Feeling Blue? The Effect of El Nino on Blue-Footed Booby Breeding Rates

Figure 1. An adult blue-footed booby stands near its nest and a juvenile (Author).

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Abstract

Known for their brilliant blue feet, the blue-footed boobies are an iconic species within the Galapagos and provide a case example on sexual selection. Unfortunately, the population of blue-footed boobies in the Galapagos has fallen to 6,400, less than a third of their numbers in 1960 (Miller et al. 2014: p. 1). El Nino, the ocean-atmosphere climate interaction linked to the warming of sea surface temperatures across the east Equatorial Pacific, has been implicated in the decrease in breeding rates of the blue-footed booby (Gibbs et al. 1987: p. 440; NOAA 2018: p. 1). This raises the question: Why does El Nino decrease blue-footed booby breeding rates in the Galapagos? In sections below, I propose three hypotheses attempting to answer this question. In tests of these three hypotheses, I will show evidence suggesting that the scarcity of sardines and the subsequent changes in foot color result in the decline in breeding rates. Evidence also suggests that mosquito ectoparasitism and vegetative growth decrease blue-footed booby reproduction but to a lesser degree. Lastly, this report looks at conservation implications for the blue-footed booby and possible solutions including limitations on the overfishing of sardines, climate change prevention, and tourism regulation.

Introduction

Three types of boobies live in the Galapagos: the blue-footed booby, the nazca booby, and the red-footed booby. The closest relative to the blue-footed booby is the Peruvian booby (Figure 2), and it’s estimated that they diverged 0.8 – 1.1 million years ago (Patterson et al. 2011: p. 181). Though 70% of blue-footed boobies live in the Galapagos, they are not endemic to the archipelago and can be found from the Gulf of California down to the coasts of Peru. Interestingly, the distribution of blue-foots in the Galapagos falls mostly below a diagonal line
from the top of Isabella to the top of San Cristobal (Figure 3). Researchers believe this is because during the warm season, the waters in the northern area of the archipelago are too warm for sardines, their primary source of food (Anderson et al. 1989: p. 215).

**Figure 2. Phylogeny of Sulidae family (Patterson et al. 2011: p. 181)**

**Figure 3. Blue-footed booby colony distribution across Galapagos (Blue-footed boobies distribution in the Galapagos Islands n.d.)**
Like other species in the archipelago, blue-footed boobies are influenced by El Nino, the ocean-atmosphere climate interaction linked to the warming of sea surface temperatures across the east Equatorial Pacific. El Nino has been linked to a sharp decrease and even cessation of breeding activity among blue-footed boobies as shown in Figure 4 (Gibbs et al. 1987: p. 440).

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<tbody>
<tr>
<td>Pairs of Blue-footed Boobies$^1$</td>
<td>620</td>
<td>0</td>
<td>$425 \pm 66^3$</td>
</tr>
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*Figure 4. Number of blue-footed booby pairs on Isla Daphne before, during, and after the 1982-83 El Nino event (Gibbs et al. 1987: p. 440).*

Given that the blue-footed boobies population has declined to less than 1/3 of their population in 1960, it’s important to understand why blue-footed booby breeding rates decrease in response to El Nino (Miller et al. 2014: p. 1). The remainder of this paper will explore three hypotheses. Hypothesis 1 is that scarcity of sardines due to rising sea surface temperatures (SST) deplete adult boobies of the carotenoids needed for blue-green feet, thus resulting in failure to attract mates. I will approach this hypothesis in two sub-hypotheses, the first being rising sea-surface temperatures, due to El Nino, decrease the number of sardines available around the Galapagos and the second being the lack of sardines lead to a loss of carotenoids for blue-green feet thus resulting in a failure to attract mates. Hypothesis 2 is heavy rainfall provides breeding grounds for mosquitos which prevent boobies from entering or remaining in infested nesting sites, and hypothesis 3 is increased rainfall leads to increased vegetative cover and less nesting habitat for boobies.

