9-1-2014

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Brian Seth Putman
Nova Southeastern University, briansethputman@yahoo.com

NSUWorks Citation

Brian Seth Putman. 2014. *Modeling Flightless Galapagos Seabirds as Impacted by El Nino and Climate Change.* Master's thesis. Nova Southeastern University. Retrieved from NSUWorks, Oceanographic Center. (24)
https://nsuworks.nova.edu/occ_stuetd/24.

NOVA SOUTHEASTERN UNIVERSITY OCEANOGRAPHIC CENTER

Modeling Flightless Galapagos Seabirds as Impacted by El Niño and Climate Change

By

Brian Seth Putman

Submitted to the Faculty of
Nova Southeastern University Oceanographic Center
In partial fulfillment of the requirements for
the degree of Master of Science with a specialty in:

Marine Biology

Nova Southeastern University

Thesis of
Brian S. Putman

Submitted in Partial Fulfillment of
the Requirements for the Degree of

Masters of Science
Marine Biology

Nova Southeastern University
Oceanographic Center
September 2014

Approved:
Thesis Committee

Bernhard Riegl

Major Professor:____9/9/2014
Bernhard M. Riegl, Ph.D., Nova Southeastern University

Committee Member: ____9/9/2014
Samuel J. Purkis, Ph.D., Nova Southeastern University

Fernando Rivera

Committee Member: ____9/9/2014
Fernando Rivera, M.Sc., Instituto Nazca, Salinas, Ecuador

Committee Member: ____9/17/2014
David Kerstetter, Ph.D., Nova Southeastern University

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Acknowledgements:

I will forever be indebted to Dr. Bernhard Riegl for his tireless reviewing my work and mentoring throughout the entirety of this project. What will remain an inspiration is his advice and inexhaustible support for my work, matched only by a profound knowledge he imbues upon all his students.

To Dr. Sam Purkis, who did more than serve on my committee. He also inspired me to learn skills I had never before considered.

To Dr. David Kerstetter who approached my work in a critical and constructive manner. His doing so taught me to never stop striving for improvement.

Special thanks is due to Alexander Humphreys, Megan Foley and Mathew Johnston. Alexander was an inspiration in the early stages of this project and kept me going. Megan is special in her continuous encouragement and caring support. Matthew earns my gratitude for his aid in expanding my understanding of computer programming.

Finally, there are my parents and brother, Jeffrey. They freely offered and gave endless practical and emotional support at any hour of any day or night for both improving my work and getting through an extremely difficult time.

Abstract:

Noteworthy species endemic to the Galapagos Islands off Ecuador are two flightless birds, the Galapagos Penguin (*Spheniscus mendiculus*) and Flightless Cormorant *(Phalacrocrax harrisi*). Both adapted increased swimming ability at the cost of flight. This however has limited their ability to find richer feeding grounds in times of low resource availability, or to escape potential predators. Their population numbers, though small, were stable. Stress on this stability has increased since human arrival. Various invasive species from pets, farm animals and rats to even mosquito vectors of avian disease accompanied humans. . *El Nino Southern Oscillation* or ENSO cycles of warm waters in the Pacific Ocean south of the Equator cause drastic drops in food sources for all Galapagos seabirds. Serious ENSO events in 1983 and 1998 caused some species' populations to drop by as much as 77%. Periodic less severe cycles may help explain how population recovery has not rebounded to earlier numbers. Reduced chick survival and adult fecundity seem to occur in concert with mild events. With available data and use of a modeling approach, this study focuses and explores their situations. Restoring population stability may include use of models, species monitoring, conservation and limiting invasive species. Usher matrices based on different climate conditions were produced using data combined from current and past census counts and weather. Models are used to compare available census data and test reliable predictors. Climate data from National Oceanic and Atmospheric Administration and the University of Florida provides for testing predictions of current and probable future climate change. Life histories of both species are regarded. Results suggest the current Cormorant population is still stable. The Penguin, however, faces a 20% probability of extinction in 100 years if current conditions remain. Extinction probability rises to 60% if climate change continues to worsen. Interventions such as captive breeding could be suitable for population recovery.

