CONSERVATION OF SOOTY TERNS ON WAKE ATOLL COMPLEX

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A Thesis

presented to

the Faculty of the Graduate School

at the University of Missouri-Columbia

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of the Requirements for the Degree

Master of Science

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by

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The undersigned, appointed by the dean of the Graduate School,

have examined the thesis entitled

CONSERVATION OF SOOTY TERNS ON WAKE ATOLL COMPLEX

presented by Lisa A. Sztukowski,

a candidate for the degree of master of Fisheries and Wildlife Sciences,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Dr. Dylan Kesler

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Dr. John Faaborg

Dad's words of wisdom: Go for it. Life is short; do what makes you happy.

And to my family,

I love you with all my heart, mind and soul.

ACKNOWLEDGEMENTS

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CONSERVATION OF SOOTY TERNS ON WAKE ATOLL COMPLEX

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ABSTRACT

I undertook two projects aimed at improving conservation efforts for Sooty Terns (*Onychoprion fuscata*). First, I investigated patterns of Sooty Tern chick survival to identify when chicks are most vulnerable and to assess the influence of daily maximum temperature, precipitation, rat predation, and vegetation density on survival. Chick survival was positively associated with age and body condition. Survival was negatively associated with daily maximum temperature and vegetation density. Thus Sooty Tern conservation and management plans could be improved by considering the potential impacts of climate change on chick survival and including vegetation management.

Seabird conservation efforts have employed rat eradication programs during the past two decades. However, the danger of non-target poisoning to seabirds has rarely been examined. In a second study, I assessed the risk of rodenticide bait to nesting Sooty Terns using placebo bait. I found no evidence of pellet ingestion based on fecal samples, postmortem inspections, and live chick observations. However, rodenticide bait handling and consumption were observed in camera-based data. Bait consumption suggests the potential for considerable impacts of rat poison on nesting Sooty Terns. Thus risks from rodenticide should be evaluated when eradication programs are planned for locations with seabirds. I also recommend that future studies begin with an evaluation of

environmentally-based fluorescence prior to formal biomarker studies as false positive

results may be contributing to current eradication failure rates.

CHAPTER 1 – PROJECT INTRODUCTION

Seabirds are an important component of marine and island ecosystems. As apex

predators, seabirds respond to changes in lower trophic levels and physical changes in the

marine environment (e.g. Ainley et al. 1995; Sydeman et al 2001). Seabirds can provide

insight into food webs, habitat quality, ecosystem health, and abiotic factors through their

survival, reproductive ecology, and activity budgets (e.g. Crains 1987; Furness and

Greenwood 1993, Furness and Camphuysen 1997, Piatt et al. 2007). Seabirds also

provide a critical link between oceans and terrestrial nutrient cycles and trophic

interactions. For example, seabird guano links marine nutrients to terrestrial landscapes.

The guano influences phytoplankton, algal and plant production, soils, herbivores, and

detritus feeding organisms (Polis and Hurd 1996; Sánchez-Piñero and Polis 2000;

Fukami et al. 2006).

Threats to seabirds mirror those of marine ecosystems and islandscapes. Seabirds

are threatened by non-native species, habitat alteration, human disturbance, global

climate change, interactions with fisheries, and pollution. The relative influence of these

threats and the extent of their impact vary within species. Thus important information for

seabird management and conservation includes understanding of abiotic and biotic

factors that affect species-specific survival.

My research focused on Sooty Terns (*Onychoprion fuscata*), an abundant

pantropical species that recently experienced local declines and extirpations (Scheiber et

al. 2002). Sooty Terns face threats similar to other seabirds. Population declines have

been attributed to egg harvest, loss of habitat, and predation (Schreiber et al. 2002). Additionally, climate conditions were linked to reduced chick survival through changes in resources, extreme weather events, chilling, and overheating (Vesey-Fitzgerald 1941; Howell and Bartholomew 1962; Ashmole 1963; Feare 1976a, c; Burger 1980; Schreiber and Schreiber 1984, 1989; Kohno et al. 1986; Duffy 1990; King et al. 1992Ratcliff et al. 1999; Schreiber 2000; Le Corre 2001; Ramos et al. 2002; Jaquemet et al. 2006; Erwin and Congdon 2007; Surman and Nicholson 2009). In this study I initiated research to investigate intraseaonal variation in chick survival and test the influence of threats on chick survival.

Current seabird conservation is focused on habitat management, invasive species control, minimizing bycatch mortality, and responding to pollution. Rat eradication programs have been used as a conservation tool for more than two decades with purported benefits to ecosystems and seabird conservation (Thomas and Taylor 2002; Clout and Russell 2006; Howald et al. 2007). Many island seabird conservation efforts have resulted in benefits for other insular flora and fauna, such as increased seedling recruitment, and number of intertidal invertebrates and native plants (Allen et al. 1994, Campbell and Atkinson 2002, Smith et al. 2006, Towns et al. 2006). Eradication programs have also been proposed as compensatory mitigation for fisheries bycatch mortality (Wilcox and Donlan 2007; Donlan and Wilcox 2008). However, the danger of non-target poisoning to seabirds during nesting has rarely been examined despite hundreds of insular eradication efforts. Thus in this study I examined the risk of handling and consuming rodenticide poison by nesting seabirds.

Background information on Sooty Terns

Sooty Terns are a colonial and abundant pantropical species with life-spans of up to 34 years. The birds delay breeding for four to ten years, and they have low annual reproductive rates (Ashmole 1963; Harrington 1974; Schreiber et al. 2002). The breeding periodicity and degree of synchrony within populations vary throughout their geographic range (Schreiber et al. 2002) and that variation is likely due to environmental cues or a lack thereof (Ashmole 1965). Sooty Terns nest on the ground in areas of sparse vegetation (Watson 1908; Vesey-Fitzgerald 1941; Robertson 1964; Feare 1976b; Schreiber and Schreiber 1989; Feare et al. 1997). Mean incubation period is 28-30 days (Scheiber et al. 2002). Nestlings are semi-precocial and capable of moving away from the nest site shortly after hatching, although they usually remain nearby for 4-10 days post-hatch (Scheiber et al. 2002). Nestlings may progressively spend more time away from the nest site, or abandon the nest site entirely as they age. Fledging age varies from 2 to 9 months and relates to environmental conditions (Scheiber et al. 2002). Sooty Terns have extended post-fledge care. Young capable of flying may remain near the nesting site for 18-21 days, however, adults and juveniles can stay together for two to three months.

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CHAPTER 2 - LOW CHICK SURVIVAL IN A LONG-LIVED SPECIES: THE EFFECTS OF TEMPERATURE, HABITAT AND AGE ON SOOTY TERNS

ABSTRACT

I evaluated factors affecting time- and age- specific variation in Sooty Tern (*Onychoprion fuscata*) chick survival. I first used age-based Cormack-Jolly-Seber (CJS) models to assess age and developmental stage survival patterns in Sooty Tern chicks from hatch to 35 days post-hatch. Chick survival was positively associated with age. My results indicate an average survival rate from hatch to fledge at 56 days post-hatch of 0.056 (range within locations in the colony 0.014 – 0.121). Changes in survival at different ages suggest that population models may be improved by incorporating finer temporal resolution. I then used results from the top-ranking age-based model, in combination with a time-based CJS model, to examine the effects of exogenous factors on survival, including daily maximum temperature, daily precipitation, predator abundance, and vegetation density. The best-fitting model included an additive relationship of daily maximum temperature, vegetation density, and body condition with daily survival of Sooty Tern chicks. Daily maximum temperature and vegetation density were negatively associated with chick survival, whereas body condition displayed a positive relationship with survival. My results suggest that management of vegetation in Sooty Tern breeding habitats may increase chick survival. Additionally, management and conservation plans should consider the potential negative impacts of climate change on Sooty Terns,

especially in areas with predicted increased temperatures. Consistently higher

temperatures may threaten chick survival and thus Sooty Tern abundance.

Key Words: *Survival, Sooty Tern, habitat, environmental conditions, body condition, intra-seasonal variation*

INTRODUCTION

Sooty Terns (*Onychoprion fuscata*) are an abundant pantropical species that recently

experienced local declines and extirpations (Schreiber et al. 2002). Population declines

have been attributed to egg harvest, loss of habitat, and predation (Schreiber et al. 2002).

Sooty Terns are colonial breeders, with life-spans of up to 34 years, delayed breeding,

and low reproductive rates (Schreiber et al. 2002). Population dynamics of long-lived

species like the Sooty Tern are thought to be most sensitive to changes in adult mortality

and least sensitive to changes in reproductive success (Cairns 1992; Pfister 1998; Feare

and Doherty 2004; Feare et al. 2007). However, low productivity over long periods

would also contribute to population declines and extirpations.

Sooty Tern populations were previously modeled to promote a greater

understanding of population dynamics (Feare 1976a, b; Feare and Doherty 2004).

Models assumed constant survival within each nest stage (Feare 1976a, b; Feare and

Doherty 2004). Studies focusing on passerines (Emberizidae, Cardinalidae), gamebirds

(Phasianidae), shorebirds (Charadriidae, Scolopacidae), and seaducks (Anatidae) indicate

that nest survival can vary by throughout the breeding season (Burhans et al. 2002;

Dinsmore et al. 2002; Jehle et al. 2004; Traylor et al. 2004; Grant et al. 2005; Wilson et

al. 2007; Smith and Wilson 2010). Although these published studies focus on nest

survival, chick survival should also vary. Research has assessed Sooty Tern reproductive

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success within each nest stage. Published information on intra-seasonal survival patterns of seabird chicks is sparse. Therefore, there is uncertainty about whether variances in survival patterns characterize seabird or subannual breeders, such as Sooty Terns. Intra-seasonal variation seems plausible, because of local biogeographic conditions, changes in behavior throughout the breeding season, chick-rearing period of 56 days or more, and the broad range of natural history characteristics exhibited by Sooty Terns, such as plasticity of breeding periodicity (Schreiber et al. 2002). Examining survival at finer temporal resolutions may improve future population models as well as provide insight into reproductive ecology and factors affecting chick survival. The potential causes of chick mortality include habitat variation, predation, and weather conditions (Burger 1982).

