would lead to increases

in annual population growth rates ($\Delta\lambda$) of salmonid runs of just small fractions of one

percentage point. The proposed enhancement of the Brooks Island Caspian tern

colony to 3,000 individuals would at most cause declines in annual population growth

rates of 0.3% for fall-run Chinook salmon and 0.02% for threatened spring-run

Chinook salmon, assuming that smolt mortality from tern predation is 100% additive.

This level of impact to the ESA-listed spring-run Chinook salmon stock is less than

the level considered acceptable by the National Marine Fisheries Service ($\Delta\lambda$ =

0.05%).

Radio-tracking of Caspian terns nesting on Brooks Island revealed that the

maximum foraging distance from the colony was 80 km. The median foraging

distance from the colony was greater in 2009 compared to 2008 (20.6 km vs. 14.0

km), average number of foraging trips per day was higher (4.4 vs. 3.4 foraging trips),

and average adult colony attendance was lower (43% vs. 52% of daylight hours).

These results indicate that the colony was more food-limited during the 2009 breeding

season, concurrent with anomalous downwelling along the coast of northern California

and reduced availability and size of marine forage fishes, such as herring, sardines,

and anchovies. Caspian terns used a number of core foraging areas within 30 km of

the Brooks Island colony, both inside and just outside the Bay. Two large core

foraging areas were close to or overlapped with the release site for juvenile salmonids

in eastern San Pablo Bay, where > 10 million hatchery-raised smolts were released

from net pens during both the 2008 and 2009 tern nesting seasons. This finding

supports the hypothesis that most juvenile salmonids consumed by terns nesting at the

Brooks Island colony were captured at or near the release site. Individual Caspian

terns displayed foraging site fidelity, suggesting that foraging at the release site for

hatchery-raised salmonids was a learned behavior by some terns. The Brooks Island

colony site is within foraging distance of adequate marine forage fish resources in

most years, and Caspian terns nesting there are not dependent on juvenile salmonids as

a food resource. Consumption of juvenile salmonids by Brooks Island terns would be

largely curtailed by modification of hatchery release practices.

Caspian Tern (*Hydroprogne caspia*) Foraging Ecology and Predation on Juvenile

Salmonids in San Francisco Bay, California

by

Lindsay J. Adrean

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 2, 2011
Commencement June 2012

Master of Science thesis of <u>Lindsay J. Adrean</u> presented on June 2, 2011.

APPROVED:

_____

Major Professor, representing Wildlife Science

_____

Head of the Department of Fisheries and Wildlife

_____

Dean of the Graduate School

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

_____

Lindsay J. Adrean, Author

ACKNOWLEDGMENTS

CONTRIBUTION OF AUTHORS

Dr. Daniel D. Roby acquired funding, assisted with study design and interpretation of results, and provided editorial comments for all chapters. Dr. Donald E. Lyons provided training in field and laboratory methods, and assisted with study design, data analysis, and interpretation of Chapters 2 and 3. Ken Collis assisted with logistics for all chapters. Allen F. Evans contributed to field work, data processing and analysis, and interpretation of results for Chapter 2.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

CASPIAN TERN (HYDROPROGNE CASPIA) FORAGING ECOLOGY AND

PREDATION ON JUVENILE SALMONIDS IN SAN FRANCISCO BAY,

CALIFORNIA

CHAPTER 1

GENERAL INTRODUCTION

Lindsay J. Adrean

The Caspian tern (*Hydroprogne caspia*) breeding population in San Francisco Bay has been declining since a peak of approximately 1,400 nesting pairs was recorded in 2004 (Collis et al., In review). Brooks Island, located in the Central Bay, is currently the site of the largest Caspian tern colony in the Bay Area and has supported an average of 80% of all nesting pairs since the year 2000 (Strong et al. 2004; Collis et al., In review). This nesting colony is apparently limited by vegetation encroaching on the preferred bare sand habitat, erosion of nesting substrate, and predation from adjacent colonies of western gulls (*Larus occidentalis*) and California gulls (*L. californicus)* (Collis et al., In review). Other available Caspian tern nesting habitat in the Bay Area consists mostly of small islands located in salt ponds. Many of these salt ponds are slated for inclusion in salt marsh restoration projects and the continued availability of Caspian tern nesting habitat in the Bay Area is uncertain (Seto et al. 2003).

The San Francisco Bay estuary has also been subject to anthropogenic and climatic influences that have caused serious declines in fish populations since the 1970's (Meng et al. 1994, Feyrer et al. 2007, Lindley et al. 2009). Salmonid populations were once prolific in the Sacramento and San Joaquin river drainages, with Chinook salmon (*Oncorhynchus tshawytscha*) and anadromous steelhead (*O. mykiss*) runs both estimated to have historically consisted of 1-2 million spawning adults (Yoshimaya et al. 1998, McEwan 2001). Two out of four runs of Chinook salmon in the Bay Area are now listed under the Endangered Species Act (ESA).

Dam construction blocks access to about 80% of historical steelhead spawning habitat in the Central Valley (Lindley et al. 2006). Both steelhead runs found in the Bay Area are listed as threatened under the ESA.

Farther north along the Pacific Coast in Oregon is East Sand Island, located in the Columbia River estuary, which supports a Caspian tern colony of approximately 9,500 breeding pairs. This colony is by far the largest of its kind in the world, and represents about two-thirds of the entire breeding population of the Pacific coast Caspian terns. Yet Caspian terns were not recorded as nesting in the Columbia River estuary prior to 1984. Over the breeding seasons of 2001 – 2006, the prey items in the diet of Caspian terns at this colony consisted of 27% juvenile salmonids on average. Bioenergetics modeling estimated that Caspian terns from this colony consumed 5.3 million juvenile salmonids per year, equivalent to about 5% of out-migrating salmonid smolts that reach the estuary (Lyons 2010). The Columbia River basin is home to 20 evolutionarily significant units (ESUs; Waples 1995) of anadromous salmonids, of which 13 are listed as threatened or endangered under the ESA. Caspian tern predation is considered a limiting factor to salmonid recovery in the Columbia River basin (Good et al. 2005). In 2006 the U. S. Fish and Wildlife Service and the U. S. Army Corps of Engineers signed Records of Decision for "Caspian Tern Management to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary". This management plan calls for a reduction in the amount of suitable Caspian tern nesting habitat on East Sand Island from five acres to less than two acres, with simultaneous

creation or enhancement of at least seven acres of tern nesting habitat at six alternative colony sites in areas outside of the Columbia River estuary in interior Oregon and northern California (USFWS 2006, USACE 2006).

Three proposed alternative Caspian tern colony sites are located within San Francisco Bay. The Caspian Tern Management Plan proposes habitat enhancement for nesting Caspian terns at Brooks Island and construction of new islands in Hayward Regional Shoreline Park and Don Edwards National Wildlife Refuge to accommodate 1,500 breeding pairs at each of the three sites (NOAA 2006). Resource managers have encountered obstacles to construction of new islands at the latter two sites, and more information on the consumption of juvenile salmonids by Caspian terns nesting on Brooks Island is desired before initiating enhancement of tern nesting habitat at this site.

In 2006 the National Marine Fisheries Service prepared a Biological Opinion, which stated that the creation of alternative Caspian tern colony sites in San Francisco Bay would not be likely to jeopardize any ESA-listed salmonid run (NOAA 2006). As part of this Biological Opinion the Corps of Engineers agreed to implement monitoring at any proposed Caspian tern nesting site where ESA-listed salmonids occurred in the diet. The Brooks Island colony was of particular concern because it is located nearest to the Sacramento River delta, where several of the ESA-listed salmonid runs enter San Francisco Bay. Salmonids were identified as < 5% of prey items during diet monitoring at this Caspian tern colony during 2003 – 2005, and <

10% of prey items during 2008 – 2009 (Collis et al., In review). In 2008, salmonids in the diet were identified to species and evolutionarily significant unit (ESU) based on smolt coded wire tags (CWTs) recovered on the Brooks Island tern colony (Evans et al. 2011). Recovered CWTs indicated that nearly all salmonid smolts consumed by terns nesting at Brooks Island were from the unlisted Central Valley fall-run Chinook salmon ESU. The fall-run Chinook ESU is the predominant salmonid run in the Bay Area and several hatchery release sites for this ESU are located within 20 kilometers of Brooks Island (FFC 2008, 2009).

Hatchery release practices can offer piscivorous waterbirds and other predators opportunities to exploit highly concentrated prey (Collis et al. 1995), which may be stressed and therefore more vulnerable to predation (Olla et al. 1992). Diet composition from a historical Caspian tern colony at Knight Island, in the Napa-Sonoma marsh complex along the northern edge of San Pablo Bay, seems to support this supposition. The diet composition of Caspian terns nesting at this site during 2003 - 2005 consisted of > 20% juvenile salmonids on average (Collis et al., In review), and the colony was located only about 10 km from net pen release sites for hatchery-raised salmonids. The Knight Island colony site is currently subject to flooding at high tide and is no longer suitable as Caspian tern nesting habitat. The data on diet composition at this former Caspian tern colony, together with the CWT recovery data from the Brooks Island colony, suggest that Caspian terns in San

Francisco Bay are opportunistic foragers that will take advantage of available prey resources located close to the colony site.

To address concerns about maintaining or increasing the size of the Caspian tern colony on Brooks Island, I conducted a study examining the magnitude of predation on juvenile salmonids and other prey types. I quantified consumption of all identified prey types in 2008 and 2009 using bioenergetics modeling. I also investigated the impact of tern predation on annual population growth rates of salmonid runs, based on the scenarios of (1) tern colony size and diet as it was in 2008 and (2) the proposed increase in tern colony size to 1,500 nesting pairs.

Caspian tern nesting productivity at Brooks Island in recent years has ranged from an annual average of 0.14 chicks raised per breeding pair to an average of 0.62 chicks raised per breeding pair (Collis et al., In review), indicating that the colony may be exposed to variable factors limiting nesting success. Through radio-tracking of foraging Caspian terns, I sought to discover commonly used foraging areas and determine whether Brooks Island is an appropriate site for a Caspian tern breeding colony based on apparent food availability. I explored the use of various areas of the Bay for foraging and examined the relationship between foraging patterns and diet composition.

The main objectives of this study of the diet and foraging ecology of Caspian terns nesting at the Brooks Island colony were to (1) quantify the number of juvenile salmonids consumed, (2) estimate impacts to ESA-listed salmonids from tern

predation, (3) investigate food availability as a potential limiting factor for the tern colony, and (4) investigate how Caspian terns exploit forage fish resources in San Francisco Bay. The results of this study will provide valuable information to aid in management decisions that will simultaneously affect the conservation of avian communities and threatened fish species in the San Francisco Bay Area.

LITERATURE CITED

Collis, K., R.E. Beaty, and B.R. Crain. 1995. Changes in catch rate and diet of northern squawfish associated with the release of hatchery-reared juvenile salmonids in a Columbia River reservoir. North American Journal of Fisheries Management 15: 346–357.

Collis, K., D.D. Roby, K.W. Larson, L.J. Adrean, S.K. Nelson, A.F. Evans, D.S. Battaglia, D.E. Lyons, T.K. Marcella, and A. Patterson. In review. Trends in Caspian tern nesting and diet in San Francisco Bay: Management implications. Submitted to *Waterbirds*.

Evans, A.F., D.D. Roby, K. Collis, B.M. Cramer, J.A. Sheggeby, L.J. Adrean, D.S. Battaglia, and D.E. Lyons. 2011. Recovery of coded wire tags on a Caspian tern colony in San Francisco Bay: A technique to evaluate impacts of avian predation on juvenile salmonids. North American Journal of Fisheries Management 31: 79-87.

Feyrer, F., M.L. Nobriga, and T.R. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences 64: 723-734.

FFC (Fishery Foundation of California). 2008. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 10p.

FFC (Fishery Foundation of California). 2009. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 11p.

Good, T.P., R.S. Waples, and P. Adams [ed]. 2005. Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-NWFSC-66. 598p.

Lindley, S.T., R.S. Schick, A. Agrawal, M. Goslin, T.E. Pearson, E. Mora, J.J. Anderson, B. May, S. Greene, C. Hanson, A. Low, D. McEwan, R.B. MacFarlane, C. Swanson, J.G. Williams. 2006. Historical population structure of Central Valley steelhead and its alteration by dams. San Francisco Estuary and Watershed Science 4: Article 3. 19p.

Lindley, S.T., C.B. Grimes, M.S. Mohr, W. Peterson, J. Stein, J.T. Anderson, L.W. Botsford, D.L. Bottom, C.A. Busack, T.K. Collier, J. Ferguson, J.C. Garza, A.M. Grover, D.G. Hankin, R.G. Kope, P.W. Lawson, A. Low, R.B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F.B. Schwing, J. Smith, C. Tracy, R. Webb, B.K. Wells, and T.H. Williams. 2009. What caused the Sacramento River fall Chinook stock collapse? U.S. Department of Commerce, NOAA Technical Memorandum. NOAA-TM-NMFS-SWFSC-447. 62p.

Lyons, D.E. 2010. Bioenergetics-based predator-prey relationships between piscivorous birds and juvenile salmonids in the Columbia River estuary. Unpubl. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 331 p.

McEwan, D. R. 2001. Central Valley steelhead. *In* R. L. Brown (ed.), Fish Bulletin 179: Contributions to the Biology of Central Valley Salmonids, vol. 1, p. 1–43. California Department of Fish and Game, Sacramento.

Meng, L., P.B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and introduced fished of Suisun marsh. Transactions of the American Fisheries Society 123: 498-407.

NOAA (National Oceanic and Atmospheric Administration). 1998. Endangered and threatened species: threatened status for two ESUs of steelhead in Washington, Oregon, and California. Federal Register 63: 53 (19 March 1998): 13347-13371.

NOAA. 2006. Biological Opinion for Caspian tern management plan to reduce predation of juvenile salmonids in the Columbia River estuary. NOAA Fisheries, Portland, Oregon.

NOAA. 2008. Fisheries off west coast states and in the western Pacific; west coast salmon fisheries; 2008 management measures and a temporary rule. Federal Register 73:85(1 May 2008):23971-23981.

NOAA. 2009. Fisheries off west coast states and in the western Pacific; West coast salmon fisheries; 2009 management measures. Federal Register 74: 85 (5 May 2009): 20610-20620.

Olla, B.L., M.W. Davis, and C. B. Schreck. 1992. Comparison of predator avoidance capabilities with corticosteroid levels induced by stress in juvenile coho salmon. Transactions of the American Fisheries Society 121: 544-547.

Seto, N., J. Dillon, W.D. Shuford, and T. Zimmerman. 2003. A review of Caspian tern (*Sterna caspia*) nesting habitat: A feasibility assessment of management opportunities in the U.S. Fish and Wildlife Service Pacific Region. U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR.

Strong, C.M., L.B. Spear, T.P. Ryan, R.E. Dakin. 2004. Forster's tern, Caspian tern, and California gull colonies in San Francisco Bay: habitat use, numbers and trends, 1982-2003. Waterbirds 27: 411-423.

USACE (U.S. Army Corps of Engineers). 2006. Record of Decision Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USACE, Portland, Oregon.

USFWS (U.S. Fish and Wildlife Service). 2006. Record of Decision: Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USFWS, Portland, Oregon.

Waples, R.S. 1995. Evolutionarily significant units and the conservation of biological diversity under the Endangered Species Act. American Fisheries Society Symposium 17: 8–27.

Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. North American Journal of Fisheries Management 18: 487-521.

CHAPTER 2

CASPIAN TERN (HYDROPROGNE CASPIA) PREDATION ON JUVENILE
SALMONIDS AND OTHER FORAGE FISHES IN SAN FRANCISCO BAY,
CALIFORNIA

Lindsay J. Adrean, Daniel D. Roby, Donald E. Lyons, Ken Collis, and Allen F. Evans

ABSTRACT

San Francisco Bay is a proposed relocation site for some of the Caspian terns (*Hydroprogne caspia*) currently nesting at the world's largest colony for the species in the Columbia River estuary. Several runs of salmonids (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act (ESA) occur in San Francisco Bay, however, and managers are concerned that increased Caspian tern predation may pose a threat to the recovery of these salmon. We used a bioenergetics modeling approach, employing estimates of tern energy requirements and proportions of energy supplied by various prey types, to estimate consumption of juvenile salmonids by Caspian terns nesting on Brooks Island in central San Francisco Bay during 2008 and 2009. Estimated salmonid consumption was 205,000 smolts (95% CI: 175,000 – 245,000 smolts) in 2008 and 167,000 smolts (95% CI: 144,000 – 191,000 smolts) in 2009. The inter-annual difference in smolt consumption was due to the smaller size of the tern colony and lower nesting success in 2009. Coded wire tags from salmon that were recovered on the tern colony were used to estimate relative stock-specific predation rates on Chinook salmon (*O. tshawytscha*) by Caspian terns nesting on Brooks Island. Predation rates on ESA-listed Central Valley spring-run Chinook (0.08%) were lower than those on unlisted fall-run Chinook (1.0%). Continuation of the current downward trend in the number of Caspian terns nesting on Brooks Island, and resulting reductions in salmonid predation, would not be sufficient to reverse salmonid declines in San Francisco Bay, regardless of salmonid stock. The proposed enhancement of the

Brooks Island Caspian tern colony to 3,000 individuals would at most cause declines in annual population growth rates (λ) of 0.3% for fall-run Chinook salmon and 0.02% for threatened spring-run Chinook, assuming mortality from tern predation is 100% additive. This level of impact to the ESA-listed spring-run Chinook stock is less than the level considered acceptable by the National Marine Fisheries Service ($\Delta\lambda$ = 0.05%).

INTRODUCTION

Caspian terns (*Hydroprogne caspia*) were first recorded nesting in San Francisco Bay in 1916 (Grinnell and Miller 1944). In 2009, nearly a century later, there were six breeding colonies of Caspian terns in the Bay Area, with a total breeding population of approximately 830 breeding pairs (Collis et al. In review). The largest of these colonies was located on a sandy spit of dredged material extending from Brooks Island near Richmond, California, where more than 80% of the breeding population in the Bay Area nested. The size of this Caspian tern colony is limited by the availability of bare sand, their preferred nesting substrate. Encroaching vegetation and erosion of nesting substrate are factors that apparently constrain the size of this colony, and predation from western gulls (*Larus occidentalis*) and California gulls (*L. californicus)* nesting immediately adjacent to the tern colony further limits its size and productivity (Collis et al., In review). Other available nesting habitat for Caspian terns in the Bay Area consists mostly of small islands located in salt ponds. Many of these salt ponds are slated for inclusion in salt marsh restoration projects and the continued availability of nesting habitat for Caspian terns in the Bay Area is uncertain (Seto et al. 2003).

Brooks Island is one of three sites in San Francisco Bay listed as a proposed alternative colony site in the 2006 Records of Decision for "Caspian Tern Management to Reduce Predation on Juvenile Salmonids in the Columbia River Estuary" (USFWS 2006). The intent of resource managers responsible for

implementing the plan was to provide additional Caspian tern nesting habitat on Brooks Island so as to accommodate up to 1,500 breeding pairs of Caspian terns, including some displaced from the Columbia River estuary. In 2006 the National Marine Fisheries Service (NMFS), which has management authority for all anadromous salmonids (*Oncorhynchus* spp.) listed under the U.S. Endangered Species Act (ESA), prepared a Biological Opinion stating that the creation of alternative Caspian tern nesting habitat on Brooks Island and two other sites in San Francisco Bay would not likely jeopardize salmonid stocks in the San Francisco Bay area that are listed under the ESA (NOAA 2006). As part of this Biological Opinion, the U.S. Army Corps of Engineers agreed to implement monitoring at the proposed alternative Caspian tern nesting sites where ESA-listed salmonids occurred in the diet.

The alternative colony site on Brooks Island was of particular concern because it is the site nearest the Sacramento River delta, where several ESA-listed salmonid runs enter San Francisco Bay (McEwan 2001, Good et al. 2005). Monitoring of Caspian tern diet at the Brooks Island colony, which occurred during 2003-2005 and resumed in 2008–2009, demonstrated that salmonids were a small part of the diet (< 10% of prey items; Collis et al. In review). In 2008, salmonids in the diet were identified to species and evolutionarily significant unit (ESU) based on smolt coded wire tags (CWTs) recovered on the tern colony (Evans et al. 2011). Recovered CWTs indicated that nearly all salmonid smolts consumed were from the unlisted Central Valley fall-run Chinook salmon (*O. tshawytscha*) ESU. The fall-run Chinook ESU is

the predominant salmonid run in the Bay Area and several hatchery release sites for

this ESU are located within 20 kilometers of Brooks Island (FFC 2008, 2009).

Fish populations in the San Francisco Bay estuary have undergone serious

declines since the 1970's (Meng et al. 1994). These declines have been attributed to

both anthropogenic and climatic factors (Feyrer et al. 2007, Lindley et al. 2009).

Salmonid populations were once prolific in the Sacramento and San Joaquin River

drainages, with Chinook salmon and anadromous steelhead (*O. mykiss*) runs both

estimated to have historically consisted of 1-2 million spawning adults (Yoshimaya et

al. 1998, McEwan 2001). Two out of four runs of Chinook salmon in the Bay Area

are now listed under the ESA; the Sacramento River winter-run Chinook salmon ESU

is currently listed as endangered, and the Central Valley spring-run Chinook salmon

ESU is listed as threatened. Both of these ESUs are currently estimated to consist of

less than 10,000 spawning adults (Good et al. 2005). Although not listed under the

ESA, low spawning returns of the Central Valley fall-run Chinook salmon ESU

prompted the Pacific Fisheries Management Council to adopt a complete closure of

commercial and recreational Chinook salmon fisheries off the coast of California and

part of Oregon in 2008 and 2009 (NOAA 2008, 2009b). Naturally-spawned

California Central Coast coho salmon (*O. kisutch*) are listed as endangered; however,

they have not been detected in stream surveys of river basins in the San Francisco Bay

area since 1995 and are considered extirpated from the area (NOAA 2005). The

Central Valley steelhead ESU has been listed as threatened under the ESA since 1998

(NOAA 1998) and the Central California Coast steelhead ESU, also listed as threatened, is found in this area of coastal California, although there is lack of consensus over whether it still survives in tributaries of San Francisco Bay (Good et al. 2005).

We used a bioenergetics model to estimate consumption of juvenile salmonids, as well as other prey types, by Caspian terns nesting at the Brooks Island colony. Bioenergetics modeling combines data on the energy requirements of a predator, the number of predators present in a system, and the composition of prey in the diet of the predator to calculate prey consumption. Use of this method was pioneered by Wiens and Scott (1975) to estimate prey consumption by several seabird species. Subsequently, bioenergetics modeling has been used to estimate consumption of fish by various piscivorous waterbird species in both freshwater and marine food webs (Furness 1978, Glahn and Brugger 1995, Madenjian and Gabrey 1995, Phillips et al. 1999). For Caspian terns, this method has previously been used to calculate juvenile salmonid consumption in the Columbia River estuary and along the mid-Columbia River (Roby et al. 2003, Antolos et al. 2005).

We collected Caspian tern diet composition information at the Brooks Island colony in 2008 and 2009 and estimated predation on individual forage fish species using a bioenergetics model. The specific objectives of this study were to:

1. Estimate the per capita consumption of juvenile salmonids by Caspian terns nesting on Brooks Island, as well as total smolt consumption by all terns at the colony.

2. Determine whether this Caspian tern colony, the largest in the San Francisco Bay area, poses a significant threat to the recovery of any ESA-listed ESU of salmonid.

3. Assess whether a near doubling in the size of the Brooks Island Caspian tern colony would pose a considerable source of mortality for any ESU of salmonid in the Bay Area.