This report will also focus on conservation issues involving the blue-footed booby and possible solutions. Their dependence on a very specific food supply and unique adaptations may
inhibit their ability to respond to new threats such as overfishing, climate change, and tourism. Though the species has been assigned “least concern” conservation status by the International Union for Conservation of Nature, their decline in population in the Galapagos is of concern (BirdLife International 2016: p. 1). Boobies are an indicator species for marine conditions, and so their decline could point to greater environmental issues. Additionally, their status as an iconic species in the Galapagos and their absence could affect tourism and the local economy.

![Image of two boobies](image.jpg)

*Figure 5. A juvenile booby attempts to coax its parent into giving it a meal (author).*

**Methods**

For this paper, I looked at careful studies on the decline of the blue-footed booby population and its relationship to El Nino, specifically the 2014 paper *Chronic lack of breeding by Galápagos Blue-footed Boobies and associated population decline* by David Anchundia and
colleagues, *Differential responses of boobies and other seabirds in the Galapagos to the 1986-87 El Nino- Southern Oscillation event* by David Anderson and his research team, and *Effects of the 1982-83 El Nino Event on Blue-Footed and Masked booby Populations on Isla Daphne Major* by H.L Gibbs and colleagues. Additional literature I looked at included graphs showing changes in sea-surface temperatures from 1995-2005, counts of nests before and after the El Nino of 1982, regurgitation contents of Nazca boobies, and changes in the amount of vegetative growth and number of nests on Daphne Major.

![Figure 6. An adult blue-footed booby observes tourists (author).](image)

**Findings**

Let me return to my findings in the order of my hypotheses. I’ll first begin with evidence I found for hypothesis 1.1 regarding rising sea-surface temperatures and the subsequent decrease in sardine population around the Galapagos. Research has shown that the diet of blue-footed
boobies is comprised almost exclusively of sardines when available. This is due to the nutritional value and high lipid content of sardines (Tompkins et al. 2017: p. 3). Additionally, sardines provide the carotenoids needed for blue-green feet. Therefore, it is important to understand how rising sea-surface temperatures influence the sardine population within the Galapagos. In a 2017 study by Emily Tompkins and colleagues, researchers looked at how ocean temperatures surrounding the Galapagos fluctuated over 30 years. Figure 7 shows the oscillation of SST in relation to the lethal and maximum spawning temperatures for sardines. During the duration of the 1997-98 El Nino event, the waters around the Galapagos were above the lethal temperature for sardines (Tompkins et al. 2017: p. 4).

Figure 7. Oscillation of sea-surface temperatures in Galapagos from prior to 1985 to after 2015 in comparison to the lethal and spawning temperature of sardines (adapted from Tompkins et al. 2017: p. 4).
In the same study, Tompkins also looked at how the diet of nazca boobies changed before and after the 1997-98 El Nino. Nazca boobies are a close relative to the blue-footed booby (see Figure 2), and similar to blue-foots, they prefer to eat sardines. Figure 8 shows the percentage of regurgitation samples that consisted of sardines and flying fish (a less nutrient sardine-substitute). Before the 1997-98 El Nino, the percentage of regurgitation consisting of sardines was around 70-80%. After the El Nino event, it was down to less than 10% (Tompkins et al. 2017: p. 3). These two pieces of evidence suggest that the population of sardines in the Galapagos decrease during El Nino.