Climate conditions have been linked to survival through extreme weather events, chilling, and overheating (Vesey-Fitzgerald 1941; Howell and Bartholomew 1962; Feare 1976a, c; Burger 1980; Kohno et al. 1986; King et al. 1992). High winds, cyclones, and typhoons can cause breeding failure and nest abandonment (Kohno et al. 1986; King et al. 1992). Flood and storm events can also wash away adults, chicks, and eggs (Burger 1980; L. S. pers. obs. 2008). Low chick survival has been associated with prolonged rain, as parents leave chicks vulnerable to chilling during heavy rain events (Howell and Bartholomew 1962; Feare 1976a, c). Overheating has also been suggested to threaten survival during the breeding season (Vesey-Fitzgerald 1941; Howell and Bartholomew 1962). In response to heat, Sooty Terns may select tall vegetation with increased cover as a means to reduce temperatures at the nest site (Burger and Gochfeld 1986; Saliva and Burger 1989).

Habitat loss has also been identified as a leading threat to seabirds (King 1985). Links between habitat and survival are prominent in habitat selection studies (Cody 1985; Saliva and Burger 1989; Hazin and Macedo 2006). Several researchers suggested that vegetation growth could reduce Sooty Tern nesting habitat (Sprunt 1948; Robertson 1964; Burger and Gochfeld 1986). Sooty Tern colonies are primarily found on bare ground, sand, coral rubble, or rocky habitat with minimal vegetation (Watson 1908; Vesey-Fitzgerald 1941; Ashmole 1963; Robertson 1964; Harrington 1974; Feare 1976b; Schreiber and Schreiber 1989; Feare et al. 1997). However, exceptions include Culebra, La Orchila, Little Tobago, and Pelsaert Island colonies, where Sooty Terns select tall vegetation possibly due to the types of predators, human disturbance, high temperatures, or lack of available open ground in these locations (Burger and Gochfeld 1986; Saliva and Burger 1989).

Finally, rat (*Rattus* spp.) predation is also widely recognized as a major threat to seabird populations (King 1985; Wilcove et al. 1998; Towns et al. 2006; Howald et al. 2007; Jones et al. 2008). Non-native mammals have led to extinctions, extirpations, and population declines of numerous endemic species through predation, competition, and disease (Atkinson 1985; King 1985; Wilcove et al. 1998; Courchamp et al. 2003; Jones et al. 2008). Rats are voracious predators of eggs, chicks, and even adult birds and have been found on 80-90% of oceanic islands (Atkinson 1985, Caut et al. 2008). Rats are not native to many tropical Pacific islands, but two species (*R. rattus* and *R. exulans*) now inhabit most Pacific islands, including many islands in which Sooty Terns breed and thus Sooty Terns may also be affected by rats (Harrison 1990; Woodward 1972; Ratcliffe et al. 1999, Feare 1976b; Schreiber et al. 2002).

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Chick body condition may also influence the susceptibility to other exogenous

factors. Studies of chick body condition in Sooty Terns have indicated that increased

mass was also positively associated with survival (Feare 1976b, 2002). In a synchronized

colony in the Seychelle Islands, Sooty Tern chicks were more likely to fledge if they

hatched during peak breeding season; those chicks attained greater weights, grew faster

and fledged earlier (Feare 1976b, 2002).

I examined factors affecting time- and age- specific variation in survival of Sooty

Tern chicks using a multi-stage approach. I first focused on identifying chick survival

patterns associated with age and developmental stage. I tested the influence of four

developmental stages, which were defined by physical and behavioral characteristics, on

daily survival. I also tested for a continuous pattern of survival with increasing age. I

then combined results from the age-specific models with an analysis of the effects on

survival of daily maximum temperature, precipitation, rat predation, and vegetation

density.

METHODS

Study site

I assessed daily survival of Sooty Tern chicks on Wake Atoll Complex during the 2009

breeding season (8 June - 11 August, 2009). The island complex is located in the central

Pacific Ocean (19º 18' 55" N, 166º 38' 21" E), and it is comprised of three islets (Wilkes,

Wake, and Peale) with a total land area of 739 hectares. Two invasive rodents, *R.

exulans* and *R. rattus,* were present on the island (U. S. Air Force 2008). The study

colony was located on Wilkes Islet where Sooty Terns nest in an open field. The nesting

habitat was characterized by a mix of bare ground, grass (Poaeceae), and puncture vine (*Tribulus terrestris*).

Survey design

I estimated daily survival of Sooty Tern chicks using mark-resight methods in four 20 m x 20 m plots. Two plots were placed in areas with nests in late-stage incubation and two plots were placed in areas with newly hatched chicks. All plots were located in areas that were visible from outside the colony, and thus plots were placed approximately 10 m from the edge of the colony border. Plots were distributed to maximize inter-plot distances to reduce interactions between treatment and control sites used to alter rat abundance. Chicks less than 25 days of age were banded with numbered aluminum bands (USGS Patuxent Bird Banding Laboratory) and unique color band combinations. Weight and flattened wing chord measurements were recorded for each bird during banding (n = 524 chicks).

I collected morphological data from known-age chicks to facilitate age estimation of chicks of unknown age. I surrounded an area of approximately 5 m^2 outside the survival survey plots that contained 20 hatching eggs with a 15 cm high fence constructed from hardware cloth to increase recapture rates. Adult terns appeared to quickly acclimate to the presence of the fence and their behavior resembled those of nearby breeding adults. All chicks within the fenced area were banded shortly after hatching and then recaptured every third night. During each capture, weight and flattened wing chord measurements were recorded. I fitted data from the known-aged chicks to a growth curve testing linear, logarithmic, power, polynomial, and exponential equations and then selecting the trendline with the highest with the highest r^2 value. I used the resulting

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equation to estimate the age of chicks that were marked within the four survival study plots. Chick growth followed an exponential trend ($y = 18.924e^{0.0196x}$) with an r^2 value of 0.8595 (Fig. 1). Visual inspection of the variation among sample individuals presented in the graph increased after 25 days post-hatch. Results from visual inspections were confirmed by an increase in standard deviation among sample individuals between 23 and 26 days post hatch (2.5 mm and 5 mm, respectively). Since growth variation among sample individuals increased after 25 days post-hatch, the survival analyses presented below included only birds that were banded during the first 25 days post-hatch.

I searched for banded individuals daily using a spotting scope from 8 June - 11 August, 2009 (resight occasions = 65). Resighting occasions occurred throughout the daylight hours; however resighting attempts were primarily made when detectability was highest either from sunrise to 10:30 or 15:30 to sunset. Resighting occasions lasted 30 minutes unless weather shortened the duration of a resighting occasion. During each resighting occasion an observer scanned the plot with a spotting scope and recorded the color combination for each chick that was observed. Although chicks usually fledge at 56-120 days post-hatch, I restricted survival estimates to chicks younger than 36 days post-hatch as resight probabilities were reduced after this time period.

Within each plot, I evaluated the frequency of rat presence, vegetation density, daily maximum temperature, daily presence or absence of precipitation, and body condition of chicks at banding. Rat abundance was altered using a treatment-control design. Plots were paired by developmental stage, and randomly assigned as a treatment or control site. Each plot was surrounded by six bait stations; four were located in the center of each side of the plot and two additional bait stations were placed near the edge

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of the colony adjacent to the plot. Bait stations were supplied with either non-toxic

placebo bait (Bell Laboratories, Inc., Madison, WI) in control plots or toxic brodifacoum

bait in treatment plots.

I used camera-based observations to assess the frequency of rat presence.

Cameras (RC55 RapidFire™ Color IR camera, Reconyx Inc., Holmen, WI) were placed

within two plots and moved between paired treatment and control plots on 24 June, 2

July, 12 July, 24 July, and 5 August, 2009. Photographs were recorded at five-minute

intervals until cameras were moved to another plot or camera batteries failed. Infrared

photographs were used to record nighttime activity of rats. I examined all photographs

collected one hour after camera placement to 15 minutes prior to observer disturbance or

until camera batteries failed ($n = 28\ 295$ photographs). Darkened photographs and

photographs with views obscured by roosting boobies or flying birds were removed from

analysis ($n = 171$ photos). I examined each photograph and recorded frequency of rat

presence, which was calculated by dividing the total number of photographs with rats

present by the number of viable photographs viewed within each plot.

Climate conditions included daily maximum temperature and the daily presence

or absence of precipitation. Daily maximum temperature was obtained from the National

Oceanic and Atmospheric Administration for the Wake Island airfield location. The

presence of precipitation varied within the atoll complex; therefore photographs from

camera-based observations were examined for precipitation. The presence or absence of

precipitation was recorded for each 24 hour period starting at midnight Coordinated

Universal Time (UTC+12).

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Vegetation density was visually estimated as percent cover within six quadrats (1 m^2) that were placed in each plot twice during the study. Percent cover was then averaged for the 12 quadrats recorded for each plot. Surveys were conducted on 24 and 30 June, 2009, in which two plots were surveyed on each date, and on 24 July, 2009 in which all plots were surveyed. Locations of the 1 m^2 quadrat samples were selected by walking nine paces in an arbitrary direction, and placing the quadrat in a random direction (generated via randomization routine in Microsoft Excel software). The observer walked into plots at night to reduce disturbance; nighttime surveys were completed with light focused near the observer's feet so the location of the quadrats was concealed at the onset of the nine steps. Vegetation density was represented by the average values found within the quadrats for each plot.