METHODS

Study Area

Caspian terns nesting at the colony on Brooks Island were studied in 2008 and 2009. Brooks Island (37°57'46"N, 122°21'18"W) is located in central San Francisco Bay within Contra Costa County, California (Figure 2.1). It is a natural island situated two kilometers to the south of the Port of Richmond, which has been augmented with dredged material that forms a sandy spit extending to the northwest of the island. Brooks Island is owned by the City of Richmond and managed by the East Bay Regional Parks District. Caspian terns nest in a "main" colony and a smaller "satellite" sub-colony, both located on the sandy spit. Breeding by Caspian terns on this island was first documented in 1988 (Strong et al. 2004). A high count of Caspian terns nesting on Brooks Island was recorded in 2004, when an estimated 1,040 breeding pairs nested on the island. Since then the colony has steadily decreased in size (Collis et al., In review).

Bioenergetics Model Structure

In this study we used a bioenergetics model based largely on that used by Roby et al. (2003; Figure 2.2), with some improvements. Input parameters for the model were measured directly at the Caspian tern nesting colony on Brooks Island and samples of prey species consumed at this colony were collected in San Francisco Bay, when possible. Parameters that could not be measured during 2008 and 2009 at Brooks Island or in San Francisco Bay were estimated based on previously published studies from San Francisco Bay or the Columbia River estuary. Seasonal and annual differences in some input parameters to the model (e.g., colony size, diet composition) were evident, so tern bioenergetics calculations were based on 11 two-week time periods (March 13 – August 13) in both 2008 and 2009, and then summed across the entire breeding season to obtain total estimated forage fish consumption. These time periods spanned the dates when Caspian terns were present at the Brooks Island colony in those two years.

A Monte Carlo simulation was used to estimate confidence intervals (CIs) of each output parameter (Furness 1978), following Roby et al. (2003). This technique uses a randomly selected set of values for the input parameters for each simulation run of the model. All input parameters were assumed to originate from a normal distribution, and 1,000 simulations of the model were completed for each year of the study. The 1,000 output values were averaged to obtain final estimates and 95% CIs.

We were able to improve upon the methods of Roby et al. (2003) in several ways. Energy requirements of Caspian tern chicks have recently been measured (Lyons and Roby 2011). We used these published values instead of values based on allometric equations. We were also able to use a measured assimilation efficiency value that was not previously available (D. Lyons, unpubl. data).

Bioenergetics Model Input Parameters

Colony Size and Number of Young

Caspian tern colony size at the peak of each breeding season was estimated using averages taken from three independent counts of high resolution aerial photography (Collis et al. 2002). The average of the total number of adult Caspian terns on-colony was converted to an estimate of total breeding pairs on-colony using ground counts of sitting and standing adult terns, made at the same time as the aerial photography, from an observation blind adjacent to the tern colony. Sitting terns were assumed to be attending a nest. Because the bioenergetics model is based on a two-week interval structure, additional estimates of colony size were needed for each two-week period over the course of the entire breeding season. Consequently, the numbers of adults present on the breeding colony were counted from observation blinds several times per week. The highest count per day was averaged over the two-week period and used to estimate colony size during each two-week interval.

Numbers of young Caspian terns on the colony during the 2008 and 2009 breeding seasons were estimated twice during each breeding season. A sample of active nests was monitored from the observation blind several times per week. The presence and number of eggs and/or chicks in each nest in the sample were recorded and used to obtain an average number of chicks hatched per nesting attempt. The total number of fledglings produced at the colony in each year was estimated by counting the number of chicks on the colony 7-10 days after the first fledgling was observed. Any chicks that had already fledged and left the colony would not be counted then, but we assumed that number was roughly balanced by the number of chicks present at the time of the count that would not survive to fledge. Chicks were captured and banded on the main colony in 2008 and the satellite colony in 2009, and we obtained the number of chicks present by counting how many were caught and estimating how many additional chicks escaped capture. For the areas where chicks were not captured (i.e., the satellite colony in 2008 and the main colony in 2009), we counted the number of chicks that we could see from a boat in the water or from the observation blind and used this as the number present.

Caspian Tern Energy Expenditure

To estimate the daily energy expenditure (DEE, kJ/day) for adult Caspian terns at Brooks Island in 2008 and 2009, we used the DEE of adult breeding Caspian terns measured at Rice Island in the Columbia River estuary in 1997 and 1998 (Roby et al. 2003). Roby et al. (2003) used the doubly labeled water technique (Lifson and

McClintock 1966, Nagy 1980) to measure field metabolic rates of adult Caspian terns captured near the end of the incubation period or very early in chick-rearing. Adult terns were injected with 0.9 mL of water labeled with ^{18}O and ^{2}H. After a holding period to allow labeled water to equilibrate with body water, an initial blood sample of about 100 ul was collected by brachial vein puncture, and terns were released. Adults were then recaptured 24 - 48 hrs later to provide a second blood sample. Blood samples were sent to Dr. G.H. Visser at the Centre for Isotope Research, University of Groningen, Netherlands, along with blood samples collected from un-injected Caspian terns, for isotopic analysis (Roby et al. 2003). We assumed that the DEE of Caspian terns nesting at Brooks Island would be similar to that of Caspian terns nesting on Rice Island, and that the DEE of terns late in incubation or very early in chick-rearing would be representative of the average DEE over the course of the breeding season.

Daily energy expenditure of Caspian tern chicks at Brooks Island in 2008 and 2009 was estimated using the DEE of captive Caspian tern chicks that were collected from the East Sand Island colony in the Columbia River estuary in 2001 (Lyons and Roby, 2011). Young chicks ($n = 10$) were raised in captivity and fed *ad libitum* diets in order to quantify daily energetic requirements until chicks reached fledging age (ca. 42 days). The mean total metabolizable energy (TME) was then calculated across all 10 chicks and daily requirements were calculated for the 42-day chick-rearing period. I assumed that the energy requirements of Caspian tern chicks at Brooks Island would be similar to those of the captive-raised chicks.

Diet Composition

To determine diet composition, records of prey items transported to the Brooks Island colony by adult Caspian terns were collected from the observation blind over the course of the breeding season. Each prey item was identified to the lowest possible taxon using binoculars and spotting scopes (Collis et al. 2002). Diet composition was then calculated for each two-week period for input to the bioenergetics model. During 2008 and 2009, no diet data were collected at the colony during the earliest two-week time period, so diet composition was assumed to be the same as during the subsequent two-week period. In 2009 there were very few diet data collected during two-week time period 10, and none were collected during two-week time period 11. For both of these periods we added the diet data from time period 9 ($n = 381$ identified prey items) to those from time period 10 ($n = 9$ prey items) and calculated diet composition using that combined data set. The number of identified prey items per two-week period was greater than 300 in seven out of 11 time periods in 2008, with a range of 23 to 788 identified items. In 2009, the number of identified prey items was greater than 300 for nine out of 11 time periods, and ranged from 128 to 733.

In both years we attempted to distinguish juvenile salmonids in tern bill-loads as either "steelhead and trout" (steelhead, rainbow trout, *O. mykiss*) or "Chinook salmon". Rainbow trout and steelhead are difficult to distinguish from one another at a distance while using only binoculars. There are several reservoirs < 15 km from

Brooks Island where rainbow trout are stocked (CDFG 2009), and juvenile steelhead migrating from spawning areas in the Sacramento and San Joaquin river drainages to the Pacific Ocean must pass through central San Francisco Bay near Brooks Island. During a radio-tracking study of Caspian terns nesting at Brooks Island, two aerial telemetry detections of Caspian terns were collected at a stocked reservoir, and several Caspian tern core use areas were located between the mouth of the Sacramento/San Joaquin River Delta and the Pacific Ocean (see Chapter 3). Consequently, it is possible that Caspian terns from Brooks Island could have consumed both rainbow trout and steelhead.

Average Mass of Prey Items

Along with identification of taxon, the total length of each tern prey item was estimated as a multiple of average Caspian tern bill length (7.0 cm; Quinn 1990). Length to mass regression equations were then generated for the most prevalent prey types in the diet of which we were able to collect samples. Total length and mass measurements of silversides (jacksmelt, *Atherinopsis californiensis*, and topsmelt, *Atherinops affinis*) and shiner surfperch (*Cymatogaster agregata*) were obtained from live fish at the Marine Science Institute (MSI), Redwood City, CA. All fish were caught in otter trawls conducted at depths of 2-15 m in the South Bay region of San Francisco Bay and kept in tanks at the MSI campus in Redwood City. Total length measurements were taken in millimeters and fish were weighed to the nearest 0.001 g using a digital top-loading balance. Northern anchovy (*Engraulis mordax*; $n = 7$) and

Pacific staghorn sculpin *(Leptocottus armatus; n* = 7) samples were obtained from

trawls conducted by the California Department of Fish and Game in San Francisco

Bay during 2004 and 2005. Of clupeids (Pacific herring, *Clupea pallasi*, and Pacific

sardine, *Sardinops sagax*), only Pacific sardines caught in 2009 by commercial

fishermen in central San Francisco Bay near Sausalito were measured (*n* = 11).

Chinook salmon fork length and body mass measurements from both the Sacramento

River delta and the mouth of San Francisco Bay were based on an 11-year data set

collected during 1995 - 2005 (MacFarlane 2010). To convert fork length to total

length we applied a ratio of 1.0851, which was obtained from a regression equation of

fork length to total length from measurements of 28 juvenile fall-run Chinook salmon

smolts collected from the Coleman National Fish Hatchery in 2009.

Energy Density of Prey Types

We used the samples collected as described above to measure total energy

content (kJ/fish) and energy density (kJ/g wet mass) of the various prey types that

comprised at least 1% of the prey items in the Caspian tern diet. After samples were

collected and measured, they were frozen until laboratory analysis. We conducted

proximate composition analysis (Reynolds and Kunz 2001) to determine the percent

water, lipid, ash-free lean dry matter (> 90% protein), and ash of prey samples. In the

laboratory, samples were thawed and measured for wet mass, then placed in a

convection oven at 60°C. Each fish was dried to constant mass and weighed again to

determine water content of wet mass by subtraction. Each fish was then ground with a

mortar and pestle into a homogenized powder or paste and placed in a leaned cotton thimble for lipid extraction. Fish samples of the same species that weighed < 2 g dry mass were pooled to obtain 2 – 3.5 g of dry matter per thimble. An aliquot of 3.5 g dry mass was taken from fish samples weighing > 3.5 g dry mass. Lipid extraction was performed using a Soxhlet apparatus and a solvent system of 7:2 (v:v) hexane/isopropyl alcohol. Dried and leaned samples were then placed in glass beakers and incinerated in a muffle furnace at 600°C for 12 h. The remaining ash was weighed to determine ash content (Anthony et al. 2000). We estimated protein content from ash-free lean dry matter (AFLDM), which consists of 94% protein (Montevecchi et al. 1984). We calculated energy content and average energy density (kJ/g wet mass) for each prey type using the published energy equivalents of 17.8 kJ/g for protein and 39.3 kJ/g for lipid (Schmidt-Nielsen 1997).

Pacific tomcod (*Microgadus proximus*; *n* = 12), leopard shark (*Triakis semifasciata*; *n* = 1), and plainfin midshipman (*Porichthys notatus*; *n* = 1) were also collected from trawls conducted by the California Department of Fish and Game in San Francisco Bay during 2004 and 2005 and subjected to the proximate analysis method described above. Because only one specimen each of leopard shark and plainfin midshipman were analyzed, the resulting energy content and energy density from each specimen was used for input to the bioenergetics model. In these two cases, we multiplied the energy density by two to estimate the standard deviation of the

measured energy density, and we multiplied the mass by 0.2 to estimate the standard deviation for mass.

Average energy density for Chinook salmon smolts was based on a 10-year data set collected during 1995 - 2001 and 2003 – 2005, using Chinook salmon smolts collected from both the Sacramento River delta and the mouth of San Francisco Bay. Lipids were extracted from these samples using a chloroform-methanol biphasic procedure and total protein was measured by the Lowry method (MacFarlane 2010).

When specimens of marine prey types from San Francisco Bay were not available for proximate composition analysis, we used measurements obtained by Roby et al. (2003) from the Columbia River estuary. These include the following prey types: steelhead, flatfish (Pleuronectidae), Pacific sandlance (*Ammodytes hexapterus*), and smelt (Osmeridae). Freshwater sunfish (*Lepomis* spp.) and bass (*Micropterus* spp.) were pooled into one prey category (centrarchids) and estimates of energy density from Antolos et al. (2005) were used, as data were not available from San Francisco Bay.

There were some cases in both years of the study when prey items could only be identified as non-salmonids. For these cases we used a weighted average based on relative proportions of non-salmonid prey types identified during each two-week time period to estimate an average energy density and average mass for this prey category. For prey types totaling < 1% of identifiable prey items in each year and for which no energy density information was available, the prey items were pooled together into an

"other" category and assigned the average energy density of all known prey types. The following prey types were included in this other category: Pacific butterfish (*Peprilus simillimus*), kelpfish (Clinidae), shrimp (Caridea), Pacific saury (*Cololabis saira*), striped bass (*Morone sexatilas*), and white croaker (*Genyonemus lineatus*).

Predation Rate Estimation

The estimates of the total numbers of juvenile salmonids consumed in 2008 and 2009 in each bioenergetics model simulation were divided by the number of Caspian terns breeding at Brooks Island in each year and averaged to calculate per capita estimates of juvenile salmonid consumption. Salmonid consumption estimates were also converted into predation rate estimates (percent of available fish) to investigate the effect of the Brooks Island Caspian tern colony on annual population growth rates of two Chinook salmon stocks that originate in the Central Valley of California: spring-run Chinook salmon and fall-run Chinook salmon. Estimates of predation rates on each Chinook salmon stock were only calculated for the first year of our study (2008) because estimates of the relative numbers of spring-run Chinook and fall-run Chinook consumed by Brooks Island terns based on smolt coded wire tags recovered on the Brooks Island tern colony were only available for that year (Evans et al. 2011). Because 99.7% of all smolt coded wire tags found on Brooks Island came from Chinook salmon released directly into San Pablo Bay (Evans et al. 2011), we took the number of smolts available to Caspian terns breeding on Brooks Island to be the total number of hatchery-raised salmon smolts released into San Pablo Bay. This

assumption results in predation rate estimates that are biased somewhat high because of the exclusion of smolts released in-river. All information on hatchery releases was obtained from the Regional Mark Information System Database (RMISD), which is maintained by the Pacific Fisheries Management Council (RMISD 1977). The relative susceptibility of each Chinook salmon run type was calculated by dividing the estimated number of coded wire tags deposited on the Brooks Island tern colony from a particular salmon run by the number of smolts from the same run that were coded wire tagged and released into San Pablo Bay. The susceptibility level of each run was then applied to the estimate of salmonid consumption generated by the bioenergetics model to estimate the total number of each run type that was consumed by Brooks Island terns in 2008. Average predation rates, expressed as a percentage, were calculated as the estimated number of smolts from each salmonid run consumed by Brooks Island Caspian terns divided by the estimated number of smolts from that run that were available to foraging terns.

We also estimated predation rates for a scenario where the Brooks Island Caspian tern colony increased in size to 3,000 breeding individuals, as proposed by the U.S. Fish and Wildlife Service (USFWS) and the U.S. Army Corps of Engineers (USACE) in their respective Records of Decision (USFWS 2006; USACE 2006). The estimate of per capita salmon consumption by Brooks Island terns in 2008 was multiplied by the proposed number of Caspian terns to obtain an estimate of salmonid consumption for this scenario of expansion in tern colony size. We followed the same

methods as described above to obtain estimates of predation rate for each salmonid run.

Change to Salmonid Population Growth Rates

We calculated the change in annual population growth rate (λ) for spring-run Chinook and fall-run Chinook in the event of a hypothetical elimination of the Caspian tern breeding colony on Brooks Island in order to evaluate the impact of tern predation at levels measured in 2008. We also estimated the predation rate on spring-run and fall-run Chinook salmon by Caspian terns nesting on Brooks Island under the scenario of a colony that increased to 3,000 nesting individuals (1,500 breeding pairs), and then used these estimates to calculate the change in λ for spring-run and fall-run Chinook salmon, should this management scenario be implemented. Initial estimates of λ for the Chinook salmon runs most consumed by Brooks Island Caspian terns were calculated using the following equation for population growth rate from Lindley et al. (2007):

Population growth rate (% per year) = (Slope of $\text{Log}(S_t)$ vs. Time) x 100,

where S_t is the annual spawning run estimate. We obtained spawning run estimates for 2001 – 2010 from the California Department of Fish and Game (CDFG) GrandTab database (CDFG 2011). The percent change in λ of salmon runs following elimination or enhancement of the Brooks Island tern colony was calculated as:

$$\Delta\lambda = [(S_f/S_i)^{1/G} - 1] \times 100,$$

where S_f is the salmon survival rate following either elimination or enhancement of the tern colony, S_i is the initial survival rate, and G is the average salmon generational time (McClure et al. 2000).

Predator control to enhance prey populations can be justified if predators affect prey abundance (Gasaway et al. 1992), but it may be necessary to determine what portion of mortality due to predation is additive versus compensatory in order to estimate the effect of mortality due to predation on prey abundance (Errington 1967). It is not known what proportion of smolt mortality caused by Caspian tern predation is additive or compensatory, but it is certainly less than 100% additive. A study relating the health status of steelhead salmon to smolt susceptibility to avian predation found that steelhead in compromised health were more susceptible to Caspian tern predation, an indication that smolt mortality from Caspian tern predation is at least party compensatory (Hostetter 2009). Consequently, we have calculated the percent change in λ for salmonid runs from tern predation under assumptions of 100%, 75%, 50%, and 25% additive mortality. The proportion of additive mortality was then applied to the variable S_f in the equation listed above for percent change in λ as follows:

$$1 - [(S_i - S_f) \times \% \text{ additive mortality}] + \text{salmonid predation rate} =$$

$$S_f \text{ including additive mortality level}$$

RESULTS

Bioenergetics Model Input

Colony Size and Numbers of Young

The peak size of the Caspian tern breeding colony at Brooks Island was 810 breeding pairs in 2008 (95% CI: 776 – 844, SE = 17, n = 3 counts). In 2009 colony size was significantly lower, at 681 breeding pairs (95% CI: 655 – 707, SE = 13, n = 3 counts).

In 2008, the average number of chicks hatched per nesting attempt was 1.29 (95% CI: 1.09 – 1.49, SE = 0.1, n = 31), and the estimated number of fledglings produced at the colony was 341. In 2009, the average number of chicks hatched per nesting attempt was not significantly different at 0.94 chicks per nesting attempt (95% CI: 0.76 – 1.12, SE = 0.09, n = 77), but the estimated total number of fledglings produced at the colony was just 97. Estimates of fledgling productivity using our methods do not allow for precise construction of confidence intervals; however, the colonies on Brooks Island are small and highly visible, so we believe these estimates to be accurate within 20% or less. Therefore, 95% confidence intervals for fledgling productivity in 2008 (273 – 409 chicks) and 2009 (78 – 116 chicks) do not overlap and suggest significantly lower nesting success in 2009.

Caspian Tern Energy Expenditure

The average energy expenditure rate of adult Caspian terns nesting at Brooks Island was assumed to be the same as that of Caspian terns nesting on Rice Island in the Columbia River estuary, or 1040 kJ/day (SD = 209.1, n = 24; Roby et al. 2003). The average energy consumption of Caspian tern chicks at Brooks Island was assumed to be the same as that of captive-raised Caspian tern chicks collected from the East Sand Island colony in the Columbia River estuary (Lyons and Roby 2011). The daily metabolizable energy requirements for captive-reared Caspian tern chicks peaked at 760 kJ/day. The mean total metabolizeable energy (TME) required by tern chicks from hatching to fledging was 18,769 kJ (Lyons and Roby 2011).

Estimates of the total energy requirements of the Caspian tern colony at Brooks Island were calculated separately for the 2008 and 2009 nesting seasons (Table 2.1). The lower tern colony size and productivity in 2009 compared to 2008 resulted in a 22% lower estimate of total energy requirement in 2009. Energy requirements of chicks accounted for 6.8% and 3.5% of total colony energy requirements in 2008 and 2009, respectively. These proportions are similar to those reported for the Rice Island Caspian tern colony (Roby et al. 2003) and for the East Sand Island Caspian tern colony (Lyons 2010), both in the Columbia River estuary.

Diet Composition

Marine and estuarine forage fish species, including northern anchovy, clupeids (herring and sardines), shiner surfperch, and silversides, accounted for approximately 68% of the identified Caspian tern prey items at the Brooks Island colony in 2008 and 58.7% in 2009 (Figure 2.3, Table 2.2). In 2008, the most prevalent prey type in the tern diet was northern anchovy (29% of prey items), followed by shiner surfperch (20% of prey items). In 2009, the most prevalent prey type was shiner surfperch (33% of prey items), while northern anchovy accounted for only 11% of prey items. Juvenile salmonids were the 4th and 5th most prevalent prey type in the diet, and accounted for 9% and 7% of identified prey items in 2008 and 2009, respectively. The following prey types accounted for less than 5% of tern diet composition in both years: Pacific staghorn sculpin, centrarchids, plainfin midshipman, juvenile Pacific tomcod, flatfish, Pacific sandlance, and juvenile leopard shark.

Average Mass of Prey Items

The most prevalent prey types in the diet of Caspian terns nesting at Brooks Island were northern anchovy, clupeids, silversides, shiner surfperch, salmonids, and Pacific staghorn sculpin. The length-mass regression equations for these prey types are presented in Table 2.3. The average total length of each prey type in the tern diet was estimated based on observations of bill load fish delivered to the breeding colony by adults in each study year and input to the corresponding length-mass regression equation to estimate average mass of each prey type (Table 2.3).

Energy Density of Prey Types

The mean energy density of each prey type was determined by proximate composition analysis of samples collected in San Francisco Bay or based on values from other published studies (Table 2.3). The prey type with the lowest energy density was plainfin midshipman, at 3.36 kJ/g wet mass, while Pacific sandlance had the highest energy density, at 5.6 kJ/g wet mass. Marine forage fishes generally had energy densities in excess of 5 kJ/g wet mass. The average energy density of Chinook salmon smolts was 4.8 kJ/g wet mass and of steelhead smolts was 4.6 kJ/g wet mass, lower than marine forage fishes but similar to estuarine prey types, such as shiner surfperch and silversides. The estimated average energy density of the "other" prey category was 4.5 kJ/g wet mass.

Bioenergetics Model Output

For each prey type, the mean energy density was combined with the proportion of biomass consumed for that prey type to estimate the percent of energy required by the tern colony that was provided by each prey type (Table 2.1). In 2008, clupeids supplied the highest proportion of total required energy of any single prey type (29.7%). In 2009, shiner surfperch and silversides supplied the highest proportions of total required energy (28.6% and 24.4%, respectively). Juvenile salmonids contributed < 6% of the total energy required by the Brooks Island Caspian tern colony in both years of the study.

Caspian terns breeding at Brooks Island consumed an estimated 38.1 metric tons (mt; 95% CI: 32.7 - 43.4 mt) of fish biomass in 2008, and an estimated 31.3 mt (95% CI: 27.2 - 35.4 mt) in 2009. The biomass consumed by the Brooks Island tern colony was highest for clupeids in 2008, with an estimated consumption of 10.3 mt (95% CI: 8.8 - 11.7 mt). In the same year, the biomass of juvenile salmonids consumed was estimated to be 2.0 mt (95% CI: 1.7 – 2.3 mt). In 2009, tern biomass consumption was highest for surfperch, with an estimated consumption of 8.9 mt (95% CI: 7.7 – 10.1 mt). Biomass consumption of juvenile salmonids in 2009 was estimated to be 1.6 mt (95% CI: 1.3 – 1.8 mt) (Table 2.4).

