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Chronic lack of breeding by Galapagos blue-footed boobies and associated population decline

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Introduction

The abundance of seabirds across the vast Pacific Ocean basin is thought to have declined by at least 99% over the past 3000 years, coincident with the spread of Polynesian humans (Steadman, 2006). Human settlements on islands lead to habitat loss, hunting, and indirect effects of predatory and other invasive animals accompanying humans (Szabo *et al.*, 2012), and these effects are thought to explain the local extinction of most seabird species on colonized islands (Steadman, 2006). The seabird populations of the Galapagos Islands, in the far east of the basin and distant from source populations of Polynesians, depart from this pattern. Paleontological data give no evidence of permanent human habitation before approximately 200 years ago (Latorre, 1997), and also no evidence of local extinction of seabird species (Steadman, 1986; Jiménez-Uzcátegui *et al.*, 2006). However, some species show clear evidence of recent anthropogenic effects that reduced population size (Vargas *et al.*, 2005; Jiménez-Uzcátegui *et al.*, 2006; Anderson *et al.*, 2008), while other species are too poorly studied to allow similar evaluations. Evaluation of possible anthropogenic effects on observed population declines must be a conservation priority.

Blue-footed boobies (*Sula nebouxii*) breed on Galapagos and on islands and headlands on the west coast of South and Central America, and Mexico. The demography and population biology of the Galapagos subspecies (*S. n. excisa*) is poorly known. However, serial data from two former breeding sites in Galapagos (Daphne Major and Punta Cevallos [Española]) indicate that an abrupt change in breeding activity occurred in approximately 1997, from irregular but frequent breeding to essentially none (Figure 1). This pattern is consistent with anecdotal observations in recent years of long-term scientists and tour guides that adult birds are seen less frequently and breeding sites are seldom occupied (DJ Anderson, unpub. data). If chronically poor breeding affects the entire subspecies, then it should be reflected in a reduced population size. Population size has been estimated only once, by Nelson in the 1960s. He concluded that "the total Galapagos population must exceed 10,000 pairs and could be substantially more" (Nelson, 1978).

The goals of this study were: 1) evaluate if the poor breeding observed since 1997 at two colonies is archipelago-wide; 2) determine the cause, and 3) estimate