Models and analysis

I assessed the factors affecting time- and age- specific variation in Sooty Tern chick survival using a multi-stage analysis. I first applied an age-based Cormack-Jolly-Seber (CJS) model in program MARK (Cormack 1964; Jolly 1965; Seber 1965; White and Burnham 1999; Dinsmore et al. 2002) to evaluate age-specific factors affecting chick survival. Age-based data structure was compiled so that resight occasions were determined by the number of days post-hatch. The structure was necessary to assess the effects of developmental stage, which was defined by physical and behavioral characteristics, and continuous trend with increasing age as Sooty Terns have a protracted breeding season. I then applied the results of the best-supported age-specific model and examined the affect of daily maximum temperature, daily precipitation, rat abundance, and vegetation density on chick survival within a time-based CJS model. The time-based

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model was structured by resight ordinal date, which was necessary to incorporate weather conditions. Although the time-based structure could incorporate proxies for age, it could not evaluate patterns of chick survival associated with age trends or developmental stage due to the non-synchronous hatch dates of Sooty Tern chicks. The detection parameter for both age- and time-specific models varied with time and among plots ($p_{(t+Plot)}$).

Age-specific models.- I used age-based CJS models to assess factors of age and developmental stage affecting Sooty Tern chick survival from hatch to 35 days post-hatch. I developed and ranked four *a priori* models in an Akaike's Information Criteria (AIC_c) framework (Burnham and Anderson 2002; Table 1). Models were associated with hypotheses that (1) survival was constant through time, $\phi(t_{Constant} + Plot)$, (2) survival varied randomly with time, $\phi(t_{Random} + Plot)$, (3) survival was associated with a continuous trend with chick age, $\phi(Age + Plot)$, and (4) survival was associated with developmental stage, $\phi(DS + Plot)$. Four developmental stages were selected to represent general behavioral and physical development, which may be associated with changes in survival (Dinsmore 1972; White et al. 1976; Ricklefs and White 1981; Schreiber et al 2002). The first stage extended from hatch to four days post-hatch and was associated with aggressive nest defense behavior by adults and continuous parental care. Chicks five to eight days of age (developmental stage two) were mobile but typically remained in close contact with adults or hid in shaded areas with an adult nearby. Chicks eight to 20 days post-hatch (developmental stage three) were likely to move between their hatch site and nearby shade provided by vegetation or rocks, had scapular feather growth, and were attended by adults less frequently. Chicks older than 20 days (developmental stage four) were mostly feathered and parental attendance was usually low. Competing models were

ranked using AIC_c with a correction for sample size; models with $\Delta AIC_c < 2.0$ and AIC_c weight of > 90% were considered to have substantial support (Burnham and Anderson 2002).

Time-specific models.- I used time-based CJS models to examine the affect of daily maximum temperature, daily precipitation, predator abundance, and vegetation density on chick survival. I included body condition at time of banding as a proxy for age in all time-specific models, because age was identified as a factor affecting survival in the previous analysis (see results). An index of body condition was defined by the residuals of a linear regression of mass against the body size indicator flattened wing chord length (predicted weight = (4.63 * wing chord length) - 60.56; $r^2 = 0.62$). Flattened wing chord length used to estimate both chick age and body condition. An individual with a positive residual was assumed to have more energy reserves and thus was considered to be in better condition than individuals with negative residuals (Schulte-Hostedde et al. 2005). The time-based models were parameterized by ordinal resight date ($n = 65$ days).

I developed a set of nine *a priori* biological hypotheses to explain the variation in daily survival of Sooty Tern chicks. Time-based models included covariates for frequency of rat presence, vegetation density, daily maximum temperature, daily presence/absence of precipitation, and additive combinations of weather variables and either of the plot-based covariates, frequency of rat presence or vegetation density. I tested all possible variable combinations, except the combination of the two plot-based covariates, frequency of rat presence and vegetation density (Table 2). Daily survival was assessed until chicks were estimated to be 35 days post-hatch, when they became too

mobile to track. Multiple competing models were ranked using an AIC_c framework to identify factors likely to influence survival (Burnham and Anderson 2002). Models were considered to be top-ranked if the second-ranked model was > 2 AIC_c units below the first-ranked model (Burnham and Anderson 2002).

RESULTS

Age-specific variation in survival

The chick survival model most supported by the age-based analysis indicated that survival was positively related to chick age, and that survival varied among plots (ϕ(Age+Plot); Fig. 2). There were no competing models as this model ranked more than 10 AIC_c units above the next-best model and received over 99% of the AIC_c weight (Table 1). Chicks suffered the highest rate of mortality during early chick rearing. The top-ranked model indicated that daily survival could be predicted with the equation

$$\phi = \frac{e^{\beta_{Intercept}+(Days\ Post-hatch*\beta_{Age})+\beta_{Plot}}}{1+e^{\beta_{Intercept}+(Tmax*\beta_{Tmax})+(Veg*\beta_{Veg})+(BC*\beta_{BC})}}$$

where $\beta_{Intercept}$ represents the survival intercept parameter (1.53 ± 42.27, 95%CI -81.32 - 84.38), β_{Age} represents the number of days post-hatch parameter (0.04 ± 0.01, 95%CI 0.03 - 0.06), β_{Plot1} represents the plot 1 parameter (0.32 ± 42.27, 95%CI -82.54 - 83.17), β_{Plot2} represents the plot 2 parameter (0.27 ± 42.27, 95%CI -82.59 - 83.12), β_{Plot3} represents the plot3 parameter (0.69 ± 42.27, 95%CI -82.16 - 83.55, β_{Plot4} represents the plot 4 parameter (-0.03 ± 42.27, 95%CI -82.89 - 82.82).

Chicks usually fledge at 56-120 days post-hatch depending on food availability and thus if these figures were extended to the duration of the chick development period, results would indicate an average estimated survival of 0.056 (range 0.014 – 0.121) from hatch to fledge at 56 days post-hatch.

   Time-specific variation in survival

The top-ranking model for the assessment of abiotic conditions, predation, and vegetation indicated an additive relationship of daily maximum temperature, vegetation density, and body condition was most associated with Sooty Tern chick survival (Table 2, Fig. 3). Both daily maximum temperature and vegetation density were negatively associated with chick survival, whereas body condition displayed a positive relationship with survival. No other model received substantial support (AIC$_c$ weight = 100%; ΔAIC$_c$ > 28). The top-ranked model indicated that daily chick survival could be predicted with the equation

$$\phi = \frac{e^{\beta_{Intercept}+(Tmax*\beta_{Tmax})+(Veg*\beta_{Veg})+(BC*\beta_{BC})}}{1 + e^{\beta_{Intercept}+(Tmax*\beta_{Tmax})+(Veg*\beta_{Veg})+(BC*\beta_{BC})}}$$

where $\beta_{Intercept}$ represents the survival intercept parameter (27.67 $\pm$ 3.36, 95%CI 21.09 – 34.25), β_{Tmax} represents the daily maximum temperature parameter (ºC; -0.69 $\pm$ 0.09, 95%CI -0.87 - -0.51), β_{Veg} represents the vegetation density parameter (-0.04 $\pm$ 0.01, 95%CI -0.05 - -0.02), β_{BC} represents the body condition parameter (0.03 $\pm$ 0.01, 95%CI 0.02 - 0.04). The variable *T$_{max}$* was represented by daily maximum temperature (C°), *Veg* was represented by the percent vegetation cover (i.e. 40 not 0.40), and *BC* was

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represented by the residuals of a linear regression of mass against the body size indicator

flattened wing chord length.

Changes in either daily maximum temperature or vegetation cover alter chick

survival. For example, the model indicated that with all other variables held at mean

values (daily maximum temperature = 33.0ºC; vegetation density = 0.48; body condition

= -5.08*10^{-5}), changes in temperature from the mean temperature for 2009 breeding

season (33.0ºC) to 33.5ºC would result in survival estimates for hatch to fledge at 56 days

of 0.66 and 0.56, respectively. Similarly, an increase in vegetation from 40-60% cover

would reduce daily survival from 0.97 to 0.94. If these numbers were extended to the

entire 56 day period between hatch and fledge, similar temperature and vegetation

changes would reduce chick survival by 15.6% and 2.9%, respectively.

The covariate for frequency of rat presence was not among the top models. The

frequency of rat presence within my plots ranged between 0.0017 and 0.0049; variation

among plots was low with similar proportions of rat presence in three of four plots.

DISCUSSION

Variations in intra-seasonal survival have been noted for passerines, ducks, geese,

seaducks and, in this case, seabirds with subannual breeding periodicity (Burhans et al.

2002; Dinsmore et al. 2002; Jehle et al. 2004; Traylor et al. 2004; Grant et al. 2005;

Walker et al. 2005; Wilson et al. 2007; Smith and Wilson 2010). I observed a positive

relationship between survival and chick age. Changes in survival at different ages

suggest that population models may be improved by incorporating finer temporal

resolution. Intra-seasonal patterns may also provide insight into species' ecology.

My results also indicated a strong relationship between daily maximum temperature and Sooty Tern chick survival. Vulnerability during early development may be related to a limited ability to thermoregulate and to reduced mobility. Although Sooty Tern fledgling body temperature remained stable when air temperatures range between 10-30°C (MacMillen et al. 1977), chicks were previously observed shivering when standing in the shade, and body temperatures increased when placed in full sun (Howell and Bartholomew 1962). Moreover, other behaviors were observed that supported an inability to theromregulate. For example, chicks too young to stand were seen crawling toward shade (Howell and Bartholomew 1962). Additionally, reduced mobility may increase vulnerability to predation by rats and hinder escape from intraspecific aggression, which is prevalent among Sooty Terns on Wake Island (L. S. pers. obs). Increased reproductive success in a highly synchronous colony was attributed to reduced losses to predation and intraspecific aggression (Feare 1976b).