Keywords:

Galapagos Penguin (*Spheniscus mendiculus*), Flightless Cormorant *(Phalacrocrax harrisi*), *Spheniscus* or Banded Penguins, ENSO cycle, Population modeling, Leslie matrix, Quasi extinction threshold, Life cycle graph

1. Introduction

1.1 Study Significance

Two flightless seabird species, the Galapagos Penguin (*Spheniscus mendiculus*) and flightless cormorant (*Phalacrocorax harrisi)*, are known from the Galapagos Islands. Previous studies have shown that their numbers have risen and contracted due to changing weather patterns, but their overall populations have been relatively small but stable (Jimenez et al., 2011). Endemic to the Galapagos Islands, off the coast of Ecuador, both species now suffer at the hands of human impacts as well as climate change, specifically within the ENSO cycle (Boersma, 1978; Vargas et al., 2006; Rosenberg, Harcourt, 1987; Tindle, 2013). There is a potentially serious decline in the local environment where they live. Fluctuating food sources and nesting sites endangered by invasive species are only two examples of concern. Overall, the increasing concern is instability in population distribution and numbers (Vargas et al., 2006). This study, therefore, will focus on the Galapagos penguin and flightless cormorant, their life-history characteristics, as well as how precarious is their survival as a species seems to be becoming. To aid this study, a “population viability model” (Morris and Doak, 2002) will be built and applied.

The property of flightlessness is a key point of interest in the study of the population dynamics of these two seabirds. Their primary dietary target, small coastal fishes, are found in most years throughout the biologically productive waters surrounding the Galapagos Islands. Evolution of flightlessness is typically associated with island biogeography, where a shift in diet to seafood is possible and there is a lack of mammalian predators (McNab, 1994). The evolutionary trade-off from flight to flightless increases their ability to swim, resulting in more efficient capability to hunt fish (Elliot et al., 2013). A gain in body size is a typical adaptation after loss of flight. This is true for many species of rails, ducks, and many other species living on most islands, such as New Zealand, where 25 to 35% of terrestrial and freshwater birds were flightless due to a lack of predators (McNab, 1994). For the Galapagos penguin and flightless cormorant, the evolutionary benefit and risk include increased diving efficiency with increased vulnerability to predation. This inherent vulnerability was no problem until human arrival also introduced predators, largely canines, felids and rodents (Brokie, 1988).

As in other parts of the world, human impact has taken multiple forms. For many generations these flightless birds of the Galapagos survived quite well. Originally, the Galapagos penguin found its ideal breeding ground on several islands with their original primary breeding ground at the small Marielas Island, off Isabella shown below in Figure 1. However, the overall breeding range has contracted significantly. Degradation of native vegetation, introduced predators like dogs and rats, and vectors of lethal diseases for birds, were introduced by humans (Borboroglu, and Boersma, 2013). Virtually all seabird populations on these islands have been declared endangered (Jimenez, 2006). Galapagos penguin populations are now so low that natural genetic diversity has been seriously reduced (Akst, 2002). Thus, these two species face the double-threat of a small and isolated population, making them vulnerable to inbreeding and demographic stochasticity or a variation in births and deaths (Vargas et al., 2005; Vargas et al, 2007). Recent decades of changing climate variability brought about by human activities have been shown in a model built by Timmermann et al., 1990 (ENSO cycles) have been shown to be problematic and further future climatic variability if current trends continue, which strongly influences life-dynamics in these two species, is likely to further compromise these species' survivability (Rosenberg and Harcourt, 1987).