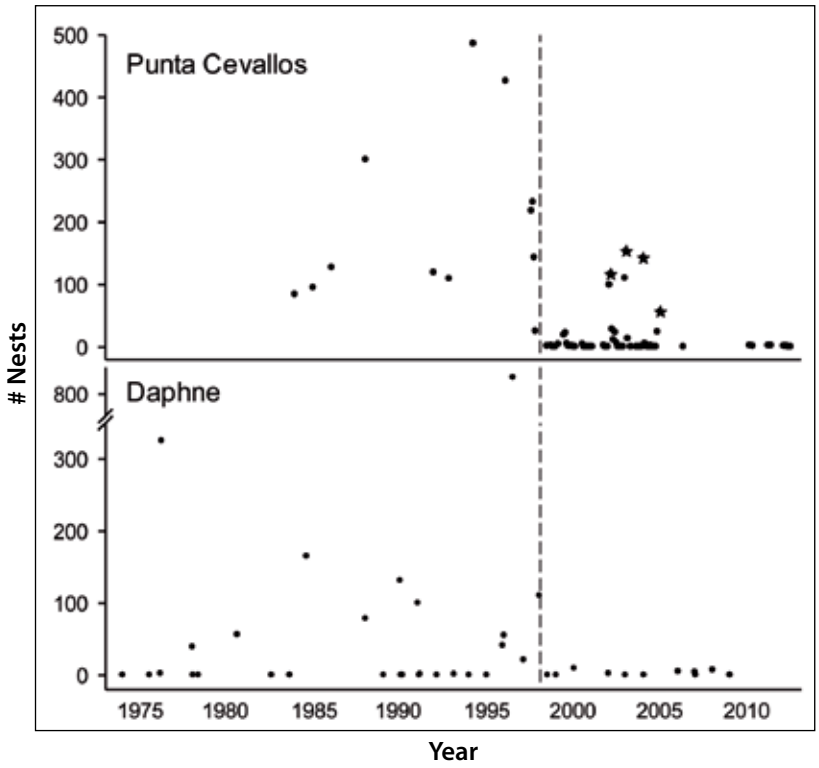

Figure 1. Numbers of active nests of blue-footed boobies at Punta Cevallos, Española (D. J. Anderson, unpub. data) and Daphne Major (P. R. Grant and B. R. Grant, unpub. data). Vertical line indicates March 1, 1997, middle of the 1997-98 ENSO event, and roughly the timing of declining sardine abundance in the Peruvian upwelling. Stars indicate the peak of a rapid increase in number of nests followed by a mass breeding failure in the subsequent 4 weeks.

the current size of the Galapagos blue-footed booby population. This paper presents the principal results of the study; for complete details, see Anchundia *et al.* (2014).

Methods

From May 2011 to June 2013, we monitored breeding at three- to five-month intervals at four of the six historically largest breeding colonies of blue-footed boobies (Daphne Major, Cabo Douglas [Fernandina], Punta Vicente Roca [Isabela], and North Seymour), and one additional recently established colony (Playa de los Perros [Santa Cruz]). A sixth regularly large and active colony, Punta Suárez (Española), and two others (Punta Pitt [San Cristobal] and Punta Cormorant [Floreana]; Figure 2) were visited less frequently (three or four times each) than were focal colonies. A seventh historically large colony, at Punta Cevallos (Española), was known to be essentially unattended through our group's other research activities there. An additional, apparently newly established, non-focal colony on Baltra was discovered in 2012 and thereafter was included as a non-focal colony. Diet was documented from regurgitation samples during visits to breeding colonies.

To estimate population size we made two surveys of the entire coastline of the islands south of the equator, including all of Isabela (1100 km of coastline of 14 islands and 20 islets), which encompasses virtually all of the historical (Nelson, 1978; Harris, 1982) and current (DJ Anderson, pers. obs.) breeding activity of the species. In the first survey, we made daytime counts in piecemeal fashion, covering the entire survey range in a boat at 1 m/s between June 3 and August 7, 2011, with a single observer using a binocular 20-100 m from the coast. In the second survey, 1-3 June 2012, five separate pairs of observers used a dependent double observer protocol (Nichols *et al.*, 2000). Over the three-day period the entire survey range was covered, one observer pair per each section of coastline.

Results

Breeding

Breeding activity was consistently low. All monitored colonies contained <15% of the historical maximum of breeding pairs on most visits. Summing across all monitored sites, the largest number of simultaneous nests observed (349) represents 698 breeding birds, only 10.9% of the population size estimate of 6423 adults (see below). Three previously unknown breeding sites were identified during the study: on Baltra with approximately 49 nesting pairs in 2012 and 94 nesting pairs in 2013; on the south coast of Fernandina west of Punta Mangle, with approximately 75 adults present and an unknown number

of nests; and on the south coast of Isabela (Los Tuneles) with nine nesting pairs in 2013. The formerly large colony at Punta Cevallos (489 nests in 1994; Townsend *et al.*, 2002) was not monitored as part of this study, but was checked frequently as part of our ongoing research there; we never observed more than three nests there during this study.

Most clutches failed without producing a nestling. On visits after one in which nests with eggs were recorded, few or no nestlings or fledglings (either living or dead) were found, although incubating adults were sometimes present. In the focal colonies in 2011, a total of 26 fledglings were observed; in 2012, 59 offspring fledged. December and January were the only months in the three-year study in which we observed large nestlings and fledglings, with the exception of the newly established Baltra colony, in which 24 fledglings were present in August 2012.