When examining the effects of biotic and abiotic factors, the best-fit model associated the additive relationship of daily maximum temperature, vegetation density, and body condition with daily survival. Both daily maximum temperature and vegetation density were negatively associated with chick survival. Body condition displayed a positive relationship with survival. Although I did not include interactions between covariates, body condition may influence the negative effects associated with high temperatures or dense vegetation cover.

Extreme temperatures and overheating have been proposed as a threat to individual seabird survival. Sooty Tern chick survival was inversely related to daily maximum temperature. Daily maximum temperature during the 2009 season exceeded

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the thermo-neutral temperature of 30°C for Sooty Terns (Howell and Bartholomew 1962; MacMillen et al. 1977) in 96.9% of survey days (28.9°C - 36.7°C, mean 32.9°C). Fourteen percent of survey days exceed 35°C, at which Sooty Terns become hyperthermic (MacMillen et al. 1977). My results were similar to those reported from the Seychelles, where reduced chick survival was attributed to sunstroke (Vesey-Fitzgerald 1941). In addition to the direct effects of overheating, indirect impacts on food availability may also reduce seabird survival. The relationship between surface air temperature and sea-surface temperatures may alter with atmospheric circulation changes. However, patterns of both surface air temperature and sea-surface temperatures are generally consistent and temperatures have increased from 1850 to 2005 (IPCC 2007). Increased sea-surface temperatures have been negatively associated with feeding frequency and food quantity presented to chicks and linked to breeding failure, thus reducing reproductive success (Ashmole 1963; Schreiber and Schreiber 1984, 1989; Duffy 1990; Ratcliff et al. 1999; Schreiber 2000; Le Corre 2001; Ramos et al. 2002; Jaquemet et al. 2006; Erwin and Congdon 2007; Surman and Nicholson 2009). Changes in sea-surface temperatures have also affected breeding periodicity and size of breeding populations resulting in changes in seabird productivity (Le Corre 2001; Ramos et al. 2002; Jaquemet et al. 2006). Additionally, increased adult mortality has also been linked to increased sea-surface temperatures (Surman and Nicholson 2009).

Sooty Tern chick survival was also inversely related to vegetation density. Vegetation density ranged from 30.9% to 71.3% in the four areas surveyed. My results are consistent with general breeding habitat as a majority of colonies are found on bare ground, sand, coral rubble, or rocky habitat with sparse vegetation (Watson 1908; Vesey-

Fitzgerald 1941; Ashmole 1963; Robertson 1964; Harrington 1974; Feare 1976b;

Schreiber and Schreiber 1989; Scheiber et al. 2002). Feare et al. (1997) found a

curvilinear relationship between nest density and vegetation density in which maximum

Sooty Tern nest densities occurred in areas with 30-50% vegetation cover. This

coincides with increased chick survival seen at lower vegetation densities in my study.

However, I did not test vegetation densities below 30% and therefore future studies may

reveal a similar curvilinear relationship between chick survival and vegetation density.

Presumably, some degree of shade is beneficial to chick survival as it would reduce

temperatures experienced by chicks. In some cases, Sooty Terns select tall vegetation

possibly due to heat stress (Burger and Gochfeld 1986; Saliva and Burger 1989).

Despite the large amount of literature relating rat predation to reduced survival,

population declines, and extirpations (King 1985; Towns et al. 2006; Jones et al. 2008),

frequency of rat presence was not among my best-fit models. There are several possible

factors influencing this result including: (1) rat abundance; (2) alternative food sources;

(3) life history characteristics of prey species, and (4) contrast between frequency of rat

presence of plots was insufficient to predict changes in survival. Rat populations are

known to vary, and rat abundance on Wake Island in 2009 was relatively low compared

to 2008 (L. S. unpublished data). The frequency of rat presence within my plots was low,

ranging between 0.0017 and 0.0049. In addition, rats may have had access to food

sources, such as eggs and young chicks, in large abandoned areas of the Sooty Tern

colony; thus rats may have not needed to enter the active areas of the colony that I

monitored. Sooty Terns are also a species that continues to persist in the presence of

invasive rats on many islands, which may be due to their nest site selection or some other

adaptive life history trait. Jones et al. (2008) noted that surface nesting species may be less susceptible to rat predation when compared to burrow nesting species.

While rat predation may not have been among the most influential factors in 2009, Sooty Terns may still benefit from rat eradications on islands as the influence that predation has on survival likely changes among breeding seasons. As noted above, rat population levels change among breeding seasons and thus the risk of predation should alter accordingly. In 2008, rats were frequently observed feeding on dead chicks and rodent attacks on chicks were recorded in camera-based data. Furthermore, more than 46% of pre- and post-fledgling Sooty Terns banded in 2008 had wounds consistent with rat predation; these wounds were absent on all birds handled in 2009. This supports the concept that predation pressure and its influence on survival may vary through time. Thus rat eradications may confer long-term benefits for Sooty Tern populations. Additionally, other species within the ecosystem may benefit from rat eradication programs (i.e. Croll et al. 2005; Whitworth et al. 2005; Smith et al. 2006; Donlan and Wilcox 2008).

Implications for management and conservation

Modeling when species are most vulnerable and the influence of factors that affect chick survival can be used to inform management and conservation decisions. Population and harvest models applying constant survival rates within each nest stage, such as those used in egg harvest management in the Seychelles Islands, may be improved by incorporating finer temporal scales. My results also suggest that management of vegetation may increase Sooty Tern nest survival, and thus abundance.

Additionally, temperatures are expected to rise in the tropical and subtropical oceans in which Sooty Terns breed (IPCC 2007), and therefore climate change will likely cause population declines. Climate predictions for the central Pacific Ocean in the area of Wake Atoll Complex predict a mean surface air temperature rise of 0.5 - 1.0°C from 2011 to 2030 and 2.5 - 3°C by 2099 (Figure 10.8 in IPCC 2007). My model indicates that with all other variables held at mean values, changes in temperature from the mean temperature for 2009 breeding season (33.0ºC) to 33.5 ºC and 36.0 ºC would result in survival estimates of 0.558 and 0.041 from hatch to fledge at 56 days, respectively and thus survival would be reduced by up to 93.8%. Management and conservation plans should consider the potential impacts of climate change on Sooty Terns, especially in areas with predicted increased temperatures. Long-term management and conservation plans may be able to incorporate aspects, such as vegetation management, to off-set expected declines in chick survival associate with higher temperatures.

ACKNOWLEDGMENTS

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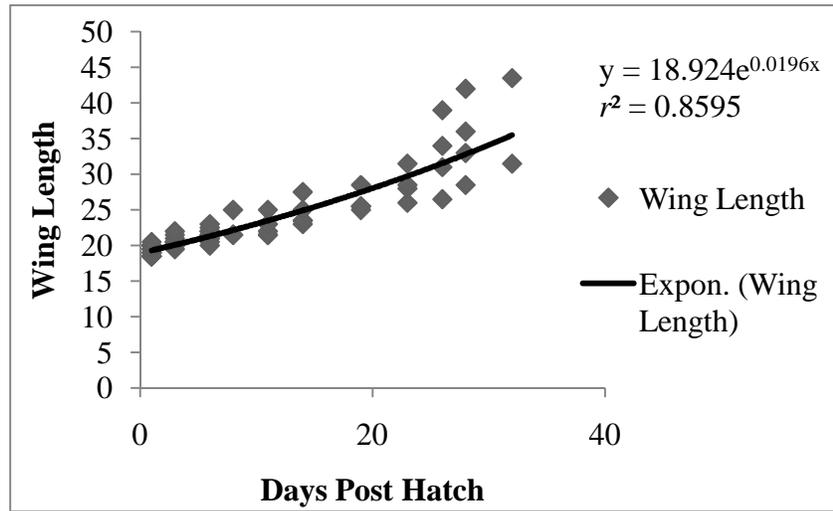
Figure 1. Chick growth followed an exponential trend based on wing chord measurements from known-aged Sooty Tern chicks ($n = 20$) within the survival survey plots on Wake Island.
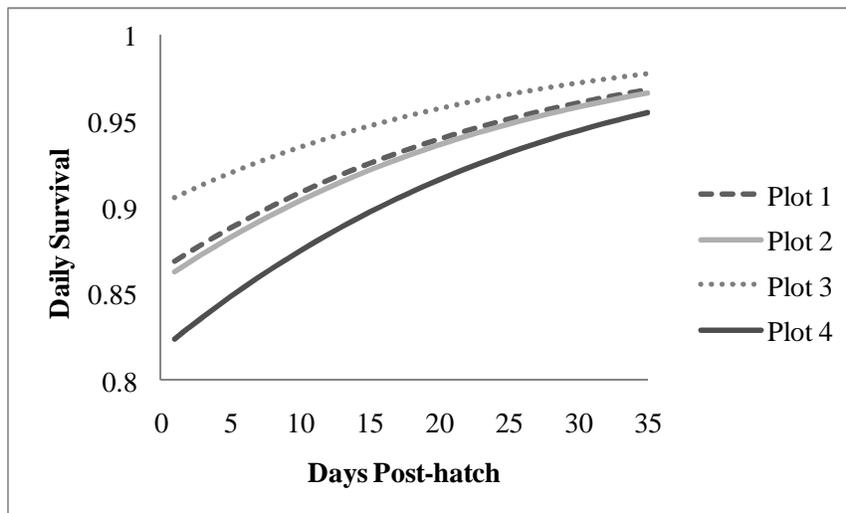
Figure 2. Daily survival of Sooty Terns was positivity associated with age and varied by plot.
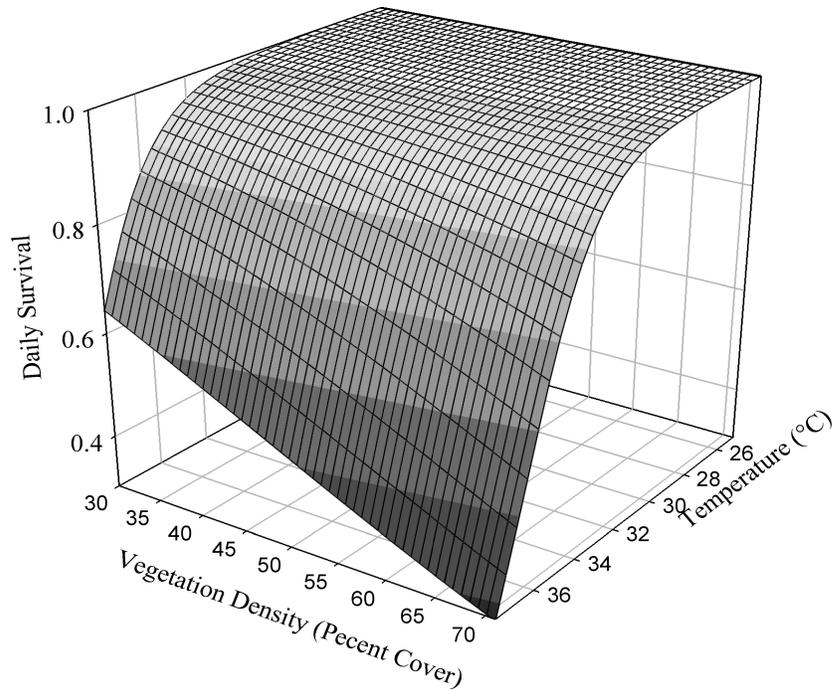
Figure 3. The best-fit exogenous model associated the additive relationship of daily maximum temperature, vegetation density, and body condition with daily survival of Sooty Terns on Wake Island. Daily survival was negatively associated with daily maximum temperature and vegetation whereas survival is positively related to body condition, graphed at the mean value of $-5.08 * 10^{-5}$.