![Percentage of diet comprised of sardines](image)

*Figure 8. Percentage of Nazca Booby diet (measured through regurgitation samples) comprised of sardines from 1985 to 2005. (Adapted from Tompkins et al. 2017: p. 4)*

Evidence also supports hypothesis 1.2 regarding how the lack of sardines lead to a loss of carotenoids for blue-green feet and thus result in a failure to attract mates. The blue-green hue of
the species’ feet is highly important in the selection of mates and act as an immunological indicator within the blue-footed booby population (Velando et al. 2006: p. 535). In times of health, lesser amounts of carotenoids are needed to bolster the immune system, and evolution has allowed for the yellow pigmented carotenoids to travel to the feet of blue-footed boobies. This results in a blue-green foot color which signals immunological health. The coloration of the feet is also an indicator of the booby’s nutritional status. For example, when researchers deprived boobies of food for forty-eight hours, they observed a decrease in foot-brightness due to the lack of carotenoids and lipids. Because foot-coloration is an indicator of immunological health and nutritional status, it is favored in sexual selection by both males and females (Velando et al. 2006: p. 535).

Since sardines provide the carotenoids needed to achieve blue-green foot color, a lack of sardines in their diet may lead to a failure to attract mates. In a study, researchers dulled the feet of female boobies with blue makeup and then compared the frequency of courtship activities from males with a control group.
Figure 9. Left: Rate of courtship per an hour among females with duller feet and the control group. Females with duller feet received less courtship (Torres et al. 2005: p. 59). Right: The feet of an adult blue-footed booby (Author).

Figure 9 shows that experimental females with duller feet received 38% less courtship in the form of sky pointing and nest material presentation than control females (Torres et al. 2005: p. 59). Similarly, in a separate experiment where males’ feet were dulled with makeup, females responded to this apparent decline in health by laying smaller eggs (Velando et al. 2006: p. 535). This suggests that a lack decline in sardine availability may lead to a decline in breeding rates.

Figure 10. The brightly colored feet of an adult BFB on Espanola Island (Author).

After testing hypothesis 1, let me proceed to evidence found in support of my second hypothesis stating that heavy rainfall provides breeding grounds for mosquitos which prevent boobies from entering or remaining in infested nesting sites. El Nino is usually accompanied by heavy rainfall. For example, during the especially harsh El Nino of 1982, Santa Cruz island had
127 inches of rainfall compared to the five year average of 8 inches (Ader 2000: p. 1). During these storms, pools of water form in the indentations on land, providing freshwater breeding sites for mosquitos. Because mosquitos are ectoparasites that take blood meals from birds and mammals, this could lead to discomfort among boobies and the abandonment of eggs and nesting sites (Anderson 1988: p. 727).

![Image of an egg in a nest](image)

*Figure 11. An blue-footed booby egg left in the remains of a nest. Unclear whether the egg hatched or was eaten by predators (author).*

Much of the research on the link between mosquitoes and egg abandonment has been conducted on the waved albatross. In 1986, Anderson’s research team studied the link between albatross reproductive success and mosquito population on Espanola Island. They observed that after heavy rainfall, precipitation had flooded the island’s large interior basin and created small pools along the coast. This resulted in breeding sites for the mosquito *Aedes taeniorhynchus* and a subsequent increase in mosquito population (Anderson 1988: p. 727). *Aedes taeniorhynchus,*
which feed on mammals and birds, were observed taking blood meals from avian and human hosts all hours of the day. In the days following the rainfall, researchers began noticing an increasing number of abandoned eggs. As a result, researchers hypothesized that egg neglect was a response to mosquitos taking blood meals from incubating adults. To test this hypothesis, researchers sampled the number of mosquitos in four sub-colonies which varied in egg desertion rates.

<table>
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<th>Subcolony</th>
<th>Total eggs</th>
<th>% eggs neglected</th>
<th>No. mosquitoes</th>
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<tr>
<td>1</td>
<td>55</td>
<td>47.3</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>5.8</td>
<td>1</td>
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*Figure 12. Number of eggs deserted and number of mosquitos observed in one minute across four different subcolonies on Espanola (Anderson et al. 1988: p.728).*

Figure 12 shows a positive correlation between the percentage of eggs neglected and the number of mosquitos. In addition to this evidence, researchers observed up to 15 mosquitos simultaneously feeding on the facial skin of incubating albatrosses. These adults often exhibited signs of distress through frequent preening and shifting positions that were not observed in non-parasitized albatross (Anderson et al. 1988: p.728).