Population size

In the 2011 coastal survey, 7379 blue-footed boobies were counted, of which two (0.03% of the total) were in juvenile plumage. That survey was conducted over an 11 week period by a single observer, with significant potential for missing or double-counting individuals. In the 2012 coastal survey, detection probabilities were high but varied by island and stretch of coastline. Model selection analysis yielded an estimate of 6423 birds (95% confidence interval = 6420-6431) for the population size of the entire Archipelago. These estimates apply to the portion of the population visible during daylight from boats within 100 m of the coast, and exclude birds away from the coast. Four lines of evidence indicate that few birds were outside the visual range of observers on the survey boats: 1) birds with GPS tags spent most of their foraging time within 200 m of an island's coast, well within visual range; 2) during boat travel between islands during the 2012 survey blue-footed boobies were sighted at a rate of only 2 birds/30 min compared to an average of 48 birds/30 min on the coast; 3) ~85% of birds sighted during the 2012 survey were resting on land and not on the move; and 4) >90% of the birds seen flying during the 2012 survey were moving parallel to the coast, rather than to or from the open ocean.

Diet

Sardines and herrings (Family Clupeidae) were the most common item in the samples, representing 80.2% of all items and 50.4% of the total weight. The fork length of the fish ranged from 3-35 cm, with a mean of 6.8 cm (SD = 3.2).

The blue-footed booby colonies visited fell into three clusters based on oceanographic habitat: the western colonies of Fernandina and Punta Vicente Roca, adjacent to the productive upwelling of the Equatorial Countercurrent with much lower sea surface temperature (SST) than elsewhere in the archipelago (Ruiz & Wolf, 2011); the central colonies of Daphne Major, North Seymour, Baltra, and Santa Cruz, adjacent to a complex merging of currents and a mosaic of SST and productivity (Witman *et al.*, 2010); and the southeastern colonies on San Cristóbal, Española, and Floreana, with less complex and less productive marine habitat. The diet composition in these regions varied, with sardines/herrings much more common and occurring more regularly in the central cluster, particularly in 2012. Sardines and herrings were 68% of the prey items in the central colonies, but 28 and 29% of those in the western and southeastern colonies, respectively.

Predicting breeding attempts

Model selection analysis indicated that breeding activity by blue-footed boobies varied by month (breeding was rare in December) and by the probability of regurgitating during diet sampling (breeding attempts were associated with more birds having food during diet sampling). Variation between years was unimportant in our modelling.

Discussion

Our results indicate that Galapagos blue-footed boobies attempted to breed very little between August 2011 and June 2013. During this period no more than 10.9% of the adult population had an active nest at any one time, and only 134 fledglings were noted. During two comprehensive coastal surveys we recorded only 77 birds in juvenile plumage (maintained until age 2-3 years; Nelson, 1978) compared to an adult population estimated as 6423 birds. We sighted only two juveniles across the Archipelago between May and August 2011, indicating that essentially no successful breeding occurred in the previous two years. We discount the possibility of temporary emigration of juveniles, based on the distribution of juveniles at sea (Anchundia *et al.*, 2014) and the abundance of juveniles in both coastal areas and between islands before 1998 (DJ Anderson, pers. obs.). The simplest interpretation of these results is chronic poor breeding from 2009 to 2012. Noting the similar situation on Española and Daphne since 1997, this chronic breeding failure may span a total of 16 years. A comparison of the 1960s estimate with our new estimate indicates a trend of a population decline, with the current population approximately 33% of Nelson's (1978) estimate for the 1960s. Acknowledging significant uncertainty in the actual values, especially for the 1960s estimate, we conclude that the population has declined in size by at least 50% since the 1960s, and probably by more than 50%.

Poor breeding has contributed to the fall in blue-footed booby population size during our study, and data from Daphne and Española suggest that breeding has been poor and that adult deaths have exceeded recruitment after birth since 1997. A simple model of population