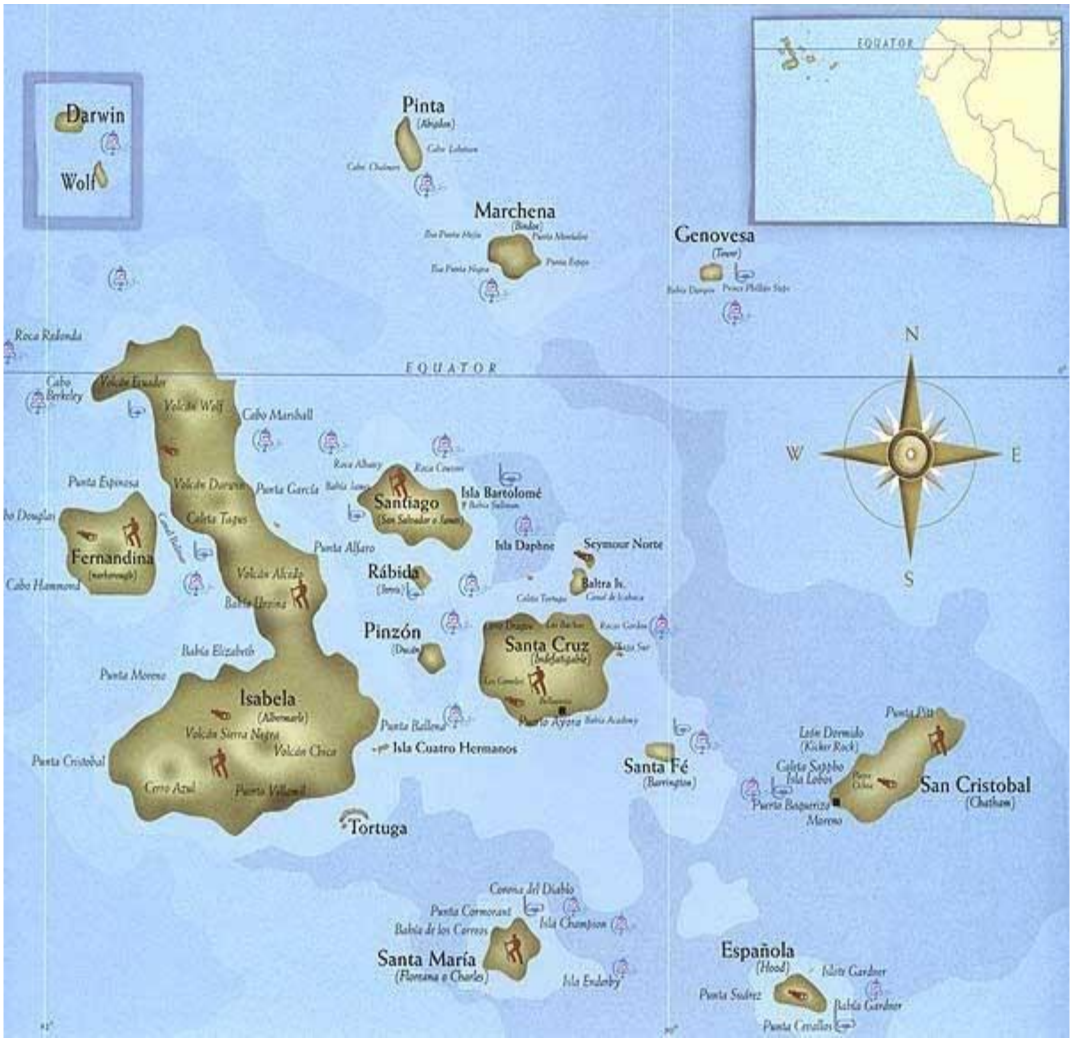

Figure 1: Map of the Galapagos Islands: (http://www.discovergalapagos.com/map.html)

1.2 Seabird extinction risk and Island Devastation:

Seabirds (birds dependent on the marine environment for at least part of the life cycle) in general are more threatened in terms of environment and habitat when compared to other birds (Croxall et al., 2012). Serious threats for all seabirds include overfishing, pollution, invasive species, habitat degradation, and rising human disturbance. Of the 346 described species of seabirds, 28% are globally threatened and 5% are critically endangered (Croxall et al., 2012). Island species, compared to continental coastal species, are worse off in this increasing trend towards threatened status. Continental or land birds have more (not unlimited) opportunity when in need of new habitats or feeding grounds and have therefore more options to move away from degraded habitat as opposed to island species.. Lower population rates and numbers, lower genetic diversity, and ever-decreasing range for life support are well documented for island seabirds (Simberloff, 1995).