It’s possible that mosquitos have a similar effect on blue-footed boobies. Like albatross, boobies nest in coastal areas where it is easier to take off and land (Hernandez
et al. 2018: p. 1). Due to their similar nesting sites, it’s possible that mosquitoes also affect blue-footed boobies. Although there is no quantitative evidence for this, there is anecdotal evidence from researchers. While studying blue-footed boobies on Espanola Island during the 1986-1987 El Nino, researchers noted that “heavy rainfall provided breeding sites for mosquitoes, hundreds of which swarmed around the few blue-footed booby chicks alive in February and which appeared to make adults reluctant to enter or remain in the inland nesting areas” (Anderson 1989: p. 727). While this anecdotal evidence does suggest that mosquitoes may play a role in the lower reproductive rates during El Nino, more quantitative research is needed.

Figure 13. A dead blue-footed booby hatchling (author).

Lastly, let me present the evidence I found supporting my third hypothesis regarding vegetation and its effect on breeding grounds. During El Nino, increased rainfall leads to an increase in vegetative growth (Gibbs et al. 1987: p. 440). Because blue-footed boobies nest on
divots on bare ground, more plant growth may inhibit their ability to make adequate nests, therefore decreasing their reproductive rates.

During the El Nino of 1982, researchers studied changes in blue-footed booby reproduction rates on Daphne Major. Daphne Major has an upper and lower crater, both of which are common breeding sites for boobies. Following El Nino, the two craters experienced different amounts of vegetation growth. The upper crater only contained sparse vegetation, whereas 46% of the lower crater floor was covered in plants such as Cacabus miersii and Heliotropium angiospermum (Gibbs et al. 1987: p. 440). Researchers then studied how breeding rates varied between the two craters.

Figure 14. Left: Daphne Major from a distance. From this angle, only the larger crater is visible (author). Right: A uninhabited blue-footed booby nest, essentially a slight divot in the soil surrounded by guano (author).

Figure 15 shows that in both craters the density of nests per square meter before and after El Nino stayed relatively static. While the number of breeding pairs in the sparsely-vegetated upper crater remained about the same from 104 pairs to 101.5 pairs, the densely-vegetated lower
crater experienced a significant drop from 516 to 323.3 pairs. This suggests that nest site limitation caused by vegetative growth led to a reduction in breeding.

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<th>LOWER</th>
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<tbody>
<tr>
<td></td>
<td># Pairs</td>
<td>Density (nests / sq m)</td>
<td># Pairs</td>
<td>Density (nests / sq m)</td>
</tr>
<tr>
<td>1982</td>
<td>104</td>
<td>0.0061</td>
<td>1982</td>
<td>516</td>
</tr>
<tr>
<td>1984</td>
<td>101.5</td>
<td>0.0063</td>
<td>1984</td>
<td>323.3</td>
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*Figure 15. The number of breeding pairs of blue-footed boobies in the upper crater compared to the lower crater. While the density of nests per/sq. meter stayed the same, the number of pairs decreased significantly in the lower crater (Adapted from Gibbs et al. 1987: p. 440)*

Additionally, vegetation remained in the lower crater until 1986, over two years after the beginning of the El Nino showing possible long term effects of El Nino (Gibbs et al. 1987: p. 440). While evidence from this study supports my hypothesis that increased rainfall and subsequent plant growth limits breeding, there needs to be more research on this issue across other islands in the archipelago and during other El Nino events.