The estimates of prey type-specific biomass consumption, along with estimated average mass of each prey type, were used to calculate estimates of the total numbers of each prey type consumed by Caspian terns nesting at Brooks Island in 2008 and 2009 (Table 2.4). We estimated the total number of fish consumed to be 1.91 million (95% CI: 1,643,099 – 2,178,382 fish) in 2008, and 1.70 million (95% CI: 1,473,255 – 1,923,607 fish) in 2009. The 95% confidence intervals for these estimates do overlap, suggesting that the difference between the two years in total number of fish consumed was not significant. The estimated total number of juvenile salmonids consumed by Brooks Island Caspian terns in 2008 was 204,911 (95% CI: 175,292 – 234,530 fish), which included approximately 200,685 fish in the "Chinook salmon" category and 4,226 fish in the "steelhead or trout" category. In 2009, the estimated total number of juvenile salmonids consumed was 167,383 (95% CI: 143,600 –

191,167 fish). This total was comprised of 163,258 "Chinook salmon" and 4,125 "steelhead or trout". As with the total amount of fish consumed, these estimates suggest a lower number of salmon consumed in 2009 compared to 2008. However, overlap in the 95% confidence intervals indicates the difference is not statistically significant.

The average per capita predation on all juvenile salmonids by adult Caspian terns nesting on Brooks Island in 2008 was 126 fish (95% CI: 108 – 145 fish) and the per capita predation on juvenile Chinook salmon was 124 smolts (95% CI: 106 – 142 smolts). The average per capita predation on all juvenile salmonids by adult Caspian terns in 2009 was 123 fish (95% CI: 105 – 140 fish) and the per capita predation on juvenile Chinook salmon was 120 smolts (95% CI: 103 – 137 smolts).   Overlapping 95% confidence intervals suggest that there was no significant difference between years in the per capita predation by terns on all salmonids or on Chinook salmon alone.

Predation Rate Estimates

A total of 21,171,527 hatchery-raised juvenile salmonids were released into San Pablo Bay during the 2008 out-migration. Fall-run Chinook salmon accounted for 94% of the total (ca. 19,874,847 smolts) and spring-run Chinook salmon for just 6% of the total (ca. 1,271,661 smolts). About 25% (5,029,315) of the fall-run Chinook smolts and 98% (1,242,388) of the spring-run Chinook smolts were marked with coded wire tags prior to release (RMISD 1977). Evans et al. (2011) estimated that

39,256 coded wire tags from fall-run Chinook smolts and 772 coded wire tags from spring-run Chinook smolts from the 2008 migration year were deposited on the Brooks Island Caspian tern colony during the 2008 nesting season. Using the number of smolts released with CWTs and the estimated numbers of CWTs recovered on Brooks Island, Evans et al. (2011) calculated predation rates of 0.78% for fall-run Chinook and 0.06% for spring-run Chinook.

Based on the bioenergetics model, we estimated that the Caspian tern colony on Brooks Island consumed 199,669 fall-run Chinook and 1,015 spring-run Chinook in 2008, equivalent to predation rates of 1.0% and 0.08%, respectively. We calculated the maximum change in annual population growth rate (λ) for a hypothetical scenario in which this Caspian tern colony no longer existed and salmon mortality due to tern predation is 100% additive in order to determine the current maximum impact of this colony on populations of Chinook salmon in San Francisco Bay. For fall-run Chinook salmon the initial population growth rate (λ) calculated from a 10-year regression was 0.7165. Elimination of mortality from predation by Brooks Island terns, assuming that this mortality was 25%, 50%, 75%, or 100% additive, would result in increases in λ of 0.08%, 0.17%, 0.25%, and 0.3% respectively. For spring-run Chinook the initial λ calculated from a 10 year regression was 0.8074. Elimination of mortality from predation by Brooks Island terns, again assuming that mortality was 25%, 50%, 75%, or 100% additive, would result in increases in λ of 0.007%, 0.01%, 0.02%, and 0.03% respectively (Table 2.5).

We also estimated Chinook salmon smolt consumption for a hypothetical scenario of an increase in the number of breeding Caspian terns on Brooks Island to 3,000 individuals (1,500 pairs), based on the per capita estimate of 124 Chinook salmon smolts consumed by the colony in 2008. A colony this size would consume approximately 372,000 Chinook salmon smolts in one breeding season, consisting of about 370,000 fall-run Chinook and 1,900 spring-run Chinook. This level of consumption is equivalent to predation rates of 1.9% for fall-run Chinook and 0.15% for spring-run Chinook smolts. At assumed additive mortality levels of 25%, 50%, 75%, and 100%, these predation rates would result in declines in λ of 0.07%, 0.14%, 0.22%, and 0.3%, respectively, for fall-run Chinook and 0.006%, 0.01%, 0.023%, and 0.02%, respectively, for spring-run Chinook (Table 2.5).

DISCUSSION

Salmonid Consumption

Our estimates of salmonid predation rates based on bioenergetics model outputs were somewhat higher (by 28 – 29%) than those calculated using CWT recoveries on the tern colony at Brooks Island. Predation rates calculated using CWT recoveries were, however, minimum estimates due to the likely deposition of some CWT tags ingested by Caspian terns in loafing and foraging areas away from the colony (Evans et al. 2011).

There were several factors that contributed to the estimated lower consumption of salmonids by Brooks Island terns in 2009 compared to 2008. The number of breeding pairs of Caspian terns at the Brooks Island colony, as well as the number of young terns raised to fledging age, was lower in 2009. This resulted in a lower total energy requirement of the colony in 2009. The number of Caspian terns nesting at the Brooks Island colony has declined 35% since 2004, likely the result of limiting factors such as vegetation encroachment on tern nesting habitat and competition from the California gull and western gull colonies that are also present on the island (Collis et al., In review). If the size of the Caspian tern colony on Brooks Island continues to decline, then the total number of juvenile salmonids consumed by the colony per year will likely also decline.

Although overall salmonid smolt consumption was lower in 2009, the per capita predation rate of juvenile salmonids by adult Caspian terns did not differ appreciably between 2008 and 2009. The number of juvenile salmonids released via net pen into eastern San Pablo Bay, ca. 20 km from Brooks Island, was 31% lower in 2009 (approximately 13.8 million salmonid smolts) compared to 2008 (approximately 20.0 million smolts; FFC 2008, 2009). The lower number of salmon released in eastern San Pablo Bay during 2009 was not reflected in lower per capita predation rates on juvenile salmonids by Caspian terns. The high use of San Pablo Bay by foraging Caspian terns (see Chapter 3) is likely due to the high availability of forage fish following releases of hatchery-raised salmon from the net pens. Hatchery-raised

salmonids can be more susceptible to avian predation due to behavioral deficits, such as lack of predator avoidance and tendency to feed at the water's surface (Olla et al. 1994, Collis et al. 2001). Hatchery releases in eastern San Pablo Bay occurred around mid-day (FFC 2008, 2009), when Caspian terns are most active (Cuthbert and Wires 1999), and regardless of tide stage. Juvenile salmonids released from the net pens were allowed to acclimate in the net pens for as little as one hour prior to release (FFC 2008). Because of the predictability of smolt releases and the short period of acclimation, released smolts were highly susceptible to a variety of predators, including Caspian terns. Individual piscivorous waterbirds are attracted to foraging flocks of conspecifics (Krebs 1974, Silverman et al. 2004), so the pre-release acclimation period in the net pens allowed Caspian terns to gather at the location of the release. A study of Caspian tern foraging behavior in San Francisco Bay using radio-telemetry also suggested that individual terns learned the location and timing of net pen releases and repeatedly returned to forage on recently released smolts (Chapter 3), indicating that modifications should be made to hatchery release practices. The per capita predation rate on salmonids by Brooks Island Caspian terns would likely decline appreciably if hatchery releases in San Pablo Bay were scheduled late in the evening and on out-going tides.

Model Biases

There are some potential biases in our fish consumption estimates that must be considered before these results are used to inform proposed management of the

Brooks Island Caspian tern colony. Estimates of smolt consumption have been shown to be sensitive to the energy expenditure rate of Caspian tern adults and total metabolizable energy requirements of juvenile Caspian terns (Roby et al. 2003). The measurements of energy expenditure rate in adult Caspian terns were taken from wild, free-ranging birds nesting at Rice Island in the Columbia River estuary. Climate differences may be a confounding factor that could cause a difference in adult energy expenditure rate for Caspian terns nesting at these two locations. Energy demand is closely related to ambient temperature (Kendeigh 1969); an inverse relationship between DEE and temperature would cause our prey consumption estimates to be biased somewhat high. Mean temperatures during the breeding season are only 3 - 4°C lower in the Columbia River estuary than in the San Francisco Bay area, however, so we would not expect a major difference in energy demand between the two sites.

We used the TME measured on captive-reared Caspian tern chicks, raised under ambient temperatures near the Columbia River estuary, to estimate energy requirements of juvenile terns at Brooks Island. It is not known how close this estimate may be to that of chicks raised on Brooks Island, so there may be some bias associated with this measurement. DEE has only varied slightly with latitude in chicks of other tern species (Klaassen 1994); consequently, we do not expect that this was a significant source of error in our model.

Our observations of fish delivered to the colony, used to estimate Caspian tern diet composition, may contribute to bias in model outputs if Caspian terns engage in

selective foraging behavior. Studies of several seabird species have shown that adults forage farther from the colony to meet their own energy requirements with higher quality prey items and closer to the colony to provision chicks with lower quality, but more accessible prey items (Weimerskirch et al. 1997, 1998). Radio telemetry studies conducted on Caspian terns have not suggested this pattern of foraging behavior (Chapter 3; Lyons et al. 2005, 2007, Anderson et al. 2007), but radio telemetry tracking may not provide sufficient sensitivity to examine this question. The bioenergetics model input parameter of the proportion of each prey type in the diet appears to contribute little to the uncertainty of model output, however, based on a sensitivity analysis (Roby et al. 2003).

Kleptoparasitism of prey items from Caspian terns by gulls is not accounted for in our model. California and western gulls nest in close proximity to Caspian terns on Brooks Island and are often observed stealing fish as the terns return to the colony to feed a mate or chicks. These events occurred at a rate of about 7.5% of fish delivery attempts by terns nesting at Brooks Island in both 2008 and 2009 (L. Adrean, unpubl. data). If Caspian terns from Brooks Island are taking more fish than required for their own energetic needs to compensate for gull kleptoparasitism, then our estimate of total predation on all prey types may be biased slightly low.

A sensitivity analysis on bioenergetics model input parameters, completed by Roby et al. (2003), indicated that uncertainty in model results is most affected by the estimate of breeding pairs at the colony. The Caspian tern colonies at Brooks Island

are linear in shape and highly visible from the observation blind or a boat in the water, however, making ground counts of sitting and standing terns quite accurate. The Brooks Island tern colony is also small and relatively easy to count using aerial photography; our resulting standard error for counts from photography was also very low. We believe that our estimates of breeding pairs at Brooks Island are reliable and contributed little to the uncertainty of our estimates of prey consumption from the bioenergetics model.

Effect of Tern Predation on Threatened and Endangered Salmonids

Although Central Valley fall-run Chinook are not listed under the ESA, they are an ESU of conservation concern and poor adult returns from this ESU resulted in the closure of commercial and recreational salmon fishing along the coast of California in 2008 and 2009 (NOAA 2008, 2009b). This resulted in considerable region-wide economic hardship; $170 million in disaster relief was distributed over the course of 2008 and 2009 by the Pacific Fisheries Management Council to individuals and businesses dependent on salmon fishing (NOAA 2009a). This salmonid run is the most susceptible to predation from the Brooks Island Caspian tern colony. The proposed increase in the size of the Caspian tern colony on Brooks Island to ca. 1,500 breeding pairs would lead to an estimated reduction in population growth rate of the fall-run Chinook ESU of up to 0.3%, assuming 100% additive mortality. The assumption of 100% additive mortality from Caspian tern predation is the wost-case scenario for the Chinook ESU, because it assumes that none of the mortality from

tern predation is compensatory. The assumption of 100% additive mortality from Caspian tern predation is now known to be unrealistic (Hostetter 2009), but in the absence of an actual measure of % additive mortality, the assumption of 100% additive mortality errs on the side of the fish population of conservation concern.

If the number of breeding pairs of Caspian terns nesting on Brooks Island fell to zero, the annual population growth rate of the fall-run Chinook ESU would be expected to increase by only as much as 0.3% (again, assuming 100% additive mortality; Table 2.5). By comparison, management actions at East Sand Island in the Columbia River estuary to reduce the size of the Caspian tern colony there are expected to result in increases to λ of over 1% for some ESA-listed salmonid stocks.

Spring-run Chinook salmon, which are listed under the ESA, were far less susceptible to predation by Brooks Island Caspian terns than unlisted fall-run Chinook salmon. A near doubling of the Caspian tern colony size at Brooks Island would lead to a decrease in the annual population growth rate (λ) of spring-run Chinook salmon of up to 0.023% (assuming 100% additive mortality). This level of reduction in population growth rate is even lower than the amount found to be acceptable for this ESA-listed salmon run by the National Marine Fisheries Service ($\Delta\lambda = 0.05\%$; NOAA 2006). If the Caspian tern colony on Brooks Island were to disappear altogether, this would lead to an expected increase in the population growth rate for the spring-run Chinook ESU of up to just 0.03% (assuming 100% additive mortality; Table 2.5).

The Sacramento River winter-run Chinook salmon ESU is currently listed as endangered under the ESA. No fish from this run were released into San Pablo Bay. Additionally, 96% of the approximately 72,000 winter-run Chinook that were released in-river were coded wire tagged (RMISD 1977), but none of these tags were recovered on Brooks Island in 2008 (Evans et al. 2011). We therefore assume that predation by Caspian terns nesting on Brooks Island is not a significant source of mortality for this ESA-listed run.

We were not able to evaluate the impact of tern predation on juvenile steelhead because estimates of the numbers of steelhead smolts out-migrating through San Francisco Bay are not available. There were no hatchery-raised juvenile steelhead released into San Pablo Bay in 2008, and none of the hatchery-raised fish released in-river were marked with coded wire tags (RMISD 1977). Consumption of *O. mykiss* was almost two orders of magnitude less than consumption of Chinook salmon, but further study is needed to determine what proportion of *O. mykiss* consumed by Brooks Island Caspian terns are stocked rainbow trout vs. ESA-listed steelhead smolts.

Salmonid consumption by Caspian terns nesting on East Sand Island in the Columbia River estuary can help put the results of this study into context. Total smolt consumption by East Sand Island terns was estimated at 3.9-5.9 million smolts/year during 2001-2006, and this level was determined to be high enough to warrant management actions to reduce the size of the colony. This is equivalent to an average per capita salmonid consumption rate of 265 smolts per adult Caspian tern per year,

more than double the amount consumed by individual Brooks Island Caspian terns in 2008 or 2009. Furthermore, the vast majority (98%) of juvenile salmonids consumed by Brooks Island Caspian terns were from the hatchery-reared, unlisted fall-run Chinook salmon ESU (Evans et al. 2011), while Caspian terns in the Columbia River estuary prey on hatchery and wild juvenile salmonids from 13 ESA-listed ESUs and 7 unlisted ESUs (Collis et al. 2001, Ryan et al. 2003). Management of the Caspian tern colony at East Sand Island is expected to improve λ by at least 1.1% for some ESUs, assuming a moderate (50%) level of additive mortality (Lyons 2010). By comparison, if the Caspian tern colony at Brooks Island increased to the proposed size of 3,000 individuals, the greatest expected declines in λ are 0.3% for the unlisted fall-run Chinook ESU and 0.023% for the threatened spring-run Chinook ESU (assuming 100% additive mortality). The net effect of the proposed reduction in the number of Caspian terns nesting in the Columbia River estuary and the proposed increase in the number nesting in San Francisco Bay would be beneficial to listed West Coast salmonid ESUs overall.

The main objectives of this study were to estimate the consumption of juvenile salmonids by Caspian terns nesting on Brooks Island and determine whether the colony at its current size or at an enhanced size poses a significant mortality risk for ESA-listed salmonids. Unlisted fall-run Chinook salmon were by far the most susceptible to predation by this Caspian tern colony. San Francisco Bay may therefore be a more acceptable colony site for Caspian terns than the Columbia River estuary,

where many salmon stocks are ESA-listed. If the Brooks Island colony continues to

decline and eventually disappears, removal of this predation pressure alone would

result in increases in salmonid population growth rates ($\Delta\lambda$) of at most fractions of one

percentage point, whereas management of the Caspian tern colony in the Columbia

River estuary is expected to yield increases in some salmon annual population growth

rates of at least 1%. If the Brooks Island Caspian tern colony increased to a nesting

population of 3,000 individuals, consumption of juvenile Chinook salmon would

negatively impact the annual population growth rates of spring-run Chinook salmon

by 0.023% or less, an amount even lower than that already deemed acceptable for this

listed stock by the National Marine Fisheries Service ($\Delta\lambda = 0.05\%$).

LITERATURE CITED

Anderson, S.K., D.D. Roby, D.E. Lyons, and K. Collis. 2007. Relationship of Caspian tern foraging ecology to nesting success in the Columbia River estuary, Oregon, USA. Estuarine, Coastal, and Shelf Science 73: 447-456.

Anthony, J.A., D.D. Roby, and K.R. Turco. 2000. Lipid content and energy density of forage fishes from the northern Gulf of Alaska. Journal of Experimental Marine Biology and Ecology 248: 53-78.

Antolos, M., D.D. Roby, D.E. Lyons, S.K. Anderson, and K. Collis. 2005. Caspian tern predation on juvenile salmonids in the Mid-Columbia River. Transactions of the American Fisheries Society 134: 466-480.

CDFG (California Department of Fish and Game). 2009. Fishing California's Central Coast Region. Retrieved online from the California Department of Fish and Game website: www.dfg.ca.gov/publications/docs/FishGuideR3.pdf.

CDFG. 2011. GrandTab database. Available for download at http://www.calfish.org/tabid/104/Default.aspx.

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

Collis, K., D.D. Roby, D.P. Craig, S. Adamany, J.Y. Adkins, and D.E. Lyons. 2002. Colony size and diet composition of piscivorous waterbirds on the lower Columbia River: implications for loses of juvenile salmonids to avian predation. Transactions of the American Fisheries Society 131: 537–550.

Collis, K., D.D. Roby, K.W. Larson, L.J. Adrean, S.K. Nelson, A.F. Evans, D.S. Battaglia, D.E. Lyons, T.K. Marcella, and A. Patterson. In review. Trends in Caspian tern nesting and diet in San Francisco Bay: Management implications. Submitted to *Waterbirds*.

Cuthbert, F.J., and L.R. Wires. 1999. Caspian Tern (*Sterna caspia*). The Birds of North America Online [A. Poole, ed.]. Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/403.

Errington, P.L. 1967. Of predation and life. Iowa State University Press, Ames, IA.

Evans, A.F., D.D. Roby, K. Collis, B.M. Cramer, J.A. Sheggeby, L.J. Adrean, D.S. Battaglia, and D.E. Lyons. 2011. Recovery of coded wire tags on a Caspian tern colony in San Francisco Bay: A technique to evaluate impacts of avian predation on juvenile salmonids. North American Journal of Fisheries Management 31: 79-87.

Feyrer, F., M.L. Nobriga, and T.R. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences 64: 723-734.

FFC (Fishery Foundation of California). 2008. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 10p.

FFC. 2009. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 11p.

Furness, R.W. 1978. Energy requirements of seabird communities: a bioenergetics model. Journal of Animal Ecology 47: 39-53.

Gasaway, W.C., R.D. Boertje, D.V. Grangaard, D.G. Kelleyhouse, R.O. Stephenson, and D.G. Larsen. 1992. The role of predation in limiting moose at low densities in Alaska and Yukon and implications for conservation. Wildlife Monographs 120: 3-59.

Glahn, J. F., and K. E. Brugger. 1995. The impact of double-crested cormorants on the Mississippi Delta catfish industry: a bioenergetics model. Colonial Waterbirds 18: 168-175.

Good, T.P., R.S. Waples, and P. Adams [ed]. 2005. Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-NWFSC-66 598 p.

Grinnell, J., and A.H. Miller. 1944. The distribution of the birds of California. Pacific Coast Avifauna 27: 172-173.

Hostetter, N.J. 2009. Susceptibility of juvenile salmonids to avian predation: are Caspian terns and double-crested cormorants only taking the sick and injured? Unpublished M.S. Thesis. Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR.

Kendeigh, S.C. 1969. Energy responses of birds to their thermal environments. Wilson Bulletin 81: 441-449.

Klaassen, M. 1994. Growth and energetics of tern chicks from temperate and polar environments. Auk 111: 525-544.

Krebs, J.R. 1974. Colonial nesting and social feeding as strategies for exploiting food resources in the great blue heron (*Ardea herodias*). Behaviour 51: 99-134.

Lifson, N., and R. McClintock. 1966. Theory of use of the turnover rates of body water for measuring energy and material balance. Journal of Theoretical Biology 12: 46-74.

Lindley, S.T., R.S. Schick, E. Mora, P.B. Adams, J.J. Anderson, S. Greene, C. Hanson, B.P. May, D. McEwan, R.B. MacFarlane, C. Swanson, and J.G. Williams. 2007. Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento-San Joaquin basin. San Francisco Estuary and Watershed Science 5: 1-26.

Lindley, S.T., C.B. Grimes, M.S. Mohr, W. Peterson, J. Stein, J.T. Anderson, L.W. Botsford, D.L. Bottom, C.A. Busack, T.K. Collier, J. Ferguson, J.C. Garza, A.M. Grover, D.G. Hankin, R.G. Kope, P.W. Lawson, A. Low, R.B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F.B. Schwing, J. Smith, C. Tracy, R. Webb, B.K. Wells, and T.H. Williams. 2009. What caused the Sacramento River fall Chinook stock collapse? U.S. Department of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. 62p.

Lyons, D.E., D.D. Roby, and K Collis. 2005. Foraging ecology of Caspian terns in the Columbia River estuary, USA. Waterbirds 28: 280-291.

Lyons, D.E., D.D. Roby, and K.Collis. 2007. Foraging patterns of Caspian terns and double-crested cormorants in the Columbia River estuary. Northwest Science 81:91-103.

Lyons, D.E. 2010. Bioenergetics-based predator-prey relationships between piscivorous birds and juvenile salmonids in the Columbia River estuary. Unpubl. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 331p.

Lyons, D.E., and D.D. Roby. 2011. Validating growth and development of a seabird as an indicator of food availability: Captive-reared Caspian tern chicks fed *ad libitum* and restricted diets. Journal of Field Ornithology 82: 88-100.

MacFarlane, B. 2010. Energy dynamics and growth of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from the Central Valley of California during the estuarine phase and first ocean year. Canadian Journal of Fisheries and Aquatic Sciences 67: 1549-1565.

Madenjian, C.P., and S.W. Gabrey. 1995. Waterbird predation on fish in western Lake Erie: A bioenergetics model application. Condor 97: 141-153.

McClure, M., B. Sanderson, E. Holmes, C. Jordon, P. Kareiva, and P. Levin. 2000. A standardized quantitative analysis of risks faced by salmonids in the Columbia River basin. National Marine Fisheries Service, Seattle, WA.

McEwan, D.R. 2001. Central Valley steelhead. *In* Brown, R.L. [ed.] Fish Bulletin 179: Contributions to the biology of Central Valley salmonids, vol. 1, p. 1–43. California Department of Fish and Game, Sacramento.

Meng, L., P.B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and introduced fished of Suisun marsh. Transactions of the American Fisheries Society 123: 498-407.

Montevecchi, W.A., and J.F. Piatt. 1984. Composition and energy contents of mature inshore spawning capelin (*Mallotus villosus*): Implications for seabird predators. Comparative Biochemistry and Physiology 78A: 15-20.

Nagy, K.A. 1980. CO_2 production in animals: Analysis of potential errors in the doubly labeled water method. American Journal of Physiology 238: 466-473.

NOAA (National Oceanic and Atmospheric Administration). 1998. Endangered and threatened species: threatened status for two ESUs of steelhead in Washington, Oregon, and California. Federal Register 63: 53 (19 March 1998): 13347-13371.

NOAA. 2005. Endangered and threatened species: final listing determinations for 16 ESUs of west coast salmon, and final 4(d) protective regulations for threatened salmonid ESUs. Federal Register 70:123 (28 June 2005): 37160-37204.

NOAA. 2006. Biological Opinion for Caspian tern management plan to reduce predation of juvenile salmonids in the Columbia River estuary. NOAA Fisheries, Portland, Oregon.