Table 1. Summary of model results in which four CJS models were compared to assess age-specific variation in Sooty Tern chick survival from hatch to 35 days post-hatch. The chick survival model most supported by the age-based analysis (in bold) indicated that survival was positively related to chick age and varied among plots. The detection parameter for all models varied with time and among plots ($p_{(t+Plot)}$).

Model[a]	AIC_c[b]	ΔAIC_c[c]	w_i[d]	K[e]	Deviance[f]
Age + Plot	**5568**	**0.00**	**0.99**	**44**	**3531**
DS + Plot	5578	10.24	0.01	47	3534
$t_{Constant}$ + Plot	5589	21.64	0.00	43	3554
t_{Random} + Plot	5592	24.21	0.00	76	3486

[a] Age continuous trend with chick age, DS developmental stage, $t_{Constant}$ survival constant through time, t_{Random} survival varies randomly with time.

[b] AIC_c Akaike's information criterion for small samples.

[c] ΔAIC_c change in AIC_c relative to the top model.

[d] w_i Akaike weight.

[e] K number of parameters.

[f] Deviance difference in the -2 log-likelihood between each model.

Table 2. Model-ranking analysis of the nine exogenous models comparing the combined effects of climate conditions, rat predation, habitat, and chick body condition indicated that the best-fitting model (in bold) associated the additive relationship of daily maximum temperature, vegetation density, and body condition with daily survival of Sooty Tern chicks. The detection parameter for all models varied with time and among plots ($p_{(t+Plot)}$).

Model	AIC_c	ΔAIC_c	w_i	K	Deviance
Veg + T$_{max}$ + BC	**5459**	**0.00**	**1**	**71**	**5311**
Veg + Rain + BC	5488	28.91	0	71	5339
T$_{max}$ + BC	5499	40.30	0	70	5353
Rat + T$_{max}$ + BC	5500	40.60	0	71	5351
Rain + T$_{max}$ + BC	5501	41.72	0	71	5352
Veg + BC	5511	52.06	0	70	5365
Rain + BC	5511	52.34	0	70	5365
Rat + Rain + BC	5513	53.40	0	71	5364
Rat + BC	5523	63.54	0	70	5376

[a] Veg Vegetation density, T$_{max}$ daily maximum temperature, BC chick body condition at banding, Rain precipitation, Rat rat abundance.

[b] AIC$_c$ Akaike's information criterion for small samples.

[c] ΔAIC_c change in AIC$_c$ relative to the top model.

[d] w_i Akaike weight.

[e] K number of parameters.

[f] Deviance difference in the -2 log-likelihood between each model.

CHAPTER 3 - ENVIRONMENTAL FLUORESCENCE AND BAIT CONSUMPTION

BY SOOTY TERNS: IMPLICATIONS FOR ERADICATION PROGRAMS

ABSTRACT

Rat (*Rattus* spp.) predation is widely recognized as a major threat to seabird populations.

Eradication programs have advanced over the last two decades with purported benefits to

ecosystems and seabird conservation. However, the danger of non-target poisoning to

seabirds has rarely been examined despite hundreds of insular eradication efforts. I

initiated research to assess the risk of rodenticide bait to nesting Sooty Terns

(*Onychoprion fuscata*) on Wake Atoll Complex. Placebo bait with a fluorescing dye was

used in a control-treatment design to track exposure and ingestion. Camera-based

observations documented bait exposure and consumption, although a lack of evidence

from fecal samples, postmortem inspections, and live chick observations suggested that

the events were infrequent. Handling and consumption rates suggest the potential for

considerable impacts of rat poison on nesting Sooty Terns. Thus care should be taken

when evaluating the risks posed to non-target species when seabirds are present. My

study also documents previously unreported environmental fluorescence, which may

increase the potential for false positive results in pre-eradication assessments of pellet

palatability, bait uptake rates, bait application methods, risks to non-target species, focal

species movement and behavior, and movement of toxins within the ecosystem based on

fluorescent biomarker studies intended to guide subsequent eradication protocols. I

recommend that future studies begin with an evaluation of environmentally-based fluorescence prior to formal biomarker studies.

Key Words: *biomarker, eradication, fluorescence, non-target species, rodenticide, Sooty Tern*

INTRODUCTION

Invasive species led to extinctions, extirpations, and population declines of numerous endemic species through predation, competition, and disease (Atkinson 1985; King 1985; Wilcove et al. 1998; Courchamp et al. 2003; Jones et al. 2008). Non-native species, particularly mammals, and habitat loss are primary threats to seabirds (King 1985; Wilcove et al. 1998; Towns et al. 2006; Howald et al. 2007; Jones et al. 2008). Rodents are the most pervasive of non-native mammals. Rats (*Rattus* spp.) have been observed on 80-90% of oceanic islands (Atkinson 1985; Towns et al. 2006; Caut et al. 2008). However, the immediate effects of rat invasions have been rarely documented (*but see* Thorsen et al. 2000) and many went undetected until species or ecosystems responded.

Rat eradications have been used as a conservation tool for more than two decades, during which projects were aimed at progressively larger islandscapes (Thomas and Taylor 2002; Clout and Russell 2006; Howald et al. 2007). Acute rodenticides and anticoagulant baits have proven effective at eliminating rats. Of these, brodifacoum, a second generation anticoagulant which is highly toxic to birds and mammals, has been the most widely-applied poison (Eason and Spurr 1995; Eason et al. 2002; Howald et al. 2007). The poisons have been deployed through bait stations, by hand-broadcast, by aerial broadcast, or with a combination of techniques (Thomas and Taylor 2002; Courchamp et al. 2003; Howald et al. 2007). The synthesis of poison type, deployment

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technique, and application timing influences susceptibility of both target and non-target species (Savarie et al. 1992).

Pre-eradication assessments of pellet palatability, bait uptake rates, bait application methods, focal species movement and behavior, and movement of toxins within the ecosystem are critical to predicting success of eradication efforts as well as determining the impacts of poison bait on non-target species (Courchamp et al. 2002; Clout and Russell 2006; Rodríguez et al. 2006). Biomarker studies are a type of pre-eradication assessment that employs non-toxic pellets containing a dye that fluoresces under ultraviolet (UV) light. The dye is most visible at night or in darkened conditions. Captured individuals, dead organisms, or fecal samples are examined under UV light to visually detect pellet consumption. The abundance and location of the fluorescence can be appraised to address questions such as uptake frequency, animal movement, and dosage levels (Savarie et al. 1992; Eason et al. 2002).

Pest control and eradication programs have documented primary (direct consumption) and secondary (consuming a poisoned individual) poisoning of non-target species (Eason and Spurr 1995; Eason et al. 2002). Experimental studies focused on predatory birds, scavengers, and non-target mammals (Eason et al. 2002). However, despite more than 284 insular eradication efforts (Howald et al. 2007), to my knowledge the risk of non-target poisoning in seabirds has rarely been examined. Published information on mortality of non-target seabirds is almost entirely limited to opportunistic events during eradication projects (e.g. Eason and Spurr 1995; Eason et al. 2002). The exception observed three species (*Larus heermanni, Sula leucogaster brewsteri, S. nebouxii*) interacting with 10 pieces of placebo bait placed inside 50 m^2 plots for 30–60

minutes; no consumption was recorded (Samaniego-Herrera et al. 2009). The lack of risk assessment information may relate to seabird absence during eradications or an assumption that seabirds would not interact with bait due to their preferred prey. However, behaviors such as manipulating inedible objects and dropped food items (e.g. Sooty Terns, Feare 1975; brown boobies *Sula leucogaster*, Nelson 1978) may cause seabirds to interact with poison bait pellets, increasing the risk of ingestion. This is a concern because rodenticide use in active seabird colonies has been occasionally proposed when birds are present year-round (U. S. Air Force 2007; U.S. Fish and Wildlife Service 2007).