shrinkage is broadly in agreement. Assuming constant annual adult mortality of 0.10 (Oro *et al.*, 2010), an initial adult population size of 20,000, and a continuous series of years ending in 2012 with no successful breeding, the hypothetical chronic breeding failure would have begun in 2001, 11 years earlier (20,000 * 0.9011 = 6276); a larger starting population (as Nelson (1978) alluded to) would bring this date even closer to 1997, when we suggest that the breeding failure began. Since 1997 the formerly large and regularly active blue-footed booby colony at Punta Cevallos has been virtually vacant, and on Daphne Major few adults are found only in a small part of the main crater, while in the past both the main and side craters sometimes held up to 1600 blue-footed boobies. Now vegetation covers much of the past breeding site. Neither island has an introduced predator, and no evidence of disease has been noted among breeders or non-breeders at either site. Although these two colonies are in separate oceanographic habitat regions of the Archipelago, they exhibit similar breeding histories, suggesting the possibility that poor breeding has been archipelago-wide since 1997, in spite of spatial habitat variation. If so, then the age structure of the current population must be strongly biased toward elderly individuals; if the death rate of blue-footed boobies increases with age, as in Nazca boobies (Anderson & Apanius, 2003), and their reproduction declines as they age (Velando *et al.*, 2006), then the birth and death processes leading to smaller population size can be expected to accelerate in the future.

Two lines of evidence implicate diet in the low rate of birth. Considering long-term data from Punta Cevallos, blue-footed boobies foraged mostly on sardines, similar to Nazca boobies (Anderson, 1989). After 1997, sardines disappeared from the Nazca booby diet, but Nazca boobies continued breeding by switching to other prey (Anderson *et al.*, unpub. data). In contrast, blue-footed boobies abandoned this colony. Data from Galapagos sea lions (*Zalophus wollebaeki*) also suggest that sardines have become less available throughout the Archipelago; sea lions foraged mostly on sardines during the 1980s (Dellinger & Trillmich, 1999), but more recently (2008-09), sardines were completely absent from their diet (Páez-Rosas & Aurioles-Gamboa, 2010).

Diet samples from blue-footed boobies, taken during our study, suggest that the central archipelago currently has a more regular availability of sardines and their close relatives Galapagos herrings than the other regions; relatively more current breeding attempts have been observed within this region. This suggests that declines in both initiation and success of breeding may be tied to sardine/herring availability (Anchundia *et al.*, 2014).

In conclusion, our data indicate chronic poor breeding and a decline in population size of Galapagos blue-footed boobies, with circumstantial evidence implicating low availability of preferred prey since approximately 1997. Since 1997 the food base has been sufficient for adults to exist but not to reproduce.

If breeding has been poor since the late 1990s, as we suspect, the age structure of Galapagos blue-footed boobies is probably biased strongly toward older individuals. Reduced survival and reproduction with aging in blue-footed boobies (Velando *et al.*, 2006; Torres *et al.*, 2011) can be expected to accelerate this iconic and genetically distinct population's decline via poor breeding ability and lower annual survival associated with old age, with important implications for biodiversity and local ecotourism.

Recommendations

Based on the findings of this study, we recommend the following:

1. Continue the archipelago-wide counts, using the same methods (Anchundia *et al.*, 2014), no less frequently than every two years. The population size has probably declined to ~30% of its size in the 1970s and documenting the continuing population trend is critical.

2. Formal studies of the population biology of clupeid fish in Galapagos are urgently needed, including any potential anthropogenic effects. These fish, especially the sardine *Sardinops sagax*, are important elements of the diet of blue-footed and Nazca boobies, sea lions, and possibly other predators in Galapagos. Our results indicate that clupeids have declined dramatically in availability since 1997, possibly from natural causes (Anchundia *et al.*, 2014).

3. Continue carrying out surveys at the 10 breeding colonies, for as long as breeding continues to be poor. We visited each colony four times per year. These visits of only several hours each provide critical information about a principal population process that influences population size, and provide the opportunity to leg-band nestlings to estimate juvenile survival. During the two years, very little successful breeding occurred, and probably has not occurred for many years, which probably accounts for the decline in population size.

4. Conduct a formal study of health, and especially of disease, in blue-footed boobies. We did not evaluate formally the possibility that diseases contribute to the population decline except by casual observations.

5. Estimate annual adult survival in the blue-footed booby population. Logistical considerations limited our ability to estimate annual adult survival: adults simply did not attend the colonies frequently enough to use appropriate mark-resight methods. With significant effort, this parameter could be estimated even under the current attendance regime, using

small radio-transmitters on adults and detection from aircraft (either Galapagos National Park patrol plane or UAVs).

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