NOAA. 2008. Fisheries off west coast states and in the western Pacific; west coast salmon fisheries; 2008 management measures and a temporary rule. Federal Register 73:85(1 May 2008): 23971-23981.

NOAA. 2009a. Commerce Secretary Gary Locke extends 2008 disaster declaration due to poor salmon returns (Press release, 30 April 2009). Retrieved from http://www.nmfs.noaa.gov/sfa/sf3/disaster.htm.

NOAA. 2009b. Fisheries off west coast states and in the western Pacific; West coast salmon fisheries; 2009 management measures. Federal Register 74: 85 (5 May 2009): 20610-20620.

Olla, B.L., M.W. Davis, and C.H. Ryer. 1994. Behavioural deficits in hatchery-reared fish: Potential effects on survival following release. Aquaculture and Fisheries Management 25: 19-34.

Phillips, R.A., D.R. Thompson, and K.C. Hamer. 1999. The impact of great skua predation on seabird populations at St. Kilda: A bioenergetics model. Journal of Applied Ecology 36: 218-232.

Quinn, J.S. 1990. Sexual size dimorphism and parental care patterns in a monomorphic and a dimorphic larid. Auk 107: 260-274.

Reynolds, S.D., and T.H. Kunz. 2001. Standard methods for destructive body composition analysis. *In* Speakman, J.R. [ed.] Body composition analysis of animals. Cambridge University Press, Cambridge, UK, 39-55.

RMISD (Regional Mark Information System Database). Continuously since 1977. Regional Mark Processing Center, Pacific States Marine Fisheries Commission, Portland, OR. Available at: http://www.rmpc.org.

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

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

Schmidt-Nielsen, K. (ed.). 1997. Animal physiology: Adaptation and environment. 5th Edition, Cambridge University Press, New York. 607 pp.

Seto, N., J. Dillon, W.D. Shuford, and T. Zimmerman. 2003. A review of Caspian tern (*Sterna caspia*) nesting habitat: A feasibility assessment of management opportunities in the U.S. Fish and Wildlife Service Pacific Region. U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR.

Silverman, E.D., R.R. Veit, and G.A. Nevitt. 2004. Nearest neighbors as foraging cues: information transfer in a patchy environment. Marine Ecology Progress Series 277: 25-35.

Strong, C.M., L.B. Spear, T.P. Ryan, R.E. Dakin. 2004. Forster's tern, Caspian tern, and California gull colonies in San Francisco Bay: habitat use, numbers and trends, 1982-2003. Waterbirds 27: 411-423.

USACE (U.S. Army Corps of Engineers). 2006. Record of Decision Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USACE, Portland, Oregon.

USFWS (U.S. Fish and Wildlife Service). 2006. Record of Decision: Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USFWS, Portland, Oregon.

Weimerskirch, H., Y. Cherel, F. Cuenot-Chaillet, and V. Ridoux. 1997. Alternative foraging strategies and resource allocation by male and female wandering albatrosses. Ecology 78: 2051-2063.

Weimerskirch, H. 1998. How can a pelagic seabird provision its chick when relying on a distant food resource? Cyclic attendance at the colony, foraging decision and body condition in sooty shearwaters. Journal of Animal Ecology 67: 99-109.

Wiens, J.A., and J.M. Scott. 1975. Model estimation of energy flow in Oregon coastal seabird populations. Condor 77: 439-452.

Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. North American Journal of Fisheries Management 18: 487-521.

Table 2.1. Energy requirements of Caspian terns nesting at Brooks Island, San Francisco Bay in 2008 and 2009 and the percent of total energy consumption by the tern colony that was derived from each prey type. Mean energy requirements are reported with standard deviation in parentheses.

	2008	2009
Energy Consumption (10^4 MJ)		
Adult terns	17.3 (1.1)	14.0 (0.9)
Juvenile terns	1.3 (0.1)	0.5 (0.1)
Total	18.6 (1.1)	14.5 (0.9)
Energy Contribution by prey type (%)		
Steelhead/Trout	0.6	0.6
Chinook salmon	5.1	4.2
Total Salmonids	**5.7**	**4.8**
Clupeids (herring & sardines)	28.6	18.5
Northern anchovy	22.3	8.1
Shiner surfperch	14.8	22.1
Goby	9.1	4.8
Silversides	8.8	22.7
Smelt	3.4	7.2
Pacific staghorn sculpin	2.5	1.8
Centrarchids	1.6	3.4
Plainfin midshipman	0.3	1
Flatfish	0.2	0.9
Leopard shark	0.1	0.3
Pacific sandlance	0.02	0.04
Pacific tomcod	0.01	0.5
Other	0.3	0.8
Unidentified non-salmonid	2.2	3.3

Table 2.2. Diet composition (% of prey items) of Caspian terns nesting at Brooks Island, central San Francisco Bay in 2008 and 2009.

Prey Type	2008	2009
Steelhead/Trout	0.3	0.2
Chinook salmon	9.9	7.8
Total Salmonids	**10.2**	**8**
Clupeids (herring & sardines)	14.4	9.4
Northern anchovy	29.1	11.3
Shiner surfperch	19.9	32.3
Goby	9.7	5.9
Silversides	5.4	14.3
Smelt	2.3	5.5
Pacific staghorn sculpin	4.4	3.3
Centrarchids	1.2	2.5
Plainfin midshipman	0.4	1.7
Flatfish	0.2	1
Leopard shark	0.07	0.1
Pacific sandlance	0.04	0.1
Pacific tomcod	0.02	0.4
Other	0.2	0.7
Unidentified non-salmonid	2.5	3.1

Table 2.3. Length – mass regression equations, average prey mass, energy density, and energy content of major prey types identified in the diet of Caspian terns nesting at Brooks Island in central San Francisco Bay, California during 2008 and 2009.

	Length to Mass Regression			2008 Prey Mass (g)			2009 Prey Mass (g)			Energy Density (kJ/g)			2008 Energy Content (kJ)	2009 Energy Content (kJ)
	Equation M=	R^2	N	Mean	SD	N	Mean	SD	N	Mean	SD	N		
Steelhead/Trout	n/a			61.20	16.3	231	61.20	16.3	231	4.61	0.86	12	282.13	282.13
Chinook salmon	(L-62.148)/4.0585	0.83	22	8.81	0.1	1	7.96	0.1	1	4.76	0.82	13	41.99	37.92
Clupeids	(L-110.18)/1.2889	0.79	14	36.97	0.2	1	16.22	0.1	1	5.34	1.23	11	197.52	86.64
Northern anchovy	(L-80.394)/3.1066	0.93	14	13.22	0.1	1	4.17	0.03	1	5.15	1.52	7	68.07	21.45
Shiner surfperch	(L-48.451)/3.3391	0.94	33	16.55	0.1	1	17.21	0.1	1	4.68	0.76	7	77.46	80.55
Goby	(L-63.098)/3.8127	0.94	17	20.01	0.2	1	16.29	0.2	1	4.43	0.95	8	88.72	72.22
Silversides	(L-96.955)/2.0156	0.85	25	38.68	0.6	1	33.26	0.3	1	4.63	0.77	11	179.11	154.04
Smelt	n/a			25.1	10.2	7	25.1	10.2	7	5.02	1.32	12	126.00	126.00
Pacific staghorn sculpin	(L-64.624)/3.0396	0.94	15	16.08	0.2	1	15.36	0.2	1	3.95	0.56	9	63.44	60.58
Centrarchids	n/a			43.70	4.1	194	43.70	4.1	194	3.46	0.33	17	151.20	151.20
Plainfin midshipman	n/a			23.90	4.8	1	23.90	4.8	1	3.36	0.67	1	80.30	80.30
Flatfish	n/a			23.30	16.6	25	23.30	16.6	25	4.19	0.38	12	97.63	97.63
Leopard shark	n/a			52.90	10.6	1	52.90	10.6	1	3.77	0.76	1	199.43	199.43
Pacific sandlance	n/a			5.60	2.9	38	5.60	2.9	38	5.62	0.46	6	31.47	31.47
Pacific tomcod	n/a			33.90	10.7	4	33.90	10.7	4	3.45	0.32	13	116.96	116.96
Other	n/a			25	5	1	25	5	1	4.5	0.9	1	112.5	112.50

Table 2.4. Mean prey consumption by Caspian terns nesting at Brooks Island, central San Francisco Bay in 2008 and 2009 expressed as total numbers of fish.

Prey Item	2008 Numbers			2009 Numbers	
	Mean (10^3)	95% CI (10^3)		Mean (10^3)	95% CI (10^3)
Steelhead/Trout	4.2	3.4 - 5.1		4.1	3.1 - 5.1
Chinook salmon	200.7	171.6 - 229.8		163.3	140 - 186.5
Total Salmonids	**204.9**	**175.3 - 234.5**		**167.4**	**143.6 - 191.2**
Clupeids	277.7	238 - 317.3		176.4	152.2 - 200.6
Northern anchovy	559.9	479.4 - 640.3		193.9	166.7 - 221.1
Shiner surfperch	364.2	312.6 - 415.9		515.3	446.5 - 584
Goby	200.1	169.3 - 230.9		98.9	84.6 - 113.3
Silversides	94.4	80.6 - 108.1		229.8	198.2 - 261.4
Smelt	51.3	43.6 - 59		108.6	93.5 - 123.6
Pacific staghorn sculpin	76.1	64.6 - 87.5		50.8	43.7 - 57.9
Centrarchids	19.6	16.4 - 22.8		40.5	35 - 46
Plainfin midshipman	7.8	6.6 - 9		22.8	19.3 - 26.3
Flatfish	3.0	2.5 - 3.4		15.9	13.7 - 18.1
Leopard shark	1.2	1 - 1.3		2.5	2.1 - 2.9
Pacific sandlance	0.9	0.8 - 1.1		2.2	1.9 - 2.5
Pacific tomcod	0.3	0.2 - 0.4		7.6	6.5 - 8.8
Other	4.2	3.5 - 4.8		12.2	10.5 - 13.8
Unidentified non-salmonid	45.3	38.1 - 52.5		53.7	46.4 - 61
Total	**1910.7**	**1643.1 - 2178.4**		**1698.4**	**1473.3 - 1923.6**

Table 2.5. Potential changes to annual population growth rates (λ) of Central Valley spring-run and fall-run Chinook salmon under two management scenarios for Brooks Island Caspian terns and over a range of potential levels of additive mortality to salmon from Caspian tern predation. Percent change to initial λ is given in parentheses.

Salmon Stock	Status	Initial λ	New λ							
			0 Caspian Tern Breeding Pairs				1,500 Caspian Tern Breeding Pairs			
			25% Additive Mortality	50% Additive Mortality	75% Additive Mortality	100% Additive Mortality	25% Additive Mortality	50% Additive Mortality	75% Additive Mortality	100% Additive Mortality
Central Valley spring-run Chinook salmon	Threatened	0.8074	0.8075	0.8075	0.8076	0.8077	0.8073	0.8073	0.8072	0.8072
			(+0.007%)	(+0.01%)	(+0.02%)	(+0.03%)	(-0.006%)	(-0.01%)	(-0.02%)	(-0.023%)
Central Valley fall-run Chinook salmon	Species of Concern	0.7165	0.7173	0.7182	0.7190	0.7199	0.7158	0.7151	0.7143	0.7136
			(+0.08%)	(+0.17%)	(+0.25%)	(+0.3%)	(-0.07%)	(-0.14%)	(-0.22%)	(-0.3%)
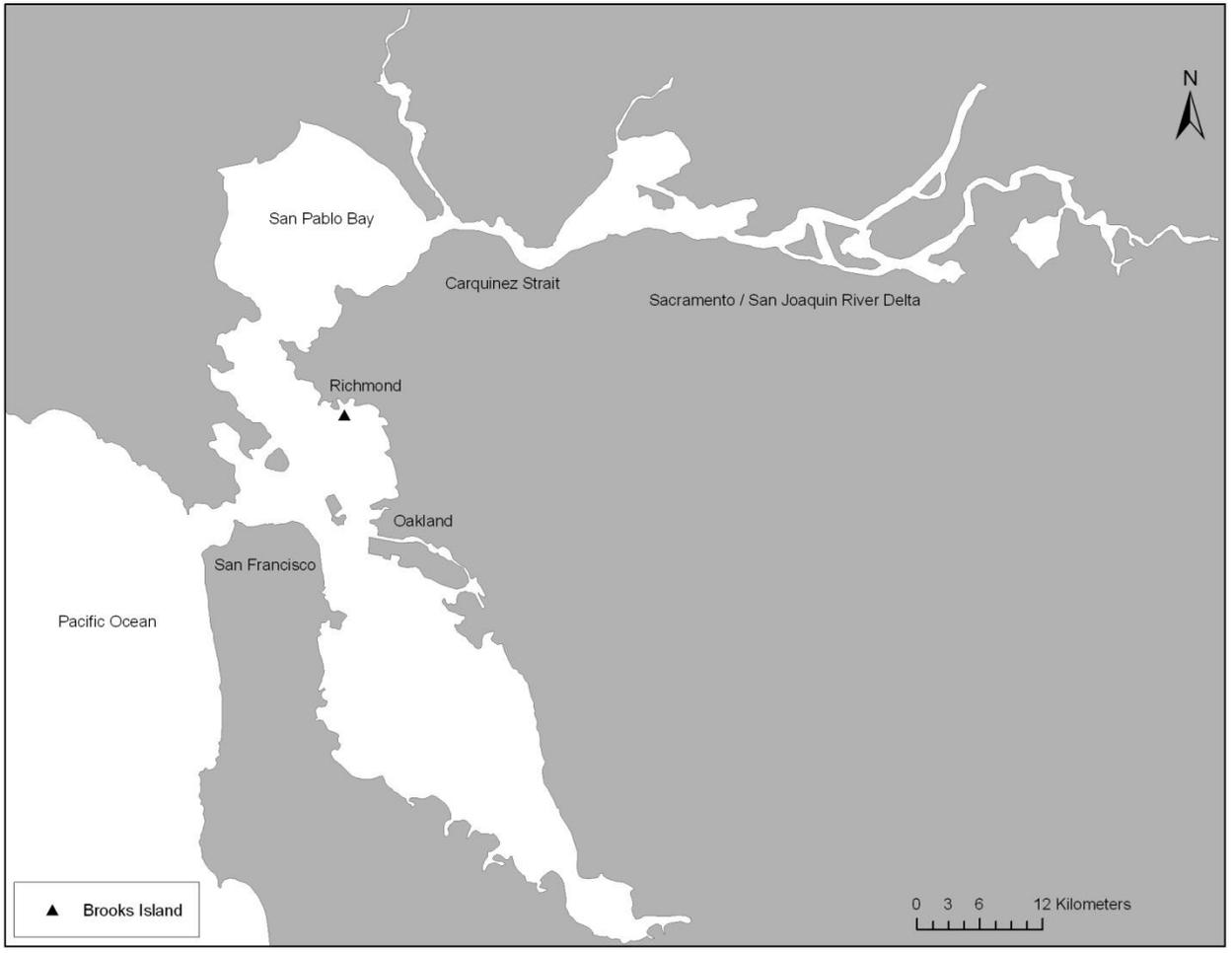
Figure 2.1. Map of the study area of San Francisco Bay showing the location of Brooks Island.
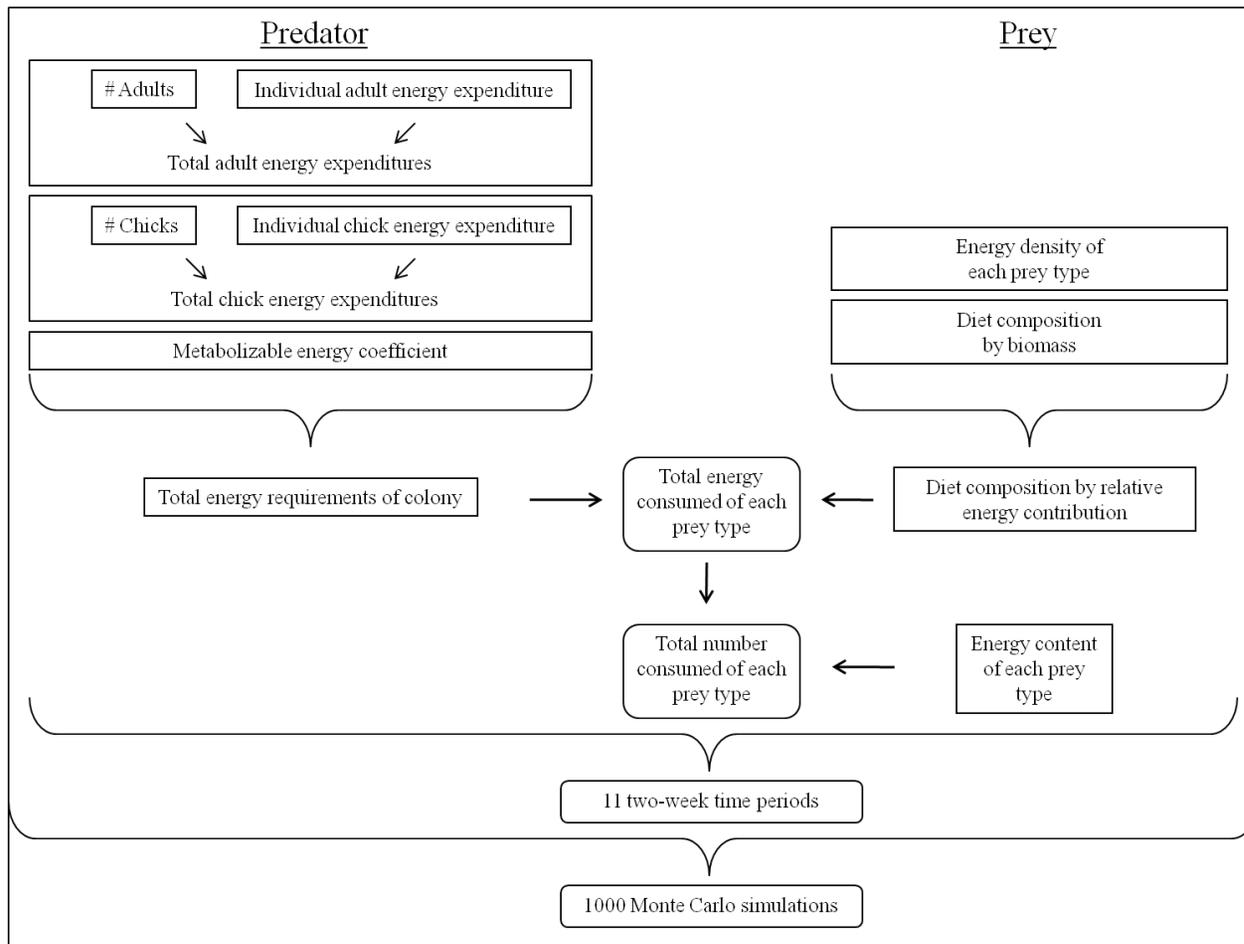
Figure 2.2. Bioenergetics model schematic used to estimate fish consumption by Caspian terns nesting at Brooks Island in San Francisco Bay, California.
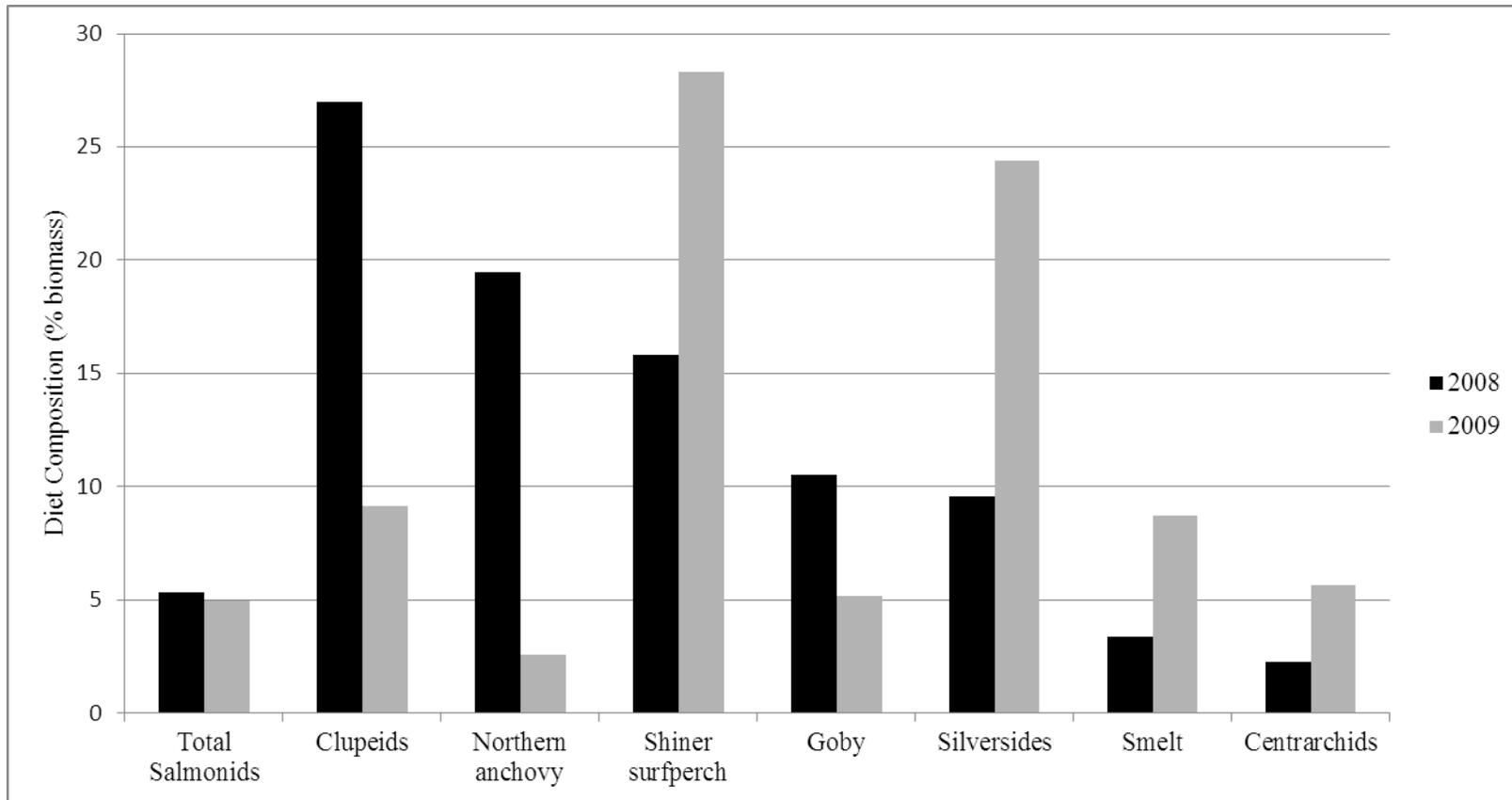
Figure 2.3. Caspian tern diet composition (% biomass of primary prey types) at the Brooks Island breeding colony in central San Francisco Bay, California during 2008 and 2009.