The Galapagos archipelago is home to some of the rarest, and most endangered seabirds, such as the critically endangered Waved Albatross (*Phoebastria irrorata*) (Jimenez 2006). Also, seabirds are sentinel organisms for environmental problems on islands, having some similarity to the proverbial canaries used by coal miners to detect dangerous gas in the mine. If observed and tracked, they may, for example, serve as sentinels for the effects of climate change. Their dependence on very specific prey items provides markers for population fluctuations in the prey, for example subtle changes in the pelagic food chain (Grémillet and Charmantier, 2010). Subtle changes in the food chain have an even greater impact when commercial fishermen overfishing the food supply is taken into account (Croxall et al., 2012). Their evolution on isolated islands also led to small population sizes, which can result in low genetic diversity. This means the islands are areas in need of conservation. Being that the various islands are small, change can have dramatic, often catastrophic effects on any ecosystem, taking with it any given species. For example, of the 217 species of birds that went extinct over the last 400 years, 200 were endemic to islands. Secondly, almost half of the world's endangered birds are endemic to islands (Brokie et al, 1988).

Beyond effects of climate change and overfishing, seabird species face still more threats compared to other birds. Well documented (Croxall et al., 2012; Borboroglu and Boersma, 2013; Vargas et al., 2005) are problems of lower population sizes which often result in declining genetic diversity, all coinciding with decreasing range or areas needed for life and reproductive support. Among other serious threats against population numbers are pollution, invasive species, habitat degradation, and tourism. Tourism, even “eco-tourism”, is only the most recent of numerous other human disturbances inflicted upon the Galapagos Islands since the first arrival of European ships.

The Galapagos Islands are an archipelago representing a unique ecosystem, which developed in relative isolation from large mainland masses, including the nearby South America. Species on islands like the Galapagos will also adapt in ecosystems with none of the usually present terrestrial predators. Unique speciation and unusual evolutionary traits in endemic birds and animals for which the Galapagos is famous are typical results (Brokie et al., 1988). The arrival of humans accompanied by pests, such as rats, and domesticated animal's changes island life. Even pets, like cats or dogs, become predators. The earlier lack of predators is a gap in the ecosystem increasing susceptibility to invasive species (Simberloff, 1995). Their already small habitat ranges for food and nesting to reproduce further decreases. If these species are to thrive, modern conservation efforts become necessary.

Rats as a predatory species have been introduced to approximately 82% of the world's Islands. Rat impact on local wildlife can be significant. Rats can grow to incredibly large populations in short periods of time, impinging upon and pushing out other species. They will eat small mammals and birds plus compete for food resources. Rats are responsible for the decline or extinction of bird species on at least 31 islands. This heavily impacts on endemic seabird populations. Rats have been especially devastating to the cormorant and penguin populations due to their inability to fly away (Brokie et al, 1988; Croxall et al., 2012; De Groot, 1983; Simberloff, 1995; Vitousek, 1995).

Rats and dogs were unknown on the Galapagos until the first European ships arrived. Both can easily invade nests, situated in tubes, caves and crevices. This problem helps explain some changes in penguin breeding areas. In part because of these rats and dogs, most breeding now occurs on southwest Isabela. Success there began in the 1990s following the elimination of feral dogs. Until the late 1970s, Mariellas Island was an important breeding site for penguins. Rat intrusions eliminated them from that island ((Croxall et al., 2012; Borborogulu and Boersma, 2013).

Pest species are not the only consideration with introduced species. Farm animals raised for food, clothing, and transportation also can