This study provides an evaluation of the risk of rodenticide bait to seabirds. I used direct observations and camera-based monitoring to study bird consumption of placebo fluorescent biomarker bait to assess the potential risk of rodenticide bait to Sooty Terns on Wake Atoll Complex. During the onset of this study, previously unreported green and red environmentally-based fluorescence was observed and methods were adjusted to account for potential false positives.

MATERIALS AND METHODS

Study site and species

I assessed the risk of rodenticide bait to nesting Sooty Terns on Wake Atoll Complex, located in the central Pacific Ocean (19º18'55" N, 166º38'21" E). The atoll complex is comprised of three islets, including Wilkes, Wake, and Peale, with a total area of 739 hectares. Rat eradication has been planned to eliminate two invasive rodents, *R. exulans* and *R. tanezumi*, likely in 2012 (U. S. Air Force 2008; per. com. Helm 2010). The study

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colony was located in a field on Wilkes Islet. The habitat consisted of varying

combinations of bare ground, grass, *Ipomoea* spp., and puncture vine (*Tribulus*

terrestris).

Sooty Terns were selected as the focal species. The species is an abundant

pantropical species that nests on many islands with introduced rodents (Woodward 1972;

Feare 1976; Harrison 1990; Ratcliffe et al. 1999; Schreiber et al. 2002). Sooty Terns nest

in large colonies with ample population sizes that are suitable for a control-treatment

design. The terns also exhibit behaviors, such as moving dropped food items and

inedible objects (Feare 1975; L. S. pers. obs. 2008, 2009), which may increase their risk

of consuming bait. Moreover, although breeding periodicity on Wake Atoll Complex is

unclear, Sooty Terns nest subannually (breeding cycles are less than 12 months) and thus

may be present during the eradication process.

Study design

Six 10 m x 10 m plots were marked in areas with newly hatched Sooty Tern chicks. Plot

locations were selected to be separated by the greatest distances possible, and all were at

least 20 m apart. Chicks frequently travel from their hatch site to nearby shade but longer

movements are limited by aggressive adult behaviors. Consequently, hatch year

individuals were unlikely to travel between plots. The plots were randomly assigned as

three treatment and three control sites. Control plots did not receive biomarker bait (Bell

Laboratories, Inc., Madison, WI). Treatment plots and a 5 m surrounding buffer received

two applications of non-toxic biomarker pellets, which were applied nine days apart.

Pellets were applied on 28 April 2010 and 7 May 2010 using hand broadcast protocols

(U. S. Air Force 2007). Eighteen kg/ha of biomarker bait was dispersed within the

treatment plots during the first application, followed by 9 kg/ha during the second

application. Biomarker pellets were formulated to resemble conservation brodifacoum

rodenticide. The pellets fluoresced green under UV light and lacked poisonous

ingredients. Dead chicks are common in Sooty Tern colonies, and all plots were cleared

of dead chicks prior to initial treatment.

Camera-based observations

I used camera-based observations to assess the potential risk of rodenticide to adults and

hatch year individuals. Within each of the three treatment plots, I placed a Reconyx

PC900 camera (Reconyx, Inc., Holmen, WI). Each camera was mounted on a 60 cm

tripod at a 45° angle aimed at four bait presentation plates constructed of 21 cm x 21 cm

off-white cloths with raised sides. Each presentation plate was stocked with four

biomarker pellets, for a total of 16 pellets per camera station. Photographs were recorded

at 10 second intervals for three days, or until camera batteries failed. After downloading

photographs, camera stations were redeployed to previously unphotographed locations

within the plot on 28 April, 2 May, 4 May, 7 May, 10 May, and 13 May 2010.

I examined a subsample of the 10 800 photographs collected during my study to

identify the likelihood of pellet consumption by adults and hatch year Sooty Terns. I

used a random number generator to select 10 10-minute observation periods from each 3-

day survey interval from 28 April 2010 through 17 May 2010. In total, I identified 60

10-minute observation periods from each of the three treatment plots. I retrieved

photographs recorded during those observation periods and scrutinized each for signs of

pellet consumption by Sooty Terns. I recorded consumption if a bait pellet disappeared

after a Sooty Tern was previously observed handling pellets with their bill before the

pellet disappeared from the presentation plate. Pellets that disappeared in the absences of

a Sooty Tern were insufficient to determine bait consumption by Sooty Terns as rats

could have retrieved the bait in the 10-second interval between photographs. I also noted

when an individual pecked at, moved or picked-up a pellet.

I also scanned the entire set of 449 804 photographs. Each set of photographs was

converted to video (10-15 frames per second) and then videos were quickly viewed for

pellet movement. When pellet movement was identified, I examined the photographs

immediately prior to and after movement to identify the cause. When the cause of pellet

movement could be determined, it was classified as one of the following: (1) adult

consumed a pellet, which was define as an individual seen with a pellet in its bill or

pecking at a pellet that disappeared in subsequent photographs; (2) chick consumed a

pellet; (3) chick moved or picked-up a pellet; (4) adult moved or picked-up a pellet; (5)

adult pecked at a pellet; and (6) chick pecked at a pellet. Pecking behavior may be

underestimated in my scans of the entire set photographs of 449 804 as pecking may not

produce noticeable pellet movement and hence reduced detectability. Chicks and adults

frequently step on, kick, and move rocks and pellets and thus not all pellet disappearances

should be considered as consumption events.

Fecal samples

I collected fecal samples from Sooty Terns as a second means of assessing bait

consumption by both adult and hatch year birds. I deployed eight 14 cm x 26 cm

collection plates composed of off-white fabric (henceforth termed drop cloths) within

each plot. Drop cloths were placed after an observer walked seven steps into a plot. The

observer entered plots at night with minimal light and thus the destination for each drop

cloth was concealed at the onset of the seven steps. Drop clothes were retrieved at six

survey intervals (total survey period was 19 days; Table 1). Both treatment and control

plots were surveyed every third night (henceforth referred to as a survey interval) from 28

April 2010 through 17 May 2010. If I failed to find a drop cloth during the next survey

interval, that sample was excluded from the analysis. New drop clothes were distributed

using the same protocol. Each drop cloth ($n = 241$) was examined under UV light to

determine the presence, absence, and color of UV fluorescence in feces. I tested for

differences in the proportion of drop cloths upon which green fluorescence was detected

between treatment and control plots applying a two-tailed Fisher's exact test (Fisher

1958).

Live chick inspections

I captured and examined the first 20 hatch year Sooty Tern chicks encountered within

each plot during each of six survey intervals. Rain prevented the completion of live chick

inspections in two plots on 13 May thus reducing the sample size ($n = 689$ chicks

examined). Cloaca, feet, ventral feathers, and bill of each live chick were examined

under UV light for fluorescence traces before each chick was released. Fluorescence

found on the cloaca and bill indicated likely bait consumption, whereas fluorescence on

the feet or ventral feathers implied exposure to bait. The rate of consumption and

exposure (proportion of individuals upon which fluorescence was detected) was

compared between treatment and control plots using a two-tailed Fisher's exact test

(Fisher 1958).

Postmortem inspections

I inspected all dead chicks retrieved from each plot during each survey interval ($n = 293$ chicks collected from six plots). I used a UV light to detect fluorescent reflectivity on the inspected bill, mouth lining, feet, cloaca, body cavity, stomach lining, and stomach contents of dead chicks. The entire external surface of desiccated individuals was inspected because dissection was not possible as the body cavity of the dried, flattened corpses were impossible to open. Individuals with liquefied organs were removed from analysis. Presence or absence of fluorescence was recorded for each individual. Sample size for each plot ranged between one and 59 individuals with an average of nine samples per survey interval. The proportion of individuals with green fluorescence was compared between treatment and control plots using a two-tailed Fisher's exact test (Fisher 1958). Throughout the study I considered differences significant at $\alpha < 0.05$.

RESULTS

Adult and hatch year Sooty Terns moved, pecked at, and rarely consumed biomarker bait pellets. I identified one occurrence of terns moving a pellet on a bait presentation plate within the scrutinized subsample (Fig. 1). Within the entire collection of 449 804 photographs, I observed one occasion when a Sooty Tern chick consumed a biomarker bait pellet, 46 pellet movement events, and 25 occasions in which individuals pecked at a pellet (Fig. 1; Table 2).

I observed fluorescence that appeared to be derived from sources other than my biomarker bait at the onset of this investigation. I observed red and green fluorescence during live chick inspections and in fecal samples in both treatment and control plots.

Biomarker fluorescence used in my study reflected green which was similar to the environmentally-based fluorescence found within the ecosystem. I further believe that green fluorescence detected in control plots, and a similar proportion observed in treatment plots, may have been introduced to the colony in marine food items brought by adult birds. I verified the presence of environmentally-based fluorescence by capturing 30 hatch year individuals at night more than 95 m from the nearest study plot to insure that chick movement between treated plots and the test area was excluded from my assessment. Chicks were arbitrarily selected from within a 4 m wide transect as an observer walked through the colony. I examined the cloaca, feet, ventral feathers, and bill of each live chick under UV light for red and green fluorescence traces before the chick was released. The presence of green fluorescence more than 95 m from the study plots was observed in three of 30 individuals, and red fluorescence was documented in one of 30 individuals outside my plots. These results provided strong evidence of an alternate source of fluorescence and thus indicated that some fluorescence was likely to occur in both treatment and control plots and may not indicate bait uptake. I assumed that sources and detectability of environmentally-based fluorescence were similar among plots.