CHAPTER 3

FORAGING ECOLOGY OF CASPIAN TERNS

(*HYDROPROGNE CASPIA*) NESTING ON BROOKS ISLAND IN

SAN FRANCISCO BAY, CALIFORNIA

Lindsay J. Adrean, Donald E. Lyons, and Daniel D. Roby

ABSTRACT

Brooks Island, located in San Francisco Bay, California, currently supports the largest breeding colony of Caspian terns (*Hydroprogne caspia*) in the Bay Area, and is one of several proposed relocation sites for some Caspian terns from the world's largest colony at East Sand Island in the Columbia River estuary of Oregon. It is uncertain, however, whether Brooks Island is suitable for expansion of the existing Caspian tern colony because availability of forage fish resources may be limiting. In addition, juvenile salmonids (*Oncorhynchus* spp.) comprise up to 10% of the diet and there are several threatened or endangered runs of juvenile salmonids found in the San Francisco Bay system that could be negatively affected. In 2008 and 2009, I used radio telemetry to investigate the foraging ecology of Caspian terns nesting on Brooks Island as a means to examine the suitability of Brooks Island for colony enhancement. Median foraging distance from the colony was greater in 2009 compared to 2008 (20.6 km vs. 14.0 km), average number of foraging trips per day was higher (4.4 vs. 3.4 foraging trips), and average adult colony attendance was lower (43% vs. 52% of daylight hours). These results indicate that the colony was more food-limited during the 2009 breeding season, concurrent with anomalous downwelling along the coast of northern California and reduced availability of marine forage fish. Caspian terns exhibited a number of core foraging areas in and just outside the Bay, and one large core foraging area overlapped with the hatchery release site for juvenile salmonids in eastern San Pablo Bay, suggesting that most salmonids consumed were captured at or

near the release site. Individual Caspian terns displayed foraging site fidelity, suggesting that foraging at the release site for hatchery-raised salmonids was a learned behavior by some terns. The Brooks Island colony site is within foraging distance of adequate marine forage fish resources in most years, and Caspian terns nesting there are not dependent on juvenile salmonids as a food resource. Consumption of juvenile salmonids by Brooks Island terns would be largely curtailed by modification of hatchery release practices.

INTRODUCTION

Caspian tern (*Hydroprogne caspia*) nesting has been recorded in the San Francisco Bay area of California since 1916 (Grinnell and Miller 1944). In 2009 there were 6 breeding colonies of Caspian terns in the Bay Area, accounting for a total of approximately 830 breeding pairs. The largest colony was located on Brooks Island where more than 80% of these pairs nested. This Caspian tern colony is currently thought to be limited by encroaching vegetation, erosion of nesting substrate, and predation from an adjacent colony of western gulls (*Larus occidentalis*) and California gulls (*L. californicus*; Collis et al. In review). Other available Caspian tern nesting habitat in the Bay Area consists mostly of small islands located in salt ponds. Many of these salt ponds are slated for inclusion in salt marsh restoration projects, and continued availability of Caspian tern nesting habitat is uncertain (Seto et al. 2003). Prey availability, however, has not been addressed as a potential factor limiting the numbers and nesting success of Caspian terns breeding in the San Francisco Bay area.

Monitoring of Caspian tern diets at Brooks Island during 2003-2005 indicated that juvenile salmonids (*Oncorhynchus* spp.) were a small part of the diet (<5% of prey items; Collis et al. In review), but when monitoring resumed in 2008-2009 the proportion of juvenile salmonids in the diet had increased to nearly 10% (see Chapter 2). Those salmonids were identified to species and evolutionarily significant unit (ESU) based on smolt coded wire tags (CWTs) recovered on the tern colony (Evans et al. 2011). Recovered CWTs indicated that nearly all smolts consumed were from the

Central Valley fall-run Chinook salmon ESU (*O. tshawytscha*), which is not listed as

threatened or endangered under the U.S. Endangered Species Act (ESA). The fall-run

Chinook ESU is the most predominant run in the Bay Area, and several hatchery

release sites for this ESU are located in eastern San Pablo Bay, within 20 kilometers of

Brooks Island (FFC 2008, FFC 2009).

In 2006, resource managers devised a management plan calling for restoration

of habitat for Caspian terns at a number of current or former colony sites in Oregon

and California, including the colony at Brooks Island (USFWS 2006). The purpose of

this management plan is to redistribute a portion of the Caspian tern colony on East

Sand Island in the Columbia River estuary of Oregon, where Caspian tern predation is

considered a limiting factor for recovery of several ESA-listed salmonid ESUs (Good

et al. 2005). The Columbia River basin is home to 20 ESUs of anadromous

salmonids (Waples 1995), of which 13 are listed as threatened or endangered under

the ESA (Good et al. 2005). The East Sand Island tern colony consumes

approximately 5% of all out-migrating salmonid smolts that reach the estuary, totaling

5 - 7 million salmonids per year (Lyons 2010).

I conducted a radio telemetry study to examine the foraging behavior and

distribution of Caspian terns nesting on Brooks Island. My primary goal was to assess

the suitability of Brooks Island as a Caspian tern colony site based on both food

availability and impacts to prey species of conservation concern. Brooks Island may

not be an optimal colony site for Caspian terns, and may exist solely because other

more suitable colony sites are not available, so I investigated foraging behavior as an

indicator of prey availability, a potential limiting factor. In 2006, the National Marine

Fisheries Service (NMFS) prepared a Biological Opinion that concluded that the

creation of additional Caspian tern nesting habitat on Brooks Island, and the associated

increase in size of the tern colony to about 1,500 pairs, would not be likely to

jeopardize the ESA-listed salmonid runs in San Francisco Bay (NOAA 2006). I aimed

to test this opinion by identifying foraging areas used by the colony and whether

individual terns display foraging site fidelity. In particular, I was interested in

detecting any overlap between salmon hatchery release sites and Caspian tern foraging

distribution. I sought to test the following hypotheses through this study:

1. Foraging behavior of Caspian terns nesting on Brooks Island (i.e., foraging trip

distance and duration, percent of time spent foraging) is consistent with a colony that

is food-limited.

2. The foraging behavior of Brooks Island Caspian terns is consistent with "hot spot"

foraging on persistent patches of aggregated prey (foraging distribution highly

aggregated).

3. Foraging distribution of Caspian terns nesting at Brooks Island indicates that birds

are focusing foraging efforts at release sites for hatchery-raised salmonid smolts in

San Francisco Bay.

METHODS

Study Area

Adult Caspian terns nesting at the breeding colony on Brooks Island were captured and radio-tagged for this study in 2008 and 2009. Brooks Island (37°57'46"N, 122°21'18"W) is located in central San Francisco Bay, Contra Costa County, California. The area surveyed for radio-tagged terns was initially delineated based on the previously published maximum foraging range for nesting Caspian terns (62 km; Gill 1976; Fig. 3.1).

Capture Methods

Adult Caspian terns were captured over the course of two days during the late incubation stage of both the 2008 and 2009 breeding seasons. The birds were captured using monofilament noose mats placed around nests containing eggs. Radio transmitters (Advanced Telemetry Systems [ATS], Isanti, Wisconsin) with unique frequencies, emitting 40 pulses/min, and weighing 9 - 10 g (~1.5% of average Caspian tern body mass) were attached to the six central retrices of each bird using plastic cable ties and Crazy Glue brand superglue, a modification of the method of Irons (1998). Each tern was fitted with a federal numbered metal leg band and two plastic colored leg bands on one leg, and a unique field readable alphanumeric plastic leg band on the other. Prior to release, each radio-tagged tern was also marked on the back and breast feathers with a temporary dye (rhodamine-B) to aid in quick

identification of individuals upon return to the breeding colony. All radio-tagged

Caspian terns were sexed from their DNA using blood samples taken from the brachial

vein and sent to Avian Biotech International (Tallahassee, FL).

Radio-tracking

Caspian tern colony attendance was monitored using a fixed antenna system

placed near the breeding colony on Brooks Island. A small "H" style antenna with a

range of approximately 1 km was mounted on a 1 m pole in the dunes adjacent to the

colony, at a distance of about 200 m from the colony edge, where human visitation did

not cause disturbance to the tern colony. A very high frequency (VHF) receiver (ATS

model R2100) and a datalogger (ATS model D5041A) were connected to the antenna

and continuously scanned through the list of deployed frequencies at a rate of 15

seconds per frequency in 2008 and 12 seconds per frequency in 2009. The datalogger

recorded each detected frequency and reported the number of pulses heard at that

wavelength. The on-colony telemetry station collected presence/absence data from 23

May until 6 July in 2008 and from 16 May until 14 June in 2009, when all radio-

tagged breeding birds had either raised their chicks to fledging age or their nesting

attempt had failed.

I conducted aerial surveys for radio-tagged terns in 2008 between 28 May and

20 June, and in 2009 between 15 May and 14 June. Surveys were conducted 3-4 times

per week during each study period. The survey path encompassed the entire study

area with the goal of locating all radio-tagged terns not present at the colony and

presumably on foraging trips. Aerial surveys were conducted from a Cessna 205

fixed-wing aircraft; both aircraft and pilot were certified by the Aviation Management

Directorate. Radio-tagged Caspian terns were detected using a single dipole antenna

attached to each wing strut of the aircraft and connected to a VHF receiver (ATS

model R2100). A switchbox facilitated tracking of single individuals by listening to

one antenna at a time and scanning for all individuals by listening to both antennae

simultaneously. The locations of individual terns were pinpointed by circling in on

the signal using one antenna until the signal was very strong and originating directly

below the aircraft (see Anderson 2007). Locations were recorded using a Garmin

handheld GPS device (Garmin GPSMAP 76CSX) and later analyzed in ArcMap

version 9.3 (ESRI 2006) using Hawth's Tools (Beyer 2007). Accuracy of GPS

locations was tested by locating eight transmitters placed at locations within the study

area unknown to the radio trackers. This resulted in an average location error of 1.0

km $\pm$ 0.2 km.

Flights originated in Concord, CA and covered the entire study area by first

heading east to Bradford Island in the Sacramento/San Joaquin River Delta before

returning west to cover the lower Delta, San Pablo Bay, the nearshore area of the

Pacific Ocean (from Point Reyes to Pacific City), Central San Francisco Bay, and

finally South San Francisco Bay. Flight duration averaged 3 hrs, 30 min in 2008.

Flight duration was slightly longer in 2009 due to the increased number of radio-

tagged individuals and averaged 4 hrs, 15 min. Aerial surveys were haphazardly

chosen to commence in the morning or afternoon, and survey start times ranged from

08:00 to 16:00 PDT. Aerial surveys were timed without regard to tide stage, and all

stages of the tidal cycle (high, ebb, low, flood) were sampled. Eight flights in 2008

and five flights in 2009 were flown on days when hatchery-raised salmon releases

were scheduled in eastern San Pablo Bay. In 2008, four of these flights overlapped the

time of release, and four were completed either prior to or after the releases. In 2009,

two flights overlapped with hatchery releases in San Pablo Bay, and three flights were

conducted after hatchery releases were completed.

Nest Monitoring

Radio-tagged Caspian terns were initially identified on the colony post-release

by observing birds whose plumage was dyed with rhodamine and subsequently by

their field readable leg bands. Nesting status of each radio-tagged tern was confirmed

by observing behavior on colony from an observation blind located at the edge of the

colony. Radio-tagged terns were considered to be actively breeding if they were

observed incubating eggs, brooding chicks, or feeding either a mate or a chick at a

nest.

Data Analysis

Colony attendance rates of seabirds are often used as an indicator of prey

availability (Cairns 1987, Monaghan et al. 1994, Kitaysky et al. 2000). Breeding adult

seabirds compensate for low prey availability by spending more time foraging and less

time at the colony. To investigate potential food limitations at the Brooks Island Caspian tern colony, I estimated colony attendance rates using the presence/absence data for each radio-tagged tern collected by the fixed telemetry system adjacent to the Brooks Island colony. Presence/absence data were corrected for missed detections using detections of a reference transmitter placed near the colony throughout the study period. Colony attendance, or proportion of time spent on-colony, during chick-rearing was calculated for each individual by dividing the number of cycles a bird was detected during daylight hours each day by the number of scans performed. Daylight hours, or all hours between the average of civil twilight times during chick-rearing, were from 04:15 to 20:00 Pacific Daylight Time (PDT). Foraging trip duration for trips taken during daylight hours was estimated by calculating the average number of scanning cycles when a radio-tagged tern was not detected on-colony, and therefore presumed to be on a foraging trip away from the colony. The average number of consecutive skipped scanning cycles for each individual radio-tagged tern was then multiplied by the average cycle time. Trips that were initiated during daylight hours, but concluded after civil twilight were also assumed to be foraging trips and were included in the analysis. The average number of foraging trips taken per day was also calculated for each radio-tagged individual. I used a Welch's t-test to compare differences in mean colony attendance between the two years of study while accounting for unequal variances. Student's t-tests were used to test for between-year

differences in foraging trip duration and the average number of foraging trips taken per day.

Multiple off-colony locations for an individual tern are not independent, so in order to describe the colony-wide foraging distribution I used a sub-sample of the data consisting of one randomly chosen off-colony location per radio-tagged individual. Using this sub-sample, I tested for sexual differences in mean foraging distance from the colony by first separating the data by year, and then employing a Welch's t-test in 2008 to account for unequal variances, and a Student's t-test in 2009 (Ramsey and Shafer 2002). I also used a Student's t-test to test for between-year differences in mean foraging distance from the colony (SAS 2009).

To investigate whether individual Caspian terns frequented particular foraging areas off-colony, I created distance matrices using Hawth's Tools (Beyer 2007) to parameterize the distances between off-colony detections for each radio-tagged tern with five or more off-colony detections, and then compare those distances to the distribution of off-colony detections among radio-tagged terns. Data from the two years were combined to compensate for small sample sizes. I calculated the distance from each off-colony detection for an individual to all of that individual's other off-colony detections, without repetition. These distances were used to calculate a mean distance between detections within an individual bird. I then created a set of randomly chosen off-colony detections from all other radio-tagged birds, equal in number to those from each individual with five or more off-colony detections. For each of these

randomly chosen sets I calculated the distance from each detection to all other

detections in the set, without repetition. The mean distance between detections for

these sets was taken as the mean distance between detections among individuals. I

calculated the difference between mean distances within and among individuals and

used a one sample t-test to determine whether the mean difference was significantly

different from zero (Ramsey and Shafer 2002, SAS 2009).

I divided the available open water foraging habitat in San Francisco Bay into

five zones for analysis of foraging distribution using the subsample of one randomly

chosen off-colony detection per bird. These zones correspond to those commonly

used in reference to the San Francisco Bay area. The Central Bay zone, where the

Brooks Island colony is located, is bordered by the San Rafael Bridge to the north, the

Golden Gate Bridge to the west, and a line between Hunters Point and San Leandro

Channel to the south. San Pablo Bay is the next zone to the north, and extends from

the San Rafael Bridge to the mouth of Carquinez Strait. East of San Pablo Bay is the

Sacramento/San Joaquin River Delta (hereafter "the Delta") zone which includes open

water areas upriver of and including Carquinez Strait. To the south, the South Bay

zone extends from the line between Hunters Point and San Leandro Channel south to

the town of Alviso. The fifth and final zone includes the nearshore marine areas

outside of San Francisco Bay, extending seaward from the Golden Gate Bridge

(Figure 3.1). Fisher's exact tests (SAS 2009) were used to test for differences in

foraging distribution (relative use of five foraging zones) between males and females

in each year, and to test for differences in the distribution of off-colony detections between years.

A fixed kernel density estimator was used in Hawth's Tools (Beyer 2007) to calculate the 25% volume contour of a subsample of off-colony detections for each year, using a 30 m grid cell size. In order to obtain an adequate sample size for each year, two randomly selected locations per bird were chosen. Kernel density estimation (KDE) is a nonparametric statistical method that is most commonly used in home range analysis of individual subjects (Seaman 1996). In this study I used KDE to calculate the 25% volume contour of the subsample of off-colony locations. My subject was therefore the breeding colony of Caspian terns, instead of one individual tern. I used the Least Squares Cross Validation method to choose a smoothing parameter. The 25% volume contour contains, on average, 25% of the probability density distribution, and is accepted as an estimate of the core-use areas of the study subject (Hyrenbach et al. 2002, Kappes et al. 2010).

Means are presented $\pm$ one standard error unless otherwise noted. All tests are taken to be significant at the level of $\alpha \leq 0.05$.

RESULTS

A total of 92 adult Caspian terns were captured on the Brooks Island breeding colony in mid-May, 42 in 2008 and 50 in 2009. Of these radio-tagged Caspian terns, 59 were subsequently confirmed to be nesting at the Brooks Island colony and were relocated off-colony at least once; 28 terns in 2008 and 31 in 2009. Of these radio-

tagged breeders, nine were females and 19 were males in 2008, and 15 were females and 16 were males in 2009.

The on-colony telemetry system did not record false detections in either year, and reference transmitters were detected 96% of the time in 2008 and 95% of the time in 2009. Due to the difference in scanning rates and numbers of radio-tagged birds in each year, the average period required for one complete scan cycle was 12 min in 2008 and nine min in 2009. In both years, observations of meal delivery rates indicated that less than 20% of absences from the colony by adult terns lasting the equivalent of one scan cycle were foraging trips, where the adult returned to the nest with a fish (L.J. Adrean, unpublished data). Consequently, colony absences lasting just one scan cycle were not considered foraging trips and were not included in calculations of average foraging trip duration or average number of foraging trips per day. Data on foraging trips recorded during chick-rearing were available for 27 birds in 2008 and 23 birds in 2009.

The distribution of average colony attendance for radio-tagged breeding adult terns during daylight hours was normal (Kolmogorov-Smirnov test, D = 0.1076, p = 0.144), so no transformations were applied prior to analysis. Average colony attendance during daylight hours in 2008 (52% of the time) was significantly higher than in 2009 (43% of the time; Welch's t-test: 95% CI: difference of 4.8 – 14.6 percentage points, $t_{37.81}$ = 4.02, p = 0.0003). There was no significant difference in average foraging trip duration (125.4 $\pm$ 4.6 min) during chick-rearing between the two

study years (Student's t-test: $t_{48} = 0.34$, p = 0.7327). There was a significant

difference in the average number of foraging trips per day by females (2.6 $\pm$ 0.2) vs.

by males (3.8 + 0.15) in 2008 (Student's t-test: $t_{25} = 4.5$, p = 0.0001), but the

difference was not statistically significant in 2009, when females averaged 4.0 $\pm$ 0.24

trips per day and males averaged 4.6 $\pm$ 0.36 trips per day (Student's t-test: $t_{21} = 1.3$, p

= 0.21). Due to the significant gender difference in the average number of foraging

trips per day in 2008, inter-annual differences were examined separately for each sex.

Both sexes undertook significantly more foraging trips in 2009 compared to 2008.

The mean inter-annual difference for females was 1.36 $\pm$ 0.32 trips per day (Student's

t-test: $t_{16} = -4.26$, p = 0.0006) and for males was 0.86 $\pm$ 0.36 trips per day (Welch's t-

test: $t_{17.324}$, p = 0.04).

I conducted a total of 24 aerial surveys to relocate Caspian terns foraging away

from the colony, 11 in 2008 and 13 in 2009. During aerial surveys it became apparent

that some radio-tagged Caspian terns from the Brooks Island colony were travelling

further than 62 km, the predetermined radius of the survey area, in a northeast

direction, so the search area radius was increased to 80 km in that direction. A total of

208 off-colony detections of radio-tagged terns were collected during the study (Fig.

3.2), 105 detections in 2008 (average number of off-colony detections per individual =

3.75, median = 4, range = 1-7) and 103 detections in 2009 (average number of off-

colony detections per individual = 3.29, median = 3, range = 1-10).

The maximum straight line distance from the Brooks Island colony that a breeding Caspian tern was detected was 80 km during each year of the study (Fig. 3.2). In 2008 a female was detected at this distance from the colony and in 2009, a male. This exceeds the previously published record for foraging distance from the breeding colony of an actively nesting Caspian tern (62 km; Gill 1976) by 18 km, or 29%. I calculated the average distance from the colony for each individual tern with two or more off-colony detections (N = 52), and compared the average foraging distances of the two sexes in both 2008 (N = 26) and 2009 (N = 26). The Kolmogorov-Smirnov test for normality indicated that the data were not normally distributed (2008: D = 0.2935, p = 0.01; 2009: D = 0.2205, p = 0.01), so a natural log transformation was applied to both data sets. In both years, the average distance travelled to foraging areas by female terns was not different from that of male terns (2008: Student's t-test, t_{24} = 0.74, p = 0.4657; 2009: Student's t-test, t_{24} = 0.02, p = 0.9877). Because there was no significant gender difference in distance travelled from colony in either year, I combined the data for the two sexes in each year for further analyses. There was a significant difference in mean natural log distance of foraging trips from the breeding colony between the two years of the study (Student's t-test: t_{50} = -2.88, p = 0.0059). The median distance of off-colony detections from the colony in 2008 was 14.0 km, whereas the median distance in 2009 was 20.6 km, 1.5 times greater than in 2008 (95% CI: 1.13 – 2.0 times greater).

There were 16 radio-tagged Caspian terns with five or more off-colony detections, comprised of eight terns in both 2008 and 2009. The average distance between off-colony detections for individual terns (16.6 km, SD = 10.4, n = 16) was significantly less than the average distance between detections among individual terns (28.6 km, SD = 13.4 km, n = 16) by an average difference of 12.0 km (one sample t-test: t_{15} = -2.7, p = 0.02).   The magnitude of this difference demonstrates that off-colony detections for an individual radio-tagged tern were not independent, and that individual Caspian terns nesting at the study colony tended to frequent particular foraging areas within foraging distance of the colony.

The off-colony detections for four of the sixteen Caspian terns with five or more off-colony detections are shown in Figure 3.6 as examples of foraging site fidelity. The detections of these individuals represent four distinctly different patterns of foraging behavior for Caspian terns nesting at one breeding colony. One tern apparently focused its foraging effort in the Delta zone, the second was detected eight times in the core use area on the eastern edge of the San Pablo Bay zone, the third was found mostly in the Central Bay zone to the northwest of the colony, and the last was primarily detected outside of San Francisco Bay in the Pacific Ocean zone.

Analyses of foraging distribution were performed using a subsample of one randomly chosen off-colony detection for each individual tern with at least two off-colony detections (Fig. 3.3). This sub-sampling procedure was used to ensure independence among off-colony detections and avoid pseudo-replication. I found no

significant gender difference in the distribution of off-colony detections among the

five zones during 2008 (Fisher's exact test: $p = 0.3597$, $N = 26$) or during 2009

(Fisher's exact test: $p = 0.6940$, $N = 26$). Consequently, I combined the data from the

two sexes in each year for subsequent analyses. The distribution of the subsample of

off-colony detections among the five foraging zones was significantly different

between the two study years (Fisher's exact test: $p = 0.0104$, $N = 52$; Figure 3.5).

Most notably, the number of off-colony detections in the San Pablo Bay zone

increased from 7 (27%) in 2008 to 14 (54%) in 2009. At the same time, detections in

the Central Bay zone decreased from 10 (38%) in 2008 to 1 (3%) in 2009. The

numbers of detections in the Delta and Pacific Ocean zones each increased between

2008 and 2009, but only by 4%.

The core use areas of Caspian terns nesting on Brooks Island, as represented

by the 25% volume contour, are depicted in Figure 3.4. These core use areas were

calculated using a subsample of two off-colony detections per radio-tagged tern for

each year in order to sufficiently increase the sample sizes (2008: $N = 52$ off colony

detections; 2009: $N = 52$ off-colony detections). These areas had the highest

probability of use by Caspian terns nesting on Brooks Island in 2008 and 2009, and

ranged from 5 - 23 km from the breeding colony in 2008 and $1.8 - 28$ km from the

breeding colony in 2009. The total area of core use identified using this method was

29 km^2 in 2008 and 13.4 km^2 in 2009. This accounts for 2.7% in 2008 and 1.3% in

2009 of the ca. 1,000 km^2 of potential open-water foraging habitat within 30 km of

Brooks Island. In 2008 the Pacific Ocean zone outside of the Golden Gate Bridge contained one 12.5 km^2 patch of core use that accounted for 43% of the total core use area. The Central Bay zone, where Brooks Island is located, contained three small patches of core use totaling 6.3 km^2, or 22% of the total core use area. Three core use patches totaling 10.2 km^2 (35% of the total core use area) were located in the San Pablo Bay zone. Two of these patches were located just downstream of the release sites of hatchery-raised juvenile salmonids. In 2009, the core use areas were much more concentrated, with 95% of the total core use area (12.7 km^2) located in two patches in the San Pablo Bay zone. The larger of these patches spanned 9.2 km^2 and directly overlapped with the hatchery-raised juvenile salmonid release sites. One core use area was found in the Central Bay zone (0.3 km^2) and one in the lower part of the Delta zone (0.4 km^2). No core use areas in either year were located in the South Bay zone.