**Conclusion**

I set out to understand the decline of the blue-footed booby population and its connection to El Nino. Through reading the findings of researchers in the field, I found that a decline in sardine availability results in carotenoid depletion and thus duller feet for boobies. Both females and males sexually select for blue-green feet, and thus the lack of sardine availability may result
in boobies struggling to attract mates. Mosquito ectoparasitism, which has been linked to egg
desertion among waved albatross, may also be causing discomfort among boobies and forcing
them to abandon nest sites. Lastly, vegetative growth due to heavy rainfall may be limiting the
availability of adequate breeding grounds and nesting sites. Evidence has suggested that all three
of these factors may play a role in the declining rates of breeding among blue-footed boobies.
However, of the three hypotheses, I feel most confident in my first hypothesis because much
research has been devoted to the study of declining sardine populations and its relationship to
boobies. Researchers such as Anchundia, Anderson, Tompkins, Gibbs and their colleagues have
written numerous papers on the topic, and there is much quantitative evidence showing the
relationship between the decline of both species. While evidence exists to support my second and
third hypotheses, I think that both could be strengthened by further research. For example, I think
it would be highly beneficial for the conservation of blue-footed boobies if a study on mosquito
parasitism specific to boobies was conducted. In addition, the effect of vegetative growth on nest
site availability has been observed on Daphne Major, but further research could replicate this
study on multiple islands across the archipelago and during various El Nino events to see if
similar results are found. Understanding why breeding rates for blue-footed boobies decline
during El Nino is important because they act as an indicator species for marine conditions and
food supply. Their decline could have implications for other marine life which depend on
sardines as a food source and could reveal other large-scale changes in ocean conditions.
Furthermore, blue-footed boobies are an iconic species in the Galapagos, and thus their
conservation is important to the local tourism economy of the archipelago.
Conservation Implications

Given the evidence presented in this paper, there are several steps for conservation of the blue-footed booby. First, studies have shown that declines in sardine population are a factor in decreased breeding rates. Lack of sardine availability due to overfishing has been documented across the Pacific, and many fishery management councils have been forced to prohibit commercial fishing due to population numbers falling below the sustainable threshold (Felix-Uraga 2004: p. 146). One solution specific to the Galapagos would be to limit sardine fishing off the coast of Peru and Ecuador. Currently, there are no regulations on small-boat fishing in Peru. While small-boat fishing is supposed to be reserved for local fisherman to feed their families and communities, fish are often caught at higher than sustainable rates and are sold commercially rather than locally (Embassy of Peru 2017: p. 1). By protecting the sardine population around the Galapagos, blue-foots could have greater access to nutrient rich sources of food.

Blue-footed booby colonies in the Galapagos could also be translocated to the Gulf of California or the coast of Peru where sardines may be more plentiful and booby populations seem to be remaining static. Though it is unclear what long-term effects this may have on the Galapagos population, albatross chicks have been translocated in Japan with limited side effects and this could be a possibility for the blue-footed booby if population numbers continue to decline (U.S. Fish and Wildlife Service 2008: p. 105).

Tourism has been shown to increase mosquito population as it provides the insects with year-round food source. One solution could be to limit the proximity of tourists to blue-footed booby colonies during rainy seasons as this could lead to a spike in mosquito population.
Because of the special circumstances of the Galapagos, tourists are able to get extremely close to wildlife, but there is limited information about how this affects the hormonal responses of animals. Further research should look more closely at stress responses due to tourists among boobies as has been documented among marine iguanas (French et al. 2010: p. 792).

Lastly, research has suggested that climate change increases the frequency and severity of El Nino (Cai et al. 2014: p. 111). Possible solutions to limit climate change include restricting carbon emissions and researching renewable forms of energy. Out of all the conservation implications listed above, climate change is the most difficult to address because of the complexity and scale of the issue. To have a noticeable impact on the Galapagos, people worldwide have to be conscious about how they produce greenhouse gases. However, as the worldwide community becomes more educated about the importance of conservation, we can begin to fight climate change and protect the blue-footed boobies.
Thank you to each and every member of my Galapagos family, including Professor Durham, Caroline Ferguson, Neil Nathan, the Stanford Alumni travelers, and my fellow students! This trip was an unforgettable experience that I will treasure forever. You all are my favorite “Dear Guests.” Special thanks to Audrey Bennett for peer reviewing my paper!