Biomarker pellet consumption was not evident in fecal samples and live chick inspections. Green fluorescence was absent from the fecal samples on the 241 drop clothes examined. Green fluorescence was encountered on 61 of 689 live Sooty Tern chicks in both treatment and control plots. A single chick was observed with a small piece of biomarker bait adhered to its ventral feathers, so there was conclusive evidence of exposure to biomarker bait. Placement of the fluorescence was primarily on the

cloacae, implying consumption of fluorescent food items. Green fluorescence was documented on the cloacas of 30 chicks in treatment plots. However, 30 chicks in control plots also had green fluorescence on their cloacas, and I did not detect significant differences in the proportions of individuals with green fluorescence in treatment and control plots ($P = 0.894$; Table 1, Fig. 2). Thus I believe that a majority of detections were likely caused by environmentally-based fluorescence rather than from chick consumption of biomarker bait.

Postmortem inspections did not indicate bait consumption by Sooty Terns. A total of 293 dead chicks were included in the analysis, yielding six individuals with green fluorescence, three from control plots and three from treatment plots. The proportions of dead individuals with green fluorescence was not significantly different among treatment and control plots ($P = 0.686$; Table 1, Fig. 2).

DISCUSSION

I observed Sooty Tern chicks on Wake Atoll Complex contacting and rarely consuming biomarker bait. One chick had a small piece of biomarker bait attached to its ventral feathers, which likely occurred when the chick laid on a moist pellet. Traces of dry biomarker were not detected on the other live chicks that were hand inspected, despite photographic records of birds laying and standing on biomarker bait. In other photographs, chicks were seen handling bait. Consumption of pellets was supported by a single camera-based series of photos. Conversely, pellet consumption was not apparent in fecal samples, postmortem inspections, or live chick observations. Whether the exposure to bait seen in my study is sufficient to cause harm, including lethal and sub-

lethal effects, is unclear as lethal doses differ among species (e.g. Eason and Spurr 1995). The acute toxicity of brodifacoum poison in birds varies between an LD50 of < 1 mg/kg and >20 mg/kg and ranges between 1% and 100% of body weight based on LD50 values (Eason and Spurr 1995).

My results indicated a risk of poison bait exposure and consumption by Sooty Terns during rat eradication. If I consider that photographs were recorded every 10 seconds and that bait presentation plates were $441cm^2$ (four plates in each photograph), I can extrapolate my observations of bait handling to the entire 2010 Sooty Tern colony (52 000 m^2). My extrapolations for individuals moving pellets were comparable between the scan of the entire set of photographs and the subsample of photographs surveyed (220 831-235 828, respectively). Although pecking behavior was absent from the subsample survey, data from the entire photographic record suggests pecking might occur 147,221 times per day throughout the colony. I also recorded one bait consumption event when the entire set of 449 804 photographs was scanned and thus I might expect 5 662 bait consumption events for each day through the colony. Extrapolating from a small sample area is likely biased as I cannot account for variations in behavior, nest density, bait density, or uptake rate that would be expected in an actual eradication deployment. Pellet density on my presentation plates was higher than most eradication application levels, which upwardly biased the estimates. Nonetheless, my calculations suggest the potential for considerable impacts of rat poison on nesting Sooty Terns.

My observations of red and green fluorescence throughout the colony indicated a source of fluorescence that was environmentally based. I suspect that the source was marine based and that the fluorescing items were brought to chicks by parents as prey

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items or marine bacteria (Nealson et al. 1984). Sooty Terns primarily forage on small

fish and squid, some of which have been documented to luminesce (Ashmole and

Ashmole 1967; Feare 1976; Harrison et al. 1983; Herring 1983; Nealson et al. 1984;

Hensley and Hensley 1995). Although naturally present, I expected higher proportions of

green fluorescence in treatment plots if biomarker bait was ingested, assuming that

sources and detectability of marine-based fluorescence are similar among plots. Since I

did not detect greater rates of green fluorescence in treatment plots, there is no evidence

from fecal samples, postmortem inspections, and live chick observations to suggest birds

consumed biomarker bait.

   Although my photographic analysis documented the potential for considerable

impacts of rat poison on nesting Sooty Terns, significant ingestion of biomarker bait was

not detected in fecal samples, postmortem inspections, and live chick observations. The

conflicting results may be attributed to extrapolating behaviors from the small sampling

area covered by the photographic dataset to a larger area and detectability of fluorescence

within the fecal samples, postmortem inspections, and live chick observations.

Consumption of pellets was rare within the photographic dataset, but should have been

sufficient to detect differences within the fecal samples, postmortem inspections, and live

chick observations if my extrapolations to a larger area were correct. Thus higher pellet

densities and variations in behavior, nest density, bait density, or uptake rate may

upwardly bias my estimates and pellet consumption may occur infrequently over a larger

area. Reported death tolls of seabirds on islands in which eradication programs have

taken place are relatively low (i.e. The Ornithological Council 2010); however, mortality

may be underestimated as birds may die at sea and surveys of bird mortalities may be

delayed in some case. Behaviors such as moving, pecking at, or physically contacting

pellets, which were more common than ingestion, may not be detectable in fecal samples,

postmortem inspections, and live chick observations if an insufficient amount of

biomarker is consumed. Similarly, ingesting small amounts of poison may or may not

cause harm to Sooty Terns. Additionally, if environmental fluorescence is not uniformly

distributed within the colony, false positives could potentially obscure significant results

within fecal samples, postmortem inspections, and live chick observations.

My study demonstrates that environmentally-based fluorescence has the potential

to bias bait consumption rates predicted by biomarker trials, and to my knowledge, the

presence of environmentally-based fluorescence on islands was not previously

considered. Failed attempts at eradication occurred on 35 islands (Lorvelec and Pascal

2005; Rodriguez et al. 2006; Howald et al. 2007). Eradication failures were attributed to

insufficient planning, the lack of pre-eradication studies, the abundance of alternative

food sources for rodents, rat behavior, and incomplete eradication of rodent populations

or reinvasion by rats, as well as complications associated with bait consumption by non-

target species (Thomas and Taylor 2002; Lorvelec and Pascal 2005; Clout and Russell

2006; Rodriguez et al. 2006; Abdelkrim et al. 2007). In addition, misleading results due

to false positives associated with environmentally-based fluorescence within pre-

eradication trials may be one factor resulting in the 10% to 20.6% eradication failure rate

reported in literature (Clout and Russell 2006; Abdelkrim et al. 2007; Howald et al.

2007). Both the environmentally-based fluorescence and some biomarker dyes, such as

the one used in this study, glow green under UV light (Savarie et al. 1992). Therefore,

without testing the prevalence of environmentally-based fluorescence, previous studies

may have underestimated dosage level of poison needed to eradicate the target species whereas palatability of bait may have been overestimated. For example, if a study determined a dosage level without considering environmental fluorescence, the dosage level may limit the availability of bait to rodents thereby resulting in eradication failure. Additionally, environmentally-based fluorescence may interfere with environmental assessments intended to track toxin movement within the ecosystem. I recommend that future studies begin with an evaluation of environmentally-based fluorescence prior to formal biomarker studies.

In summary, though fecal samples, postmortem inspections, and live chick observations did not indicate pellet ingestion, camera-based data documented bait exposure and consumption. Thus, care should be taken when evaluating the risks posed to non-target species when seabirds are present. In addition, pre-eradication studies should include evaluations of environmentally-based fluorescence prior to formal biomarker studies as false positives could contribute to current eradication failure rates.