DISCUSSION

Food Limitation

The results for colony attendance, number of foraging trips per day, average foraging distance from the colony, and distribution of foraging birds all indicate that the Caspian tern colony on Brooks Island was more food-limited in 2009 compared to 2008. In 2008, average colony attendance was greater than 50%, meaning that nests with chicks were attended by both parents concurrently at least part of the time, and

productivity (average of 0.42 chicks fledged per breeding pair) was similar to the three-year average for this colony during 2003-2005 (0.47 chicks per pair; Collis et al., In review). The lower colony attendance at Brooks Island in 2009 (43% of daylight hours) indicates that chicks were left unattended at the colony for some portion of the day while both adults were foraging off-colony. Although the average duration of foraging trips was not significantly different between the two years of the study, the lower colony attendance in 2009 was associated with a higher average number of foraging trips per day. Scarcity of large, high-quality prey items, such as lipid-rich marine forage fish, could have necessitated increased rates of foraging trips by Caspian terns in order to meet their chicks' energy requirements with higher numbers of lower quality estuarine or riverine fishes (see Chapter 2).

The lower colony attendance in 2009 was associated with much lower productivity (0.14 chicks per pair) compared to 2008, or any other year when productivity was monitored at this colony (Collis et al., In review). During periods of chick neglect, when neither parent is present at the nest site, chicks are more susceptible to predation, intra-specific adult-chick aggression, and exposure to the elements, which can all lead to lowered productivity. The Brooks Island Caspian tern colony is located adjacent to a large gull colony, consisting of both California and western gulls. When juvenile Caspian terns were left alone for longer periods in 2009, they were more vulnerable to predation by gulls. Gull predation was considered the main factor limiting Caspian tern chick survival at the Brooks Island colony in 2009

(Collis et al., In review). The breeding population of California gulls in San Francisco Bay has steadily increased during 1982 - 2010 (Strong et al. 2004, SFBBO 2010), and gull predation on Caspian tern chicks, as well as kleptoparasitism and competition for nest sites, has intensified at the Brooks Island tern colony.

The average foraging distance from the colony for Caspian terns nesting at Brooks Island was greater in 2009 and there was greater use of the San Pablo Bay zone and less use of the Central Bay zone compared to 2008. This coincided with a decline in stocks of marine forage fish during that year (PFMC 2010), which was reflected in a decline in marine forage fish in the diet of Caspian terns at Brooks Island (Collis et al., In review; see Chapter 2). The percent biomass of clupeids (herring and sardines) in the diet of Brooks Island terns was 27% in 2008 and only 9% in 2009. Also, commercial landings of northern anchovy in California declined by 81% in 2009 compared to 2008 (CDFG 2010), and the percent biomass of northern anchovy in the diet of Brooks Island Caspian terns decreased from 19.5% in 2008 to 2.6% in 2009. Low anchovy landings are generally associated with years of warm or El Niño ocean conditions. Northern anchovy landings in California during the 10 years between 2000 and 2009 were lowest in 2003, a moderate El Niño year, and in 2009 (CDFG 2010, PFMC 2010). In 2009, a shift to El Niño conditions in the California Current System took place late in the year, after the Caspian tern breeding season. But there was an anomalous downwelling event in May and June, which proved to be the strongest downwelling event in 40 years (PFEL 2011) and resulted in warm El Niño-

like sea surface temperatures during the peak of the Caspian tern breeding season at

Brooks Island. Not only were marine forage fish such as northern anchovy and

clupeids less available in 2009 than in 2008, they were also much smaller and had 60 –

70% less total energy content per fish (see Chapter 2). The proportion of schooling

estuarine fish, such as silversides (jacksmelt, *Atherinopsis californiensis*; topsmelt,

Atherinops affinis) and shiner surfperch (*Cymatogaster agregata*), commonly found in

San Pablo Bay where Caspian terns increased foraging effort, increased in the diet

during 2009. These fish were less affected by anomalous ocean conditions and their

overall energy density remained relatively stable, providing an alternate food source

for Brooks Island Caspian terns.

Although the Caspian tern colony on Brooks Island was apparently strongly

food-limited in 2009, this year was one of anomalous El Niño-like ocean conditions

that resulted in declines of the numbers, size, and energy content of marine forage fish

that serve as important food sources for Caspian terns nesting at Brooks Island.

Historical records show that these types of ocean conditions occur quasi-periodically,

but they are nevertheless considered anomalous. In 2008, the amount of marine forage

fish identified in the diet was closer to the three-year average during 2003-2005

(40.8%; Roby et al. 2003, 2004, 2005). Foraging behavior of Caspian terns breeding

at the Brooks Island colony in 2008 was similar to that of Caspian terns breeding at

the very large colony on East Sand Island in the Columbia River estuary during 2001,

a year when availability of marine forage fish did not appear to be limiting (Anderson

et al. 2007). Average foraging trip distance from East Sand Island was 13.9 km and

daytime colony attendance was 62.5% in 2001 (Anderson et al. 2007), while the

Brooks Island Caspian terns foraged at almost the same average distance from the

colony (14.0 km) and were found at the colony during 52% of daylight hours in 2008.

Average foraging distance was approximately 20 km and colony attendance was

below 50% of daylight hours at both colonies in years when marine forage fish were

less available. Contrary to my hypothesis, food limitation at the Brooks Island

Caspian tern colony, as indicated by foraging behavior, appears to be anomalous. In

most years forage fish resources, marine forage fishes in particular, are far more

available than in 2009.

Foraging Distribution

Gender differences in spatial foraging patterns of Caspian terns have been

suggested by the observed differences in parental roles at the nest (Quinn 1990). In

both years of my study, however, no gender differences were observed in foraging

distance from colony or foraging distribution. These findings are similar to those of

Anderson et al. (2007) for Caspian terns breeding in the Columbia River estuary, and

provide further evidence that both sexes in this species have similar foraging

distributions away from the colony. I did document a significant difference between

the two sexes, however, in the number of foraging trips per day in 2008, a year when

there was little evidence at the colony of a limitation in food availability. In 2009,

both sexes increased the number of foraging trips per day, but the increase by females

was proportionally greater (52%) than that of males (23%), and there was not a significant sexual difference in the number of foraging trips per day. This suggests that gender differences in provisioning rates to young may decline during years of low food availability. With males already spending more time away from the nest, females may disproportionately increase foraging effort in order to compensate for low provisioning rates.

The distance between off-colony detections for each radio-tagged tern was significantly less than the distance between off-colony detections among radio-tagged terns, indicating that the off-colony detections of individual terns are more aggregated than the off-colony detections of breeding terns from this colony as a whole. This supports my hypothesis that Caspian terns nesting on Brooks Island exhibit "hot spot" foraging site fidelity, instead of utilizing all available foraging habitats to the same extent as other terns nesting at the colony. This is contrary to the findings of Sirdevan and Quinn (1997), who found high variation in the use of particular foraging sites by individual Caspian terns nesting in the Great Lakes Region; my results may constitute the first strong evidence of foraging site fidelity in Caspian terns. This foraging strategy is employed by other seabirds, such as common terns (*Sterna hirundo*; Becker et al. 1993), black-legged kittiwakes (*Rissa tridactyla*; Irons 1998), and double-crested cormorants (*Phalacrocorax auritus*; Anderson et al. 2004), and is thought to be an adaptation to increase foraging efficiency when prey patches are somewhat persistent and/or require specialized tactics to efficiently exploit.

Foraging site fidelity by Caspian terns nesting at Brooks Island in San Francisco Bay suggests that foraging at hatchery release sites for juvenile salmonids is a learned behavior and that terns can remember areas of reliable food availability. I did find, however, that only some individuals focused their foraging effort in the area of the hatchery-raised salmonid release sites, while other individuals chose to return to areas where estuarine or marine forage fish would be expected in denser aggregations than juvenile salmonids. Juvenile salmonids accounted for only about 5% of the biomass of prey consumed by Caspian terns nesting at the Brooks Island colony in the two years of this study, whereas marine forage fish accounted for up to 45% (see Chapter 2). Although Caspian terns at Brooks Island are not strongly dependent on juvenile salmonids, our findings on foraging site fidelity lend support to a recommendation that modifications to hatchery release practices are warranted if reductions in Caspian tern predation on juvenile salmonids in San Francisco Bay are desired. Further investigation is required to determine whether Caspian terns develop a degree of specialization on certain prey types by returning to the same foraging areas.

In 2008 and 2009, nearly 20 million and 13 million hatchery-raised juvenile salmon, respectively, were released into eastern San Pablo Bay, just west of Carquinez Strait (FFC 2008, FFC 2009). Caspian tern core use areas identified in both years of this study were located in the vicinity of or directly overlapping this release location, and provides support for the hypothesis that Caspian terns nesting on Brooks Island

focus some foraging effort at sites where hatchery-raised salmonids are regularly

released. Greater than 90% of hatchery-raised salmonids released into eastern San

Pablo Bay in 2008 and 2009 belonged to the unlisted Central Valley fall-run Chinook

salmon stock (RMISD 1977), and recoveries of smolt coded wire tags on the Brooks

Island Caspian tern colony indicate that this stock is by far the most susceptible to

predation by Caspian terns from Brooks Island (Evans et al. 2011). No core use areas

were identified in the mid or upper delta where wild ESA-listed and salmon stocks

would be more commonly found. These results, taken together, confirm the

Biological Opinion prepared by the National Marine Fisheries Service (NOAA 2006)

that enhancing the numbers of Caspian terns nesting at Brooks Island would not likely

jeopardize any ESA-listed salmonid run in the San Francisco Bay area.

Low spawning returns of the Central Valley fall-run Chinook salmon stock,

however, prompted commercial and recreational fishing closures off the coast of

California and part of Oregon in 2008 and 2009 (NOAA 2008, 2009), suggesting that

reductions in Caspian tern predation on this salmonid run may be desirable. Hatchery-

raised juvenile salmonids have been shown to be susceptible to Caspian tern predation

in areas other than San Francisco Bay (Collis et al. 2001), and modifications to

hatchery release practices have been suggested. The releases of 13 – 20 million

hatchery-raised juvenile salmonids ca. 20 km from the Brooks Island Caspian tern

colony in 2008 and 2009 occurred during daylight hours when Caspian terns are most

active. Conducting releases early in the night and on an out-going tide may help to

reduce Caspian tern predation rates on juvenile salmonids in this system.

LITERATURE CITED

Anderson, C.D., D.D. Roby, and K. Collis. 2004. Conservation implications of the large colony of Double-crested Cormorants on East Sand Island, Columbia River estuary, Oregon, U.S.A. Waterbirds 27: 155-160.

Anderson, S.K., D.D. Roby, D.E. Lyons, and K. Collis. 2007. Relationship of Caspian tern foraging ecology to nesting success in the Columbia River estuary, Oregon, USA. Estuarine, Coastal, and Shelf Science 73: 447-456.

Becker, P.H., D. Frank, and S.R. Sudmann. 1993. Temporal and spatial pattern of common tern (*Sterna hirundo*) foraging in the Wadden Sea. Oecologia 93: 389 – 393.

Beyer, H. 2007. Hawth's tools for ArcGIS. www.spatialecology.com

Blockpoel, H., G.D. Tessier, and R.A. Andress. 1997. Successful restoration of the Ice Island Common tern colony requires on-going control of ring-billed gulls. Colonial Waterbirds 20: 98 – 101.

Cairns, D.K. 1987. Seabirds as monitors of marine food supplies. Biological Oceanography 5: 26 – 271.

CDFG (California Department of Fish and Game). 2010. Review of selected California fisheries for 2009: coastal pelagic finfish, market squid, red abalone, Dungeness crab, Pacific herring, groundfish/nearshore live-fish, highly migratory species, kelp, California halibut, and sandbasses. CalCOFI Report 51: 14-38.

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

Collis, K., D.D. Roby, K.W. Larson, L.J. Adrean, S.K. Nelson, A.F. Evans, D.S. Battaglia, D.E. Lyons, T.K. Marcella, and A. Patterson. In review. Trends in Caspian tern nesting and diet in San Francisco Bay: Management implications. Submitted to Waterbirds.

ESRI. 2006. ArcMap 9.3. Redlands, California.

Evans, A.F., D.D. Roby, K. Collis, B.M. Cramer, J.A. Sheggeby, L.J. Adrean, D.S. Battaglia, and D.E. Lyons. 2011. Recovery of coded wire tags on a Caspian tern colony in San Francisco Bay: A technique to evaluate impacts of avian predation on juvenile salmonids. North American Journal of Fisheries Management 31: 79 - 87.

FFC (Fishery Foundation of California). 2008. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 10p.

FFC. 2009. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 11p.

Gill, R.E. 1976. Notes on the foraging of nesting Caspian terns *Hydroprogne caspia*. California Department of Fish and Game 62: 155.

Good, T.P., R.S. Waples, and P. Adams [ed]. 2005. Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Dept. Commerce, NOAA Technical Memorandum NMFS-NWFSC-66, 598p.

Hyrenbach, D.K., P. Fernandez, D.J. Anderson. 2002. Oceanographic habitats of two sympatric North Pacific albatrosses during the breeding season. Marine Ecology Progress Series 233: 283-301.

Irons, D.B. 1998. Foraging area fidelity of individual seabirds in relation to tidal cycles and flock feeding. Ecology 79: 647-655.

Kappes, M.A., S.A. Shaffer, Y. Tremblay, D.G. Foley, D.M. Palacios, P.W. Robinson, S.J. Bograd, and D.P. Costa. 2010. Hawaiin albatrosses track interannual variability of marine habitats in the North Pacific. Progress in Oceanography 86: 246-260.

Kitaysky, A.S., G.L. Hunt, Jr., E.N. Flint, M.A. Rubega, and M.B. Decker. 2000. Resource allocation in breeding seabirds: responses to fluctuations in their food supply. Marine Ecology Progress Series 206: 283–296.

Kress, S.W. 1983. The use of decoys, sound recordings, and gull control for re-establishing a tern colony in Maine. Colonial Waterbirds 6: 185 – 196.

Lyons, D.E., D.D. Roby, and K Collis. 2005. Foraging ecology of Caspian terns in the Columbia River estuary, USA. Waterbirds 28: 280-291.

Lyons, D.E. 2010. Bioenergetics-based predator-prey relationships between piscivorous birds and juvenile salmonids in the Columbia River estuary. Unpubl. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 331 pp.

Millspaugh J.J., and J.M. Marzluff. 2001. Radio tracking and animal populations. Academic Press, San Diego, California. 474 pp.

Monaghan, P., P. Walton, S. Wanless, J.D. Uttley, and M.D. Burns. 1994. Effects of prey abundance on the foraging behavior, diving efficiency, and time allocation of breeding Guillemots *Uria aalge*. Ibis 136: 214-222.

NOAA (National Oceanic and Atmospheric Administration). 2006. Biological Opinion for Caspian tern management plan to reduce predation of juvenile salmonids in the Columbia River estuary. NOAA Fisheries, Portland, Oregon.

NOAA. 2008. Fisheries off west coast states and in the western Pacific; west coast salmon fisheries; 2008 management measures and a temporary rule. Federal Register 73:85(1 May 2008): 23971-23981.

NOAA. 2009. Fisheries off west coast states and in the western Pacific; west coast salmon fisheries; 2009 management measures. Federal Register 74: 85 (5 May 2009) 20610-20620.

PFEL (Pacific Fisheries Environmental Laboratory). 2011. North America historical upwelling index database. Available for download at: http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html

PFMC (Pacific Fisheries Management Council). 2010. Status of the Pacific Coast coastal pelagic species fishery and recommended acceptable biological catches. Stock assessment and fishery evaluation – 2010. Available for download at: http://www.pcouncil.org/coastal-pelagic-species

Quinn, J.S. 1990. Sexual size dimorphism and parental care patterns in a monomorphic and a dimorphic larid. Auk 107: 260-274.

Ramsey, F.L. and D.W. Schafer. 2002. The statistical sleuth, 2nd edition. Wadsworth Group, Pacific Grove, CA, 742 pp.

RMISD (Regional Mark Information System Database). Continuously since 1977. Regional Mark Processing Center, Pacific States Marine Fisheries Commission, Portland, OR. Available at: http://www.rmpc.org. January 2011.

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

Roby, D.D., K. Collis, S.K. Nelson, K. Larson, C. Couch, and P.J. Klavon. 2003. Caspian tern nesting ecology and diet in San Francisco Bay and Interior Oregon: final 2003 annual report. Available for download: http://www.birdresearchnw.org/.

Roby, D.D., K. Collis, S.K. Nelson, K. Larson, and K. Bixler. 2004. Caspian tern nesting ecology and diet in San Francisco Bay and Dungeness National Wildlife Refuge: 2004 final report. Available for download: http://www.birdresearchnw.org/.

Roby, D.D., K. Collis, S.K. Nelson, K. Larson, and K. Bixler. 2005. Caspian tern nesting ecology and diet in San Francisco Bay: final annual report. Available for download: http://www.birdresearchnw.org/.

SAS Institute Inc. 2009. SAS version 9.2. SAS Institute Inc., Cary, NC.

Seaman, D.E,. and R.A. Powell. 1996. An Evaluation of the accuracy of kernel density estimators for home range analysis. Ecology 77: 2075-2085.

Seto, N., J. Dillon, W.D. Shuford, and T. Zimmerman. 2003. A review of Caspian tern (*Sterna caspia*) nesting habitat: A feasibility assessment of management opportunities in the U.S. Fish and Wildlife Service Pacific Region. U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR.

SFBBO (San Francisco Bay Bird Observatory). 2010. Colonial waterbird nesting summary for San Francisco Bay, 2010. Available for download: http://www.sfbbo.org/docs.

Sirdevan, J.E., and J.S. Quinn. 1997. Foraging patterns of Caspian Terns (*Sterna caspia*) determined using radio-telemetry. Colonial Waterbirds 20: 429-435.

Strong, C.M., L.B. Spear, T.P. Ryan, and R.E. Dakin. 2004. Forster's tern, Caspian tern,and California gull colonies in San Francisco Bay: habitat use, numbers and trends, 1982 – 2003. Waterbirds 27: 411-423.

USFWS (U.S. Fish and Wildlife Service). 2006. Record of Decision: Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USFWS, Portland, Oregon.

Waples, R.S. 1995. Evolutionarily significant units and the conservation of biological diversity under the Endangered Species Act. American Fisheries Society Symposium 17: 8–27.
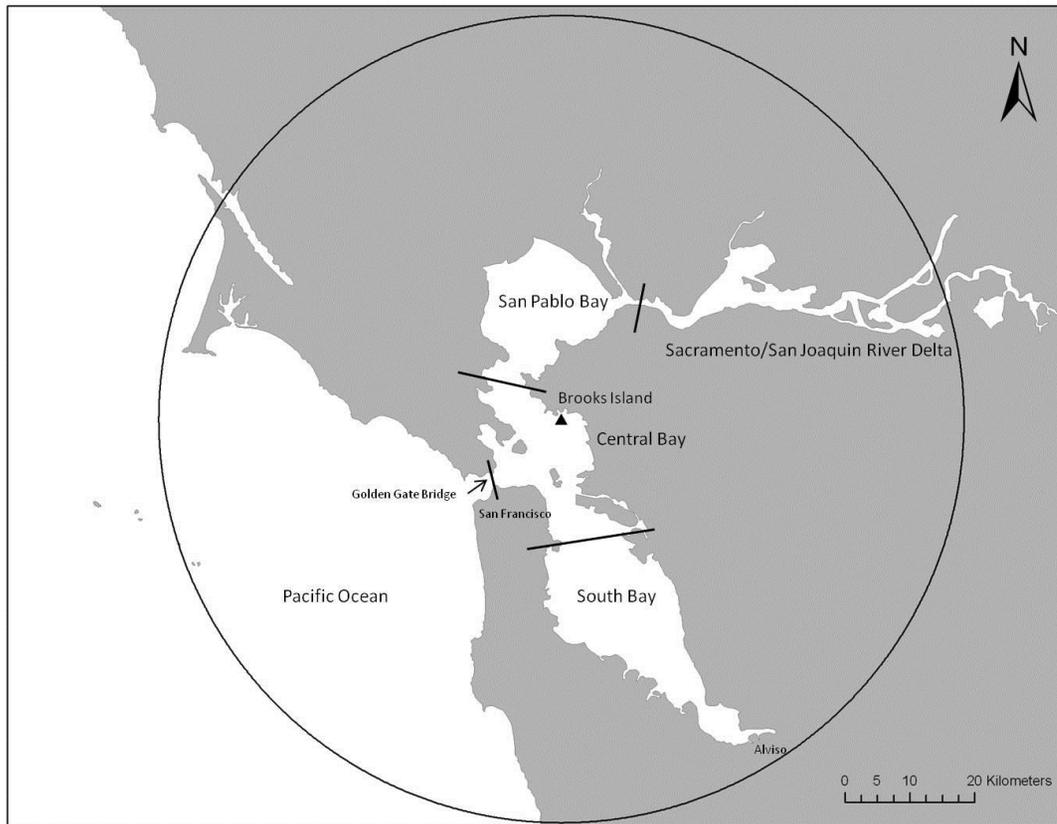
Figure 3.1. Map of the study area in San Francisco Bay showing the location of the Brooks Island Caspian tern colony, the 62 km radius aerial survey area, and the boundaries of the five foraging zones used for analyses of foraging distribution of radio-tagged Caspian terns.
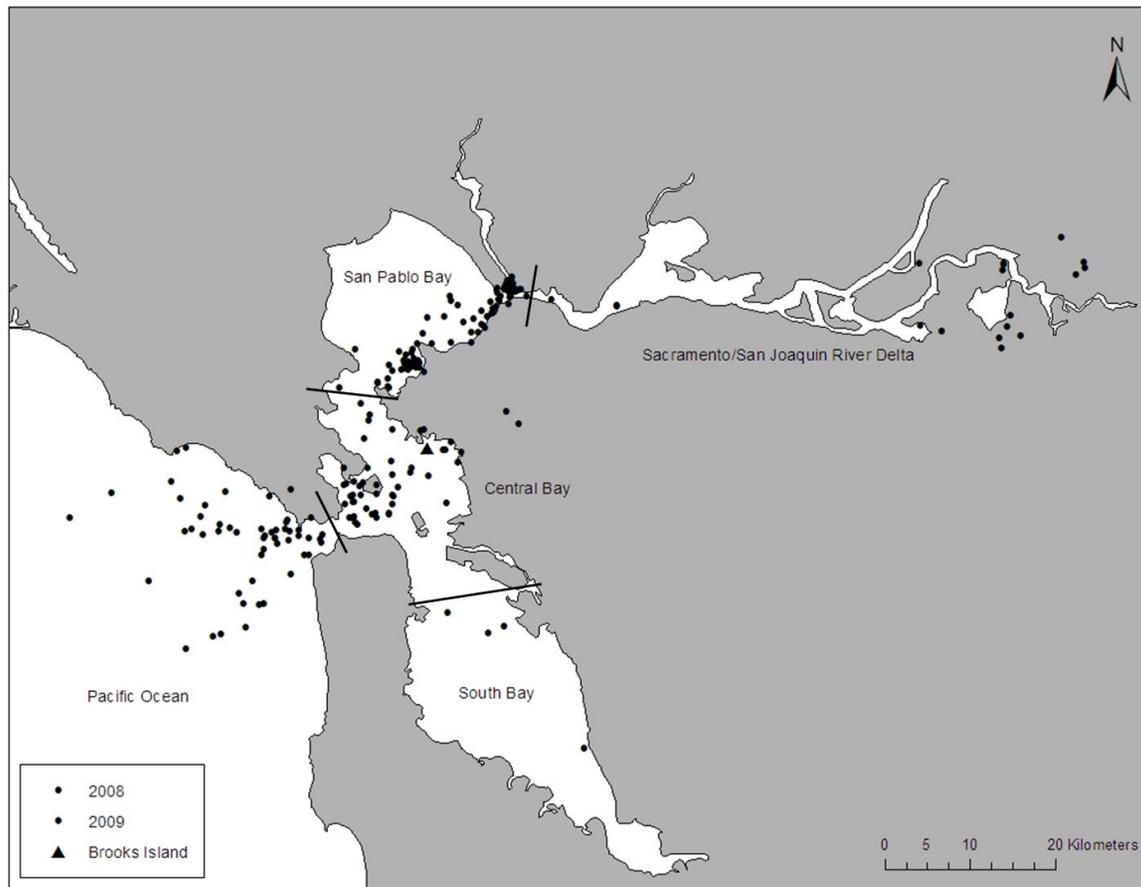
Figure 3.2. Map of the study area in San Francisco Bay showing the Brooks Island Caspian tern colony and all off-colony radio-telemetry detections collected from nesting Caspian terns during the 2008 and 2009 breeding seasons.
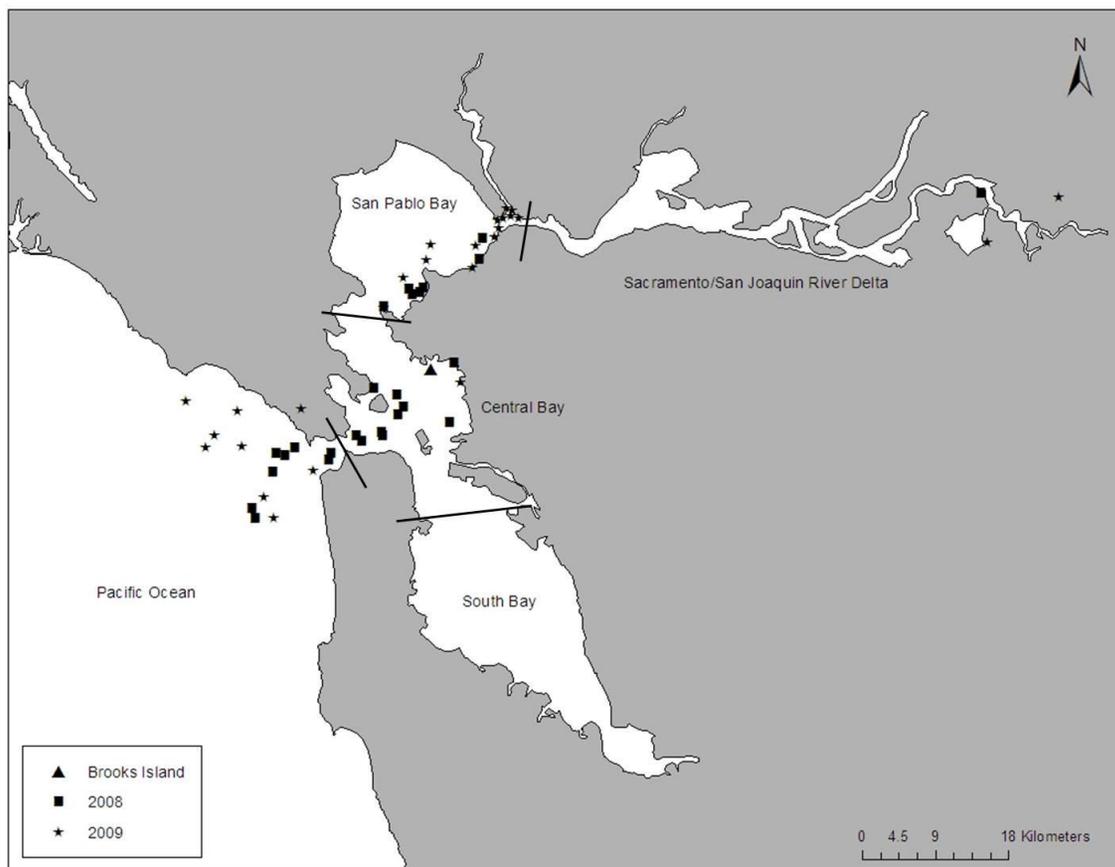
Figure 3.3. Map of the study area in San Francisco Bay showing the boundaries of the five foraging zones and the subsample of off-colony radio-telemetry detections for Caspian terns nesting at Brooks Island that was used for analyses of foraging distribution.

A.
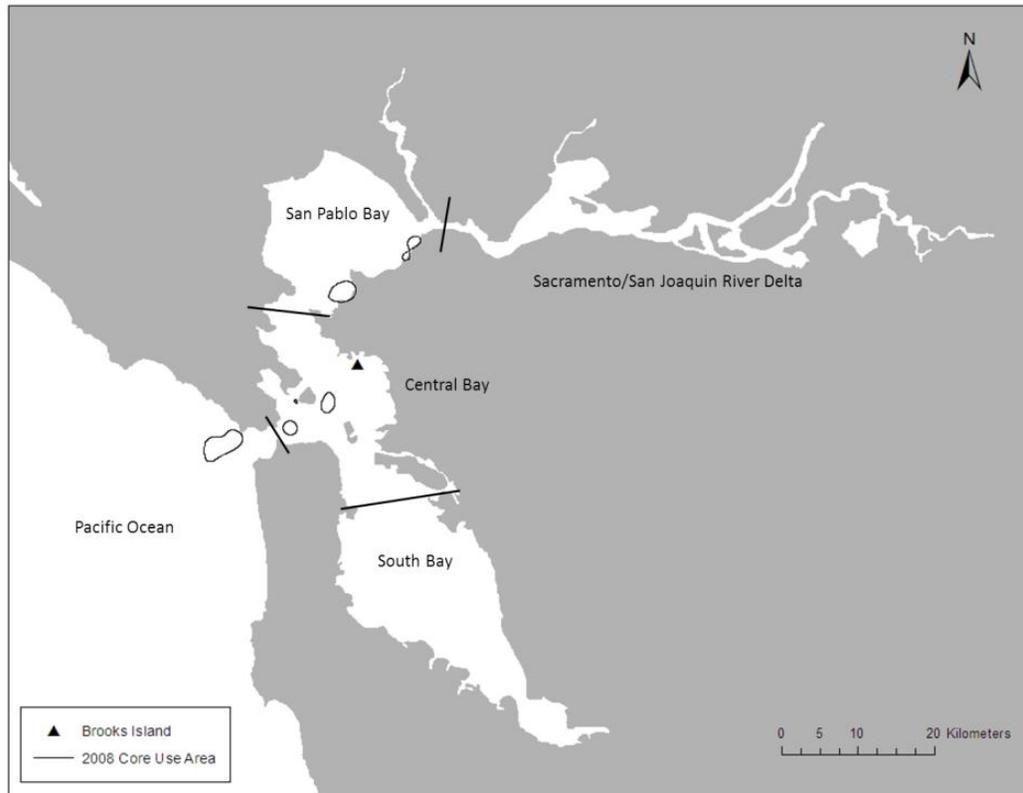
Figure 3.4. Maps of the study area in San Francisco Bay showing the 25% volume contour representing core use foraging areas by Caspian terns nesting at Brooks Island in 2008 (A) and 2009 (B).

B.
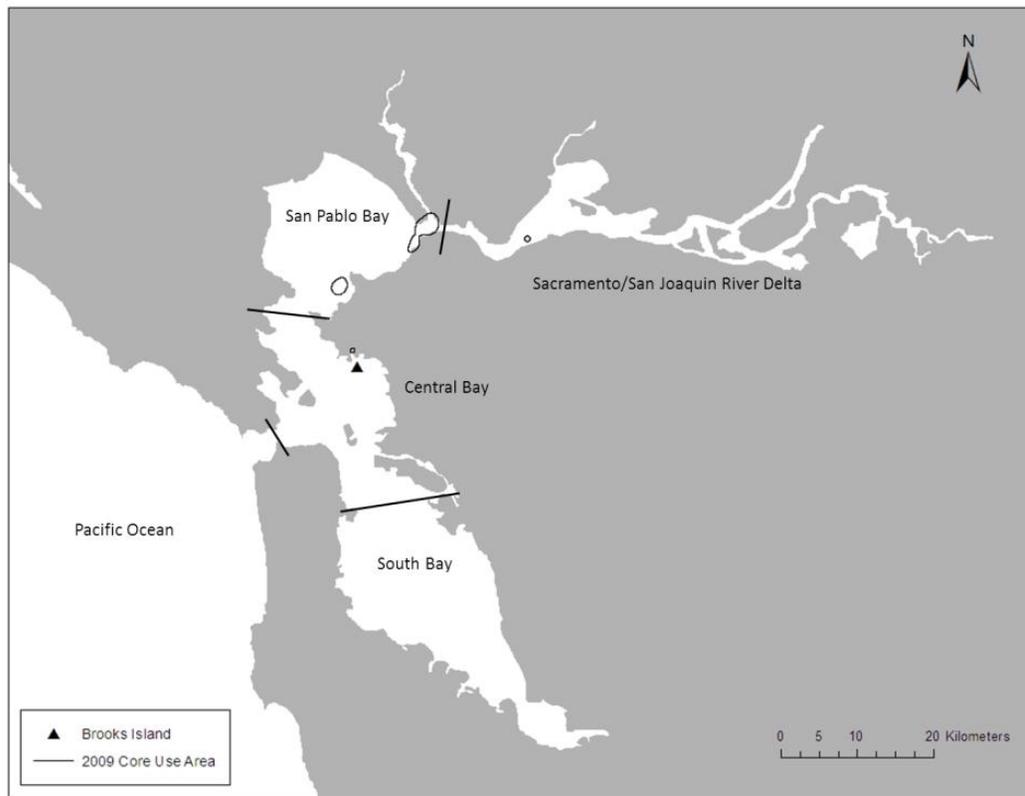
Figure 3.4 (Continued). Maps of the study area in San Francisco Bay showing the 25% volume contour representing core use foraging areas by Caspian terns nesting at Brooks Island in 2008 (A) and 2009 (B).
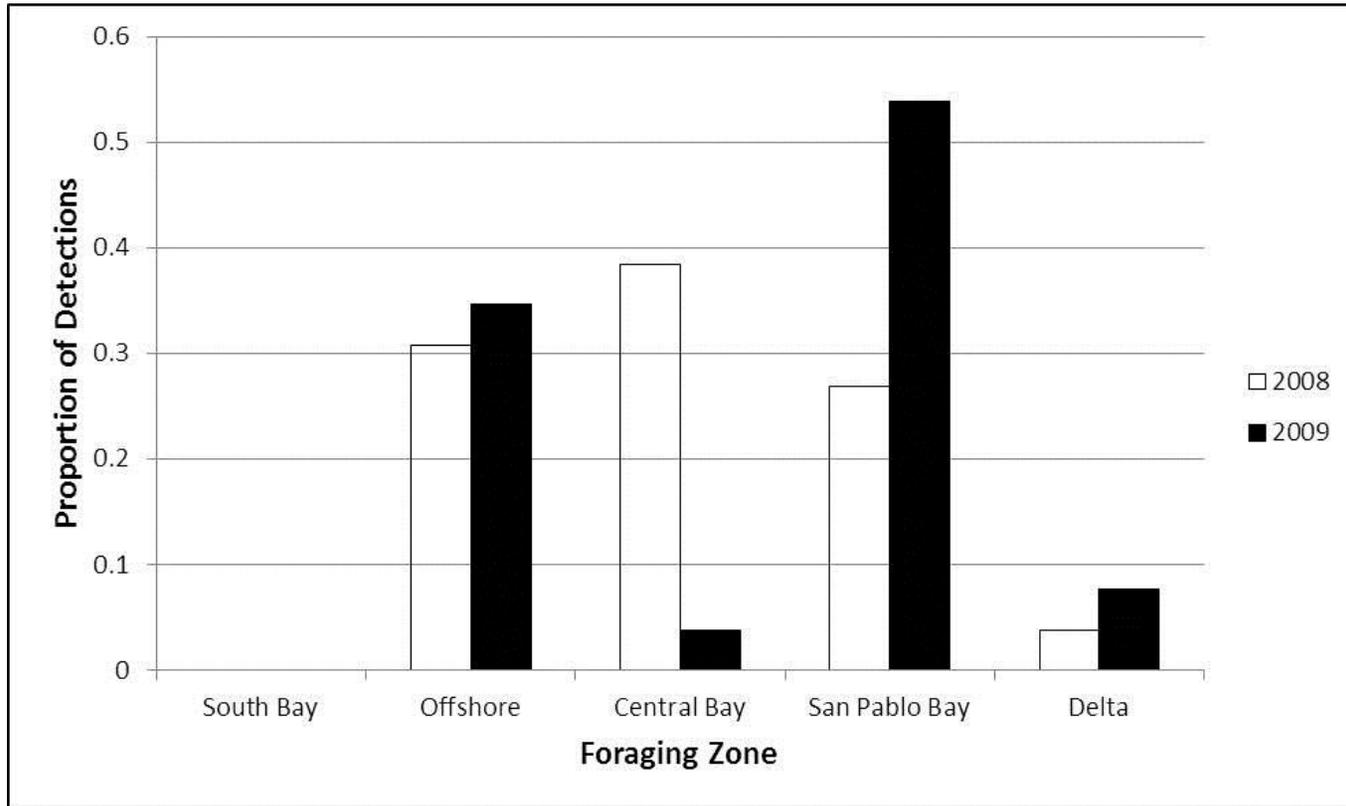
Figure 3.5. Proportion of off-colony detections of Caspian terns nesting on Brooks Island that were located in each of five foraging zones in the San Francisco Bay area, by year. Data used in this figure represent one randomly selected off-colony detection from each radio-tagged nesting tern.
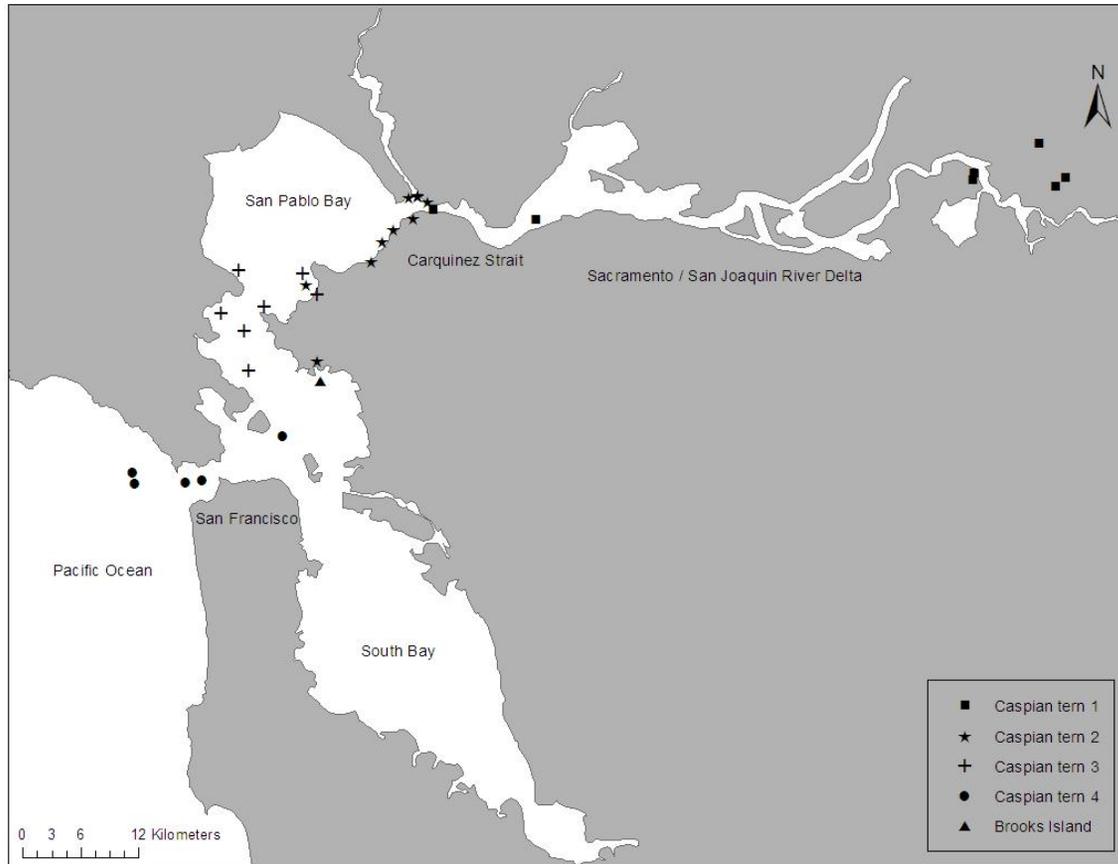
Figure 3.6. Map of the study area in San Francisco Bay showing off-colony detections for four different Caspian terns that were nesting on Brooks Island as representative of four different foraging strategies.

CHAPTER 4

SYNOPSIS AND CONCLUSIONS

Lindsay Adrean

This study of Caspian tern diet and foraging ecology was initiated in response to concern over a management plan that included increasing the number of breeding Caspian terns in San Francisco Bay (USFWS 2006). Caspian tern predation on juvenile salmonids in the Columbia River estuary has been identified as a factor limiting recovery of threatened and endangered salmonids in the Columbia Basin (Good et al. 2005). Compensation for management to decrease the numbers of nesting Caspian terns in the Columbia River estuary is the primary reason for the proposed increase in the San Francisco Bay area. There are also, however, salmonids listed under the Endangered Species Act (ESA) in San Francisco Bay. There were four main objectives of my study: (1) quantify the number of juvenile salmonids consumed, (2) estimate impacts to ESA-listed salmonids from tern predation, (3) investigate food availability as a potential limiting factor for the tern colony, and (4) investigate how Caspian terns exploit forage fish resources in San Francisco Bay.

Consumption of juvenile salmonids by Caspian terns nesting on Brooks Island was between 175,000 and 235,000 smolts in 2008, and between 144,000 and 191,000 smolts in 2009. Chinook salmon accounted for > 97% of the total juvenile salmonids consumed. Complete elimination of estimated smolt losses due to Brooks Island terns in 2008, by itself, would result in increases in annual population growth rates ($\Delta\lambda$) of only small fractions of one percentage point for each of the Chinook salmon runs in San Francisco Bay. The increase in the annual population growth rate of threatened Central Valley spring-run Chinook, even assuming that 100% of the tern-caused

mortality was additive, would be 0.03%. This would increase the current estimated annual population growth rate of 0.8074 to just 0.8077. Central Valley fall-run Chinook salmon, an evolutionarily significant unit (ESU) of conservation concern, would see an increase in λ of 0.3% (assuming 100% additive mortality from tern predation), increasing the current estimated annual population growth rate from 0.7165 to at most 0.7199. By comparison, the proposed management to reduce the size of the Caspian tern colony in the Columbia River estuary is expected to increase annual population growth rates for some salmonid stocks by at least 1%, assuming that tern-caused mortality is 100% additive. The proposed increase in size of the Brooks Island breeding colony of Caspian terns to 1,500 pairs would cause declines in the annual population growth rates (λ) of the spring-run and fall-run Chinook salmon ESUs of 0.023% and 0.3%, respectively, assuming that 100% of the tern-caused mortality is additive. This would result in population growth rates of 0.8072 for the threatened spring-run Chinook ESU and 0.7136 for the unlisted fall-run Chinook ESU.

   To place these results into a broader perspective, I compared these potential changes in salmonid population growth rates to those associated with a Caspian tern colony where management to reduce Caspian tern predation on salmonids was deemed warranted. Caspian terns nesting at the East Sand Island colony in the Columbia River estuary of Oregon consume approximately 4 – 6 million juvenile salmonids annually, many of which belong to ESA-listed ESUs (Lyons 2010). This is equivalent to an average per capita salmonid consumption rate of 265 smolts per adult Caspian tern per

year, more than double the amount consumed by individual Brooks Island Caspian terns in 2008 or 2009.   At the Brooks Island Caspian tern colony, 98% of the ca. 205,000 Chinook salmon smolts consumed in 2008 belonged to the unlisted fall-run Chinook salmon ESU. Therefore, Brooks Island in San Francisco Bay may be a preferred colony site for Caspian terns, based on the lower dependence on juvenile salmonids by terns at this site compared to the Columbia River estuary.

For even further perspective on the results of my study, I looked at other sources of mortality for juvenile fall-run and spring-run Chinook salmon in the Sacramento – San Joaquin River system. The Sacramento – San Joaquin River delta is important both as a migration corridor and a rearing area for several anadromous fish species; some juvenile salmonids spend one to three months in the Delta before moving downstream to the Bay (Williams 2006). Juvenile salmonid survival in this part of the system is, however, quite low. Mean point estimates of survival range from 35 - 50% (Perry et al. 2010), although estimates vary by migration route (Perry et al. 2010) and annual water conditions (Kjelson and Brandes 1989).

Salmonid smolt survival in the Delta is impacted by water diversions (Newman and Brandes 2010, Perry et al. 2010); water projects are considered an important anthropogenic factor contributing to the decline of Chinook salmon from the Central Valley (Lindley et al. 2009). Specifically, the two major pumping stations located in the south Delta, operated by the State Water Project (SWP) and the federal Central Valley Project (CVP), export water to southern California, the San Joaquin

Valley, and the San Francisco Bay Area for both agricultural and municipal uses. Not

only are fish originating in tributaries of the San Joaquin River susceptible to

entrainment at these stations, but fish migrating through the north Delta in the

Sacramento River can become entrained if they enter Georgiana Slough or the Delta

Cross Channel, a manmade channel built to divert water from the Sacramento River

for export.

In 2008, the year when smolt CWT recoveries from the Brooks Island tern

colony are available, approximately 32.5 million hatchery-raised, unlisted fall-run

Chinook salmon smolts were released into the Sacramento-San Joaquin system.

Documented direct mortality of fall-run Chinook smolts at the CVP and SWP Delta

fish facilities totaled 9,599 fish, which amounts to 0.08% of all hatchery-raised fish

from this run, whereas Caspian terns nesting on Brooks Island consumed

approximately 200,000 fall-run Chinook or 0.6% of the total run. A loss of 12,005

threatened spring-run Chinook salmon smolts was reported for both fish facilities

combined (Aasen 2009), which would correspond to 0.4% of the approximate three

million hatchery-raised spring-run Chinook smolts that were released into the system

in 2008 (RMISD 1977). This is an order of magnitude greater than the number of

spring-run Chinook smolts taken by Caspian terns nesting on Brooks Island in 2008,

according to my bioenergetics model estimates (1,017 fish, or 0.04% of all hatchery-

raised spring-run Chinook in the system). Chinook salmon with adipose fins intact

accounted for > 97% of the Chinook smolts salvaged at the two fish facilities (Aasen

2009), indicating that entrained Chinook smolts included a high proportion of wild

fish. Conservation of wild stocks is of the utmost importance, as maximizing the

diversity of the ESU is one goal of the recovery strategy for the Central Valley spring-

run Chinook ESU (NMFS 2009).

The current impact of the Brooks Island Caspian tern colony on ESA-listed

spring-run Chinook salmon is substantially less than the direct mortality incurred by

the Delta water export facilities (Aasen 2009). Comparisons of the impacts of Brooks

Island Caspian terns and the Delta water diversions on unlisted fall-run Chinook

indicate that Brooks Island Caspian terns are the greater source of mortality.

Estimates of Chinook smolt loss due to direct mortality from the water export system

are minimum estimates, however, because of uncertainty surrounding the values used

in loss calculations and the lack of indirect mortality quantification (Kimmerer et al.

2008, NMFS 2008). Fish losses at the water export facilities are currently calculated

assuming 75% efficiency of fish collection louvers, but more recent analysis has

suggested that efficiency may be $< 50\%$, and losses would therefore be double the

reported values (NMFS 2008). Current loss estimates do not include pre-screen

predation on juvenile salmonids by piscivorous fish. Kimmerer et al. (2008) estimated

smolt losses at the fish facilities from entrainment and salvage for a range of pre-

screen survival rates that combined louver efficiency and pre-screen predation. A pre-

screen survival rate of 30% yielded a mortality estimate of 10% of all Chinook smolts

leaving the Delta (Kimmerer 2008). If mortality at the fish facilities is closer to 10%,

fish losses to both listed and unlisted salmonid ESUs would be much higher than current reported estimates. Indirect mortality from the side effects of water pumping, such as extended fish migration times and simplification of habitat, has not been quantified but may also be substantial (NMFS 2008). This lends further support to the conclusion that current salmon loss estimates due to water pumping are only minimum estimates.