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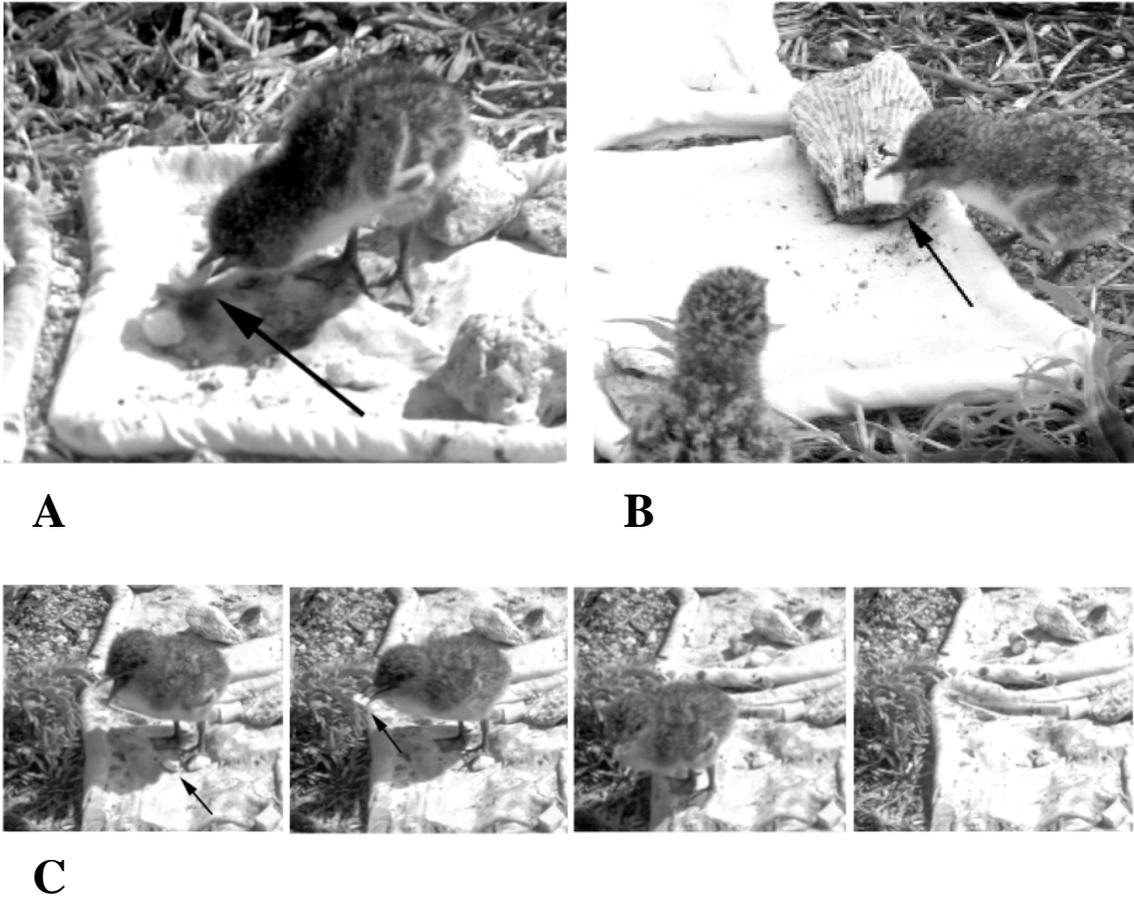
Figure 1. Photographic series illustrating Sooty Tern chicks physically contacting (A and B) and consuming (C) biomarker bait on Wake Island in 2010. (A and B) Chick handled the pellet, indicated by the arrow, but then dropped the pellet. (C) The pellet indicated by the arrows was grasped and then ingested, which was demonstrated in the subsequent photographs. Note that bait appears fluorescent green in actual color photographs, which enhanced my ability to detect handling and consumption.
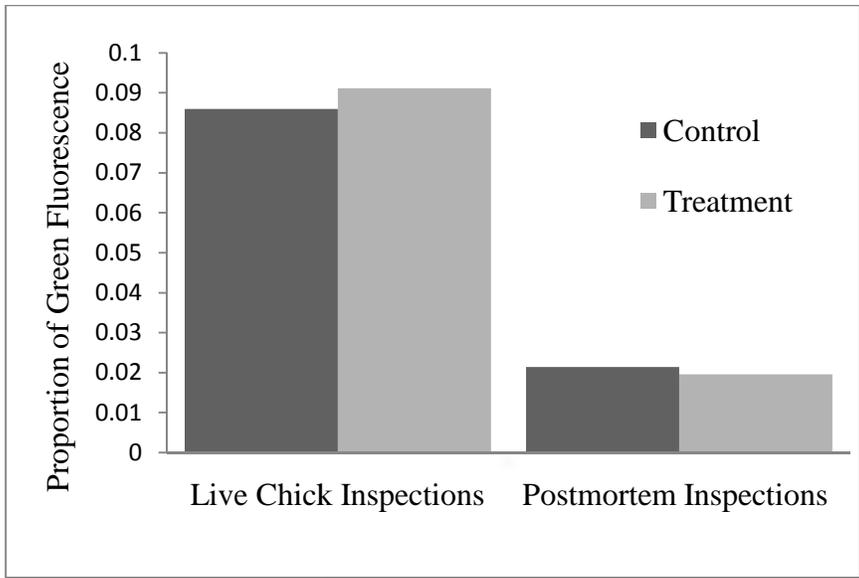
Figure 2. Proportion of green fluorescence found in postmortem inspections, and live chick observations surveys in treatment and control plots.

TABLES

Table 1. Survey results for postmortem and live chick inspections of Sooty Terns on
Wake Island in 2010 during a biomarker bait trial. Specimens with green fluorescence
indicated biomarker bait contact or consumption, or accumulation of fluorescing material
from environmental sources.

Survey Date	**Postmortem [n (samples) / % with Green Fluorescence]**		**Live Chick [n (samples) / % with Green Fluorescence]**	
	Control	Treatment	Control	Treatment
5/2/2010	--	--	60 / 0.0	60 / 0.0
5/4/2010	32 / 0.0	64 / 0.0	60 / 13.3	60 / 11.6
5/7/2010	40 / 7.5	37 / 2.7	60 / 18.3	60 / 25.0
5/10/2010	27 / 0.0	28 / 0.0	60 / 5.0	60 / 3.3
5/13/2020*	11 / 0.0	13 / 0.0	49 / 6.1	40 /15.0
5/17/2010	30 / 0.0	11 / 18.1	60 / 8.3	60 / 1.7

* Two plots collected during the day on 5/15/2010. Surveys were delayed due to

prolonged precipitation.

CHAPTER 4 - SUMMARY CONCLUSIONS

Seabirds respond to alterations in lower trophic levels and physical changes in the marine environment, and thus threats to seabirds reflect those of marine ecosystems and islandscapes in which they inhabit. Results from investigations of the ecology of widely distributed marine species can be used to understand oceanic ecosystems and inform management and conservation programs. I choose to focus on Sooty Terns, a pantropical species that is threatened by non-native species, habitat alteration, and global climate change. I undertook two projects aimed at improving conservation efforts for Sooty Terns.

My first study investigated when Sooty Tern chicks were most vulnerable to mortality. I found that chick survival was positively associated with age. My results indicate an average nestling survival rate from hatch to fledge at 56 days post-hatch of 0.056 (range within locations in the colony 0.014 – 0.121). I also assessed the influence of daily maximum temperature, precipitation, rat predation, and vegetation density on Sooty Tern chick survival. The best-fitting model included an additive relationship of daily maximum temperature, vegetation density, and body condition. Daily maximum temperature and vegetation density were negatively associated with chick survival, whereas body condition displayed a positive relationship with survival. Sooty Tern conservation should include habitat management. Sooty Tern chick survival was inversely related to vegetation density. Therefore reducing vegetation density may increase Sooty Tern nest survival, and thus abundance.

Management and conservation plans should consider the potential impacts of climate change on Sooty Terns, especially in areas with predicted increased temperatures. My study indicated a threat of overheating, as daily maximum temperatures were inversely associated with chick survival. Temperatures are expected to rise in the tropical and subtropical oceans in which Sooty Terns breed (IPCC 2007), and therefore climate change will likely affect Sooty Tern populations. Climate predictions for the central Pacific Ocean in the area of Wake Atoll Complex predict a mean surface air temperature rise of 0.5 - 1.0°C from 2011 to 2030 and 2.5 - 3°C rise in temperatures by 2099 (Figure 10.8 in IPCC 2007) which may reduced chick survival by up to 93.8%. Long-term management and conservation plans may be able to incorporate vegetation management to mitigate expected declines in chick survival associate with higher temperatures.

Rat predation is also widely recognized as a major threat to seabird populations (King 1985; Wilcove et al. 1998; Towns et al. 2006; Howald et al. 2007; Jones et al. 2008). Consequently, rat eradications have been used as a conservation tool for more than two decades (Thomas and Taylor 2002; Clout and Russell 2006; Howald et al. 2007) with purported benefits to ecosystems and seabird conservation (e.g. Allen et al. 1994, Campbell and Atkinson 2002, Smith et al. 2006, Towns et al. 2006). However, eradication efforts also pose risks to non-target species including seabirds. Threats to seabirds from rodenticide bait distribution have rarely been examined despite hundreds of insular eradication efforts (*but see* Samaniego-Herrera et al. 2009). I studied rodenticide bait exposure and consumption in Sooty Terns. Behaviors such as moving, pecking at, or physically contacting pellets were more common than ingestion. Whether exposure to bait was sufficient to cause lethal and sub-lethal effects in the birds was unclear because

lethal doses differ among species (e.g. Eason and Spurr 1995). The acute toxicity of brodifacoum poison in birds varies between an LD50 of < 1 mg/kg and >20 mg/kg and ranges between 1% and 100% of body weight based on LD50 values (Eason and Spurr 1995). However, extrapolations of handling and consumption rates to the entire colony suggest the potential for considerable impacts of rat poison on nesting Sooty Terns. Thus care should be taken to evaluate the risks posed to non-target species when seabirds are present.

My study also documents previously unreported environmental fluorescence and demonstrated the potential to bias biomarker trials intended to guide subsequent eradication protocols. Eradication projects are costly and time-intensive (e.g. Howald et al. 2007; Wilcox and Donlan 2007) and predicting the success of eradication relies on critical information obtained through pre-eradication assessments of pellet palatability, bait uptake rates, bait application methods, focal species movement and behavior, and movement of toxins within the ecosystem (Courchamp et al. 2002; Clout and Russell 2006; Rodríguez et al. 2006). Thus, without testing the prevalence of environmentally-based fluorescence, previous studies may have underestimated dosage level of poison needed to eradicate the target species whereas palatability of bait may have been overestimated. Additionally, environmentally-based fluorescence may interfere with environmental assessments intended to track toxin movement within the ecosystem. Thus misleading pre-eradication results may be one factor contributing to current eradication failure rates. I recommend that future studies begin with an evaluation of environmentally-based fluorescence prior to formal biomarker studies.

The results of this study have specific implications for Sooty Terns conservation and management as well as broader ramifications for seabirds and islandscape. Specifically, Sooty Tern conservation and management may benefit by using survival models with fine temporal resolution. My studies also highlight mechanisms potentially causing Sooty Tern population declines. My models indicated that both habitat management and climate change can impact Sooty Terns chick survival. Management and conservation plans should consider the potential impacts of climate change on Sooty Terns. More broadly, assumptions about seabird-rodenticide interactions should be revisited. Planners should study species-specific risks associated with rodenticide and toxicity levels of the proposed pesticide. Environmentally-based fluorescence should also be examined prior to pre-eradication trial. Although environmentally-based fluorescence may be specific to the locality of this study, eradications are costly, time-intensive and rarely receive funds for a second eradication attempt. A relatively small investment in fluorescence studies may provide substantial returns in successful eradications based on unbiased assessments of non-target species mortality, pellet palatability, bait uptake rates, bait application methods, focal species movement and behavior, and movement of toxins within the ecosystem.

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