We were not able to determine effects of Caspian tern predation on ESA-listed steelhead stocks in San Francisco Bay. Both steelhead runs that were once found in San Francisco Bay are currently listed as threatened under the ESA. Rainbow trout are not listed. It was not possible to visually distinguish at a distance steelhead from rainbow trout held by Caspian terns on the colony, and Caspian terns were found to forage in areas with both steelhead smolts and stocked rainbow trout. Unfortunately, hatchery-raised steelhead and stocked rainbow trout were not marked with coded wire tags during our study. Further research is necessary to determine the ratio of steelhead smolts to rainbow trout consumed by Caspian terns in San Francisco Bay and estimate impacts to ESA-listed steelhead runs. This could be accomplished by implanting coded wire tags in rainbow trout that are stocked in the reservoirs close to Brooks Island, where Caspian terns are known to forage.

My third and fourth objectives were addressed by radio-tracking breeding Caspian terns from the Brooks Island colony. In 2008, the Caspian tern productivity at Brooks Island and the amount of marine forage fish in the diet was similar to the

three-year average for 2003-2005. In 2009, however, Caspian tern productivity at

Brooks Island was lower by about 70%, and marine forage fish contributed much less

to the diet.   This coincided with an anomalous downwelling event during the Caspian

tern breeding season in 2009, which proved to be the strongest downwelling event in

40 years (PFEL 2011) and resulted in declines in the numbers, size, and energy

content of marine forage fish that serve as important food sources for Caspian terns

nesting at Brooks Island. Taken together, this information indicates that 2008 was

representative of a more typical year of food availability. The foraging habits of these

birds in 2008 indicate that, in most years, adequate forage fish resources are available

to support the existing colony size. This colony site provides access to marine,

estuarine, and riverine foraging habitats and provides terns with a wide array of

potential prey species. This is important, particularly in years of anomalous ocean

conditions, which are expected periodically. Low availability of marine forage fish

due to poor ocean conditions was associated with an increase in foraging distance and

a decline in colony attendance for Caspian terns nesting at Brooks Island in 2009.

This response has been observed during years of poor ocean conditions at other

Caspian tern colonies (Anderson et al. 2007), and should not be taken as an indication

that a colony site is unsuitable. Consumption of estuarine fish species increased as the

Brooks Island Caspian terns increased foraging in San Pablo Bay to compensate for

the lack of marine forage fishes, especially clupeids and anchovies, in the Central Bay.

At the same time, per capita consumption of juvenile salmonids at the hatchery release

sites in San Pablo Bay did not change significantly. This is an important observation because I found that Caspian terns nesting on Brooks Island displayed foraging site fidelity and one high-use foraging area overlapped with release sites for hatchery-raised salmon in eastern San Pablo Bay. It is not surprising that an opportunistic forager, such as the Caspian tern, would repeatedly take advantage of any prey type that was regularly released during the day, five days per week, in groups of several hundred thousand fish, over 2 months or more, and close to their breeding colony. There was no evidence, however, that Caspian terns increased foraging effort at the hatchery release sites to compensate for the reduced availability of marine forage fish in 2009. Although salmonids have higher energy density than estuarine species, such as shiner surfperch and silversides, the energy content of individual fish of those species is much higher than for Chinook salmon due to the larger average size of surfperch and silversides. This makes some estuarine species a potentially more significant alternative food source than juvenile salmonids to Caspian terns in years when availability of marine forage fishes is limited.

The results of both of my studies combined suggest that Brooks Island in San Francisco Bay is an appropriate site for Caspian tern nesting, and the continued existence of the colony at its current or an increased size will have no detectable effect on ESA-listed salmonids. Unlisted Central Valley fall-run Chinook salmon smolts were the most susceptible salmonid run to Caspian tern predation, but an enhanced Caspian tern colony would decrease the annual population growth rate of this ESU by

a mere fraction of one percentage point. This ESU is not listed under the ESA, but it does have high economic value. Several changes in release practices for hatchery-raised Chinook smolts could be implemented that would likely dramatically reduce the level of predation, both by Caspian terns and other smolt predators, on this ESU, should it be considered necessary.

First, the current methods of salmon release in San Pablo Bay expose salmon smolts to an array of avian predators. Visual foragers, such as Caspian terns, generally do not forage at night. Timing smolt releases during nighttime hours would greatly reduce the magnitude of avian predation occurring at release sites. In addition, if smolt releases occurred early in the night on an out-going tide, it would ensure that smolts were well-dispersed before avian predators resumed foraging at dawn. Second, although Caspian tern nesting habitat is limited in other parts of San Francisco Bay, construction of new nesting habitat in the South Bay is an option. Increasing the distance between the nesting colony and hatchery release sites would likely reduce Caspian tern predation on juvenile salmonids. Juvenile salmonids account for < 1% of prey items in the diet of Caspian terns nesting at South Bay colonies and high tern nesting success has been recorded at some colonies (Collis et al., In review). All core use areas for Brooks Island terns that were identified in this study were located less than 30 km from the colony, and average foraging distances during the breeding season reported at other Caspian tern colonies were also less than 30 km (Lyons et al. 2005, Anderson et al. 2007). I did find, however, that some nesting Caspian terns

from Brooks Island traveled up to 80 km from the nest site to particular foraging areas and that Caspian terns remember and return to previously-used foraging areas. The distance between the San Pablo Bay hatchery salmon release sites and the farthest reaches of the South Bay is only about 70 km. Some, although much less, predation on juvenile salmonids at hatchery releases by Caspian terns nesting in the South Bay would be expected. For this reason, implementing changes to current salmon release methods would be the most effective means to reduce predation by Caspian terns and other avian predators on hatchery-raised juvenile salmonids in the San Francisco Bay area.

Caspian terns have been nesting in San Francisco Bay since the early 1900's (Grinnell and Miller 1944) and are currently protected by the Migratory Bird Treaty Act of 1918. Central Valley salmonid populations have experienced serious declines and several ESUs are now federally listed under the ESA. The results of my study on Caspian tern diet and foraging ecology provide data that will be useful in developing informed management decisions that balance the needs of both a native predator and its imperiled prey.

BIBLIOGRAPHY

Aasen, G. 2009. Fish salvage at the State Water Project's and Central Valley
    Project's fish facilities during 2008. Interagency Ecological Program for the
    San Francisco Estuary Newsletter 22: 36-43.

Anderson, C.D., D.D. Roby, and K. Collis. 2004. Conservation implications of the
    large colony of Double-crested Cormorants on East Sand Island, Columbia
    River estuary, Oregon, U.S.A. Waterbirds 27: 155-160.

Anderson, S.K., D.D. Roby, D.E. Lyons, and K. Collis. 2007. Relationship of
    Caspian tern foraging ecology to nesting success in the Columbia River
    estuary, Oregon, USA. Estuarine, Coastal, and Shelf Science 73: 447-456.

Anthony, J.A., D.D. Roby, and K.R. Turco. 2000. Lipid content and energy density
    of forage fishes from the northern Gulf of Alaska. Journal of Experimental
    Marine Biology and Ecology 248: 53-78.

Antolos, M., D.D. Roby, D.E. Lyons, S.K. Anderson, and K. Collis. 2005. Caspian
    tern predation on juvenile salmonids in the Mid-Columbia River. Transactions
    of the American Fisheries Society 134: 466-480.

Becker, P.H., D. Frank, and S.R. Sudmann. 1993. Temporal and spatial pattern of
    common tern (*Sterna hirundo*) foraging in the Wadden Sea. Oecologia 93:
    389 – 393.

Beyer, H. 2007. Hawth's tools for ArcGIS. www.spatialecology.com

Blockpoel, H., G.D. Tessier, and R.A. Andress. 1997. Successful restoration of the
    Ice Island Common tern colony requires on-going control of ring-billed gulls.
    Colonial Waterbirds 20: 98 – 101.

Cairns, D.K. 1987. Seabirds as monitors of marine food supplies. Biological
    Oceanography 5: 26 – 271.

CDFG (California Department of Fish and Game). 2009. Fishing California's Central
    Coast Region. Retrieved online from the California Department of Fish and
    Game website: www.dfg.ca.gov/publications/docs/FishGuideR3.pdf.

CDFG (California Department of Fish and Game). 2010. Review of selected
        California fisheries for 2009: coastal pelagic finfish, market squid, red abalone,
        Dungeness crab, Pacific herring, groundfish/nearshore live-fish, highly
        migratory species, kelp, California halibut, and sandbasses. CalCOFI Report
        51: 14-38.

CDFG. 2011. GrandTab database. Available for download at
        http://www.calfish.org/tabid/104/Default.aspx.

Collis, K., R.E. Beaty, and B.R. Crain. 1995. Changes in catch rate and diet of
        northern squawfish associated with the release of hatchery-reared juvenile
        salmonids in a Columbia River reservoir. North American Journal of Fisheries
        Management 15: 346–357.

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

Collis, K., D.D. Roby, D.P. Craig, S. Adamany, J.Y. Adkins, and D.E. Lyons. 2002.
        Colony size and diet composition of piscivorous waterbirds on the lower
        Columbia River: implications for loses of juvenile salmonids to avian
        predation. Transactions of the American Fisheries Society 131: 537–550.

Collis, K., D.D. Roby, K.W. Larson, L.J. Adrean, S.K. Nelson, A.F. Evans, D.S.
        Battaglia, D.E. Lyons, T.K. Marcella, and A. Patterson. In review. Trends in
        Caspian tern nesting and diet in San Francisco Bay: Management implications.
        Submitted to Waterbirds.

Cuthbert, F.J., and L.R. Wires. 1999. Caspian Tern (*Sterna caspia*). The Birds of
        North America Online [A. Poole, ed.]. Ithaca: Cornell Lab of Ornithology;
        Retrieved from the Birds of North America Online:
         http://bna.birds.cornell.edu/bna/species/403.

Errington, P.L. 1967. Of predation and life. Iowa State University Press, Ames, IA.

ESRI. 2006. ArcMap 9.3. Redlands, California.

Evans, A.F., D.D. Roby, K. Collis, B.M. Cramer, J.A. Sheggeby, L.J. Adrean, D.S. Battaglia, and D.E. Lyons. 2011. Recovery of coded wire tags on a Caspian tern colony in San Francisco Bay: A technique to evaluate impacts of avian predation on juvenile salmonids. North American Journal of Fisheries Management 31: 79-87.

Feyrer, F., M.L. Nobriga, and T.R. Sommer. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences 64: 723-734.

FFC (Fishery Foundation of California). 2008. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 10p.

FFC. 2009. Final Report: San Francisco Bay estuary acclimation of Central Valley hatchery raised Chinook salmon project. FFC, Elk Grove, CA. 11p.

Furness, R.W. 1978. Energy requirements of seabird communities: a bioenergetics model. Journal of Animal Ecology 47: 39-53.

Gasaway, W.C., R.D. Boertje, D.V. Grangaard, D.G. Kelleyhouse, R.O. Stephenson, and D.G. Larsen. 1992. The role of predation in limiting moose at low densities in Alaska and Yukon and implications for conservation. Wildlife Monographs 120: 3-59.

Gill, R.E. 1976. Notes on the foraging of nesting Caspian terns *Hydroprogne caspia*. California Department of Fish and Game 62: 155.

Glahn, J. F., and K. E. Brugger. 1995. The impact of double-crested cormorants on the Mississippi Delta catfish industry: a bioenergetics model. Colonial Waterbirds 18: 168-175.

Good, T.P., R.S. Waples, and P. Adams [ed]. 2005. Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-NWFSC-66. 598p.

Grinnell, J., and A.H. Miller. 1944. The distribution of the birds of California. Pacific Coast Avifauna 27: 172-173.

Hostetter, N.J. 2009. Susceptibility of juvenile salmonids to avian predation: are Caspian terns and double-crested cormorants only taking the sick and injured? Unpublished M.S. Thesis. Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR.

Hyrenbach, D.K., P. Fernandez, D.J. Anderson. 2002. Oceanographic habitats of two sympatric North Pacific albatrosses during the breeding season. Marine Ecology Progress Series 233: 283-301.

Irons, D. B. 1998. Foraging area fidelity of individual seabirds in relation to tidal cycles and flock feeding. Ecology 79: 647-655.

Kappes, M.A., S.A. Shaffer, Y. Tremblay, D.G. Foley, D.M. Palacios, P.W. Robinson, S.J. Bograd, and D.P. Costa. 2010. Hawaiin albatrosses track interannual variability of marine habitats in the North Pacific. Progress in Oceanography 86: 246-260.

Kendeigh, S.C. 1969. Energy responses of birds to their thermal environments. Wilson Bulletin 81: 441-449.

Kimmerer, W.J. 2008. Losses of Sacramento River Chinook salmon and Delta smelt to entrainment in water diversions in the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 6: 1-27.

Kitaysky, A.S., G.L. Hunt Jr., E.N. Flint, M.A. Rubega, and M.B. Decker. 2000. Resource allocation in breeding seabirds: responses to fluctuations in their food supply. Marine Ecology Progress Series 206: 283–296.

Kjelson, M.A., and P.L. Brandes. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento-San Joaquin rivers, California. *In* C.D. Levings, L.B. Holtby, and M.A. Henderson [ed.] Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks. Canadian Special Publication of Fisheries and Aquatic Sciences 105: 100-115.

Klaassen, M. 1994. Growth and energetics of tern chicks from temperate and polar environments. Auk 111: 525-544.

Krebs, J.R. 1974. Colonial nesting and social feeding as strategies for exploiting food resources in the great blue heron (*Ardea herodias*). Behaviour 51: 99-134.

Kress, S.W. 1983. The use of decoys, sound recordings, and gull control for re-establishing a tern colony in Maine. Colonial Waterbirds 6: 185 – 196.

Lifson, N., and R. McClintock. 1966. Theory of use of the turnover rates of body water for measuring energy and material balance. Journal of Theoretical Biology 12: 46-74.

Lindley, S. T., R.S. Schick, A. Agrawal, M. Goslin, T.E. Pearson, E. Mora, J.J. Anderson, B. May, S. Greene, C. Hanson, A. Low, D. McEwan, R.B. MacFarlane, C. Swanson, J.G. Williams. 2006. Historical population structure of Central Valley steelhead and its alteration by dams. San Francisco Estuary and Watershed Science 4: Article 3. 19p.

Lindley, S.T., R.S. Schick, E. Mora, P.B. Adams, J.J. Anderson, S. Greene, C. Hanson, B.P. May, D. McEwan, R.B. MacFarlane, C. Swanson, and J.G. Williams. 2007. Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento-San Joaquin basin. San Francisco Estuary and Watershed Science 5: 1-26.

Lindley, S.T., C.B. Grimes, M.S. Mohr, W. Peterson, J. Stein, J.T. Anderson, L.W. Botsford, D.L. Bottom, C.A. Busack, T.K. Collier, J. Ferguson, J.C. Garza, A.M. Grover, D.G. Hankin, R.G. Kope, P.W. Lawson, A. Low, R.B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F.B. Schwing, J. Smith, C. Tracy, R. Webb, B.K. Wells, and T.H. Williams. 2009. What caused the Sacramento River fall Chinook stock collapse? U.S. Department of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. 62p.

Lyons, D.E., D.D. Roby, and K Collis. 2005. Foraging ecology of Caspian terns in the Columbia River estuary, USA. Waterbirds 28: 280-291.

Lyons, D.E., D.D. Roby, and K.Collis. 2007. Foraging patterns of Caspian terns and double-crested cormorants in the Columbia River estuary. Northwest Science 81:91-103.

Lyons, D.E. 2010. Bioenergetics-based predator-prey relationships between piscivorous birds and juvenile salmonids in the Columbia River estuary. Unpubl. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 331 pp.

Lyons, D.E., and D.D. Roby. 2011. Validating growth and development of a seabird as an indicator of food availability: Captive-reared Caspian tern chicks fed *ad libitum* and restricted diets. Journal of Field Ornithology 82: 88-100.

MacFarlane, B. 2010. Energy dynamics and growth of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from the Central Valley of California during the estuarine phase and first ocean year. Canadian Journal of Fisheries and Aquatic Sciences 67: 1549-1565.

Madenjian, C.P., and S.W. Gabrey. 1995. Waterbird predation on fish in western Lake Erie: A bioenergetics model application. Condor 97: 141-153.

McClure, M., B. Sanderson, E. Holmes, C. Jordon, P. Kareiva, and P. Levin. 2000. A standardized quantitative analysis of risks faced by salmonids in the Columbia River basin. National Marine Fisheries Service, Seattle, WA.

McEwan, D.R. 2001. Central Valley steelhead. *In* Brown, R.L. [ed.] Fish Bulletin 179: Contributions to the biology of Central Valley salmonids, vol. 1, p. 1–43. California Department of Fish and Game, Sacramento.

Meng, L., P.B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and introduced fished of Suisun marsh. Transactions of the American Fisheries Society 123: 498-407.

Millspaugh J.J., and J.M. Marzluff. 2001. Radio tracking and animal populations. Academic Press, San Diego, California. 474 pp.

Monaghan, P., P. Walton, S. Wanless, J.D. Uttley, M.D. Burns. 1994. Effects of prey abundance on the foraging behavior, diving efficiency, and time allocation of breeding Guillemots *Uria aalge*. Ibis 136: 214-222.

Montevecchi, W.A., and J.F. Piatt. 1984. Composition and energy contents of mature inshore spawning capelin (*Mallotus villosus*): Implications for seabird predators. Comparative Biochemistry and Physiology 78A: 15-20.

Nagy, K.A. 1980. CO_2 production in animals: Analysis of potential errors in the doubly labeled water method. American Journal of Physiology 238: 466-473.

Newman, K.B., and P.L. Brandes. 2010. Hierarchical modeling of juvenile Chinook salmon survival as a function of Sacramento–San Joaquin Delta water exports. North American Journal of Fisheries Management 30: 157-169.

NMFS (National Marine Fisheries Service). 2008. Draft Biological Opinion on the long-term Central Valley Project and State Water Project operations criteria and plan. NMFS Southwest Regional Office, Long Beach, CA.

NMFS. 2009. Public draft recovery plan for the evolutionarily significant units of Sacramento River winter-run Chinook salmon and Central Valley spring-run Chinook salmon and the distinct population segment of Central Valley Steelhead. Sacramento Protected Resources Division. NMFS Southwest Regional Office, Sacramento, California.

NOAA (National Oceanic and Atmospheric Administration). 1998. Endangered and threatened species: threatened status for two ESUs of steelhead in Washington, Oregon, and California. Federal Register 63: 53 (19 March 1998): 13347-13371.

NOAA. 2005. Endangered and threatened species: final listing determinations for 16 ESUs of west coast salmon, and final 4(d) protective regulations for threatened salmonid ESUs. Federal Register 70:123 (28 June 2005): 37160-37204.

NOAA. 2006. Biological Opinion for Caspian tern management plan to reduce predation of juvenile salmonids in the Columbia River estuary. NOAA Fisheries, Portland, Oregon.

NOAA. 2008. Fisheries off west coast states and in the western Pacific; west coast salmon fisheries; 2008 management measures and a temporary rule. Federal Register 73:85(1 May 2008): 23971-23981.

NOAA. 2009a. Commerce Secretary Gary Locke extends 2008 disaster declaration due to poor salmon returns (Press release, 30 April 2009). Retrieved from http://www.nmfs.noaa.gov/sfa/sf3/disaster.htm.

NOAA. 2009b. Fisheries off west coast states and in the western Pacific; West coast salmon fisheries; 2009 management measures. Federal Register 74: 85 (5 May 2009): 20610-20620.

Olla, B.L., M.W. Davis, and C.H. Ryer. 1994. Behavioural deficits in hatchery-reared fish: Potential effects on survival following release. Aquaculture and Fisheries Management 25: 19-34.

Perry, R.W., J.R. Skalski, P.L. Brandes, P.T. Sandstrom, A.P. Klimley, A. Ammann, and B. MacFarlane. 2010. Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta. North American Journal of Fisheries Management 30: 142-156.

PFEL (Pacific Fisheries Environmental Laboratory). 2011. North America historical upwelling index database. Available for download at: http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html

PFMC (Pacific Fisheries Management Council). 2010. Status of the Pacific Coast coastal pelagic species fishery and recommended acceptable biological catches. Stock assessment and fishery evaluation – 2010.

Phillips, R.A., D.R. Thompson, and K.C. Hamer. 1999. The impact of great skua predation on seabird populations at St. Kilda: A bioenergetics model. Journal of Applied Ecology 36: 218-232.

Quinn, J.S. 1990. Sexual size dimorphism and parental care patterns in a monomorphic and a dimorphic larid. Auk 107: 260-274.

Ramsey, F.L. and D.W. Schafer. 2002. The Statistical Sleuth. (2nd Edition). Pacific Grove, CA, Wadsworth Group.

Reynolds, S.D., and T.H. Kunz. 2001. Standard methods for destructive body composition analysis. *In* Speakman, J.R. [ed.] Body composition analysis of animals. Cambridge University Press, Cambridge, UK, 39-55.

RMISD (Regional Mark Information System Database). Continuously since 1977. Regional Mark Processing Center, Pacific States Marine Fisheries Commission, Portland, OR. Available at: http://www.rmpc.org.

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

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

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

SAS Institute Inc. 2009. SAS version 9.2. SAS Institute Inc., Cary, NC.

Schmidt-Nielsen, K. (Ed.). 1997. Animal physiology: Adaptation and environment. 5th Edition, Cambridge University Press, New York. 607 pp.

Seaman, D.E. and R.A. Powell. 1996. An Evaluation of the accuracy of kernel density estimators for home range analysis. Ecology 77: 2075-2085.

Seto, N., J. Dillon, W.D. Shuford, and T. Zimmerman. 2003. A review of Caspian tern (*Sterna caspia*) nesting habitat: A feasibility assessment of management opportunities in the U.S. Fish and Wildlife Service Pacific Region. U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR.

SFBBO (San Francisco Bay Bird Observatory). 2010. Colonial waterbird nesting summary for San Francisco Bay, 2010. Available for download: http://www.sfbbo.org/docs.

Silverman, E.D., R.R. Veit, and G.A. Nevitt. 2004. Nearest neighbors as foraging cues: information transfer in a patchy environment. Marine Ecology Progress Series 277: 25-35.

Sirdevan, J. E., and J. S. Quinn. 1997. Foraging patterns of Caspian Terns (*Sterna caspia*) determined using radio-telemetry. Colonial Waterbirds 20: 429-435.

Strong, C.M., L.B. Spear, T.P. Ryan, R.E. Dakin. 2004. Forster's tern, Caspian tern, and California gull colonies in San Francisco Bay: habitat use, numbers and trends, 1982-2003. Waterbirds 27: 411-423.

USACE (U.S. Army Corps of Engineers). 2006. Record of Decision Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USACE, Portland, Oregon.

USFWS (U.S. Fish and Wildlife Service). 2006. Record of Decision: Caspian tern management to reduce predation of juvenile salmonids in the Columbia River estuary. USFWS, Portland, Oregon.

Waples, R.S. 1995. Evolutionarily significant units and the conservation of biological diversity under the Endangered Species Act. Am. Fish. Soc. Symp. 17: 8–27.

Weimerskirch, H., Y. Cherel, F. Cuenot-Chaillet, and V. Ridoux. 1997. Alternative foraging strategies and resource allocation by male and female wandering albatrosses. Ecology 78: 2051-2063.

Weimerskirch, H. 1998. How can a pelagic seabird provision its chick when relying on a distant food resource? Cyclic attendance at the colony, foraging decision and body condition in sooty shearwaters. Journal of Animal Ecology 67: 99-109.

Wiens, J.A., and J.M. Scott. 1975. Model estimation of energy flow in Oregon coastal seabird populations. Condor 77: 439-452.

Williams, J.G. 2006. Central Valley salmon: a perspective on Chinook and Steelhead in the Central Valley of California. San Francisco Estuary and Watershed Science 4.

Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. North American Journal of Fisheries Management 18: 487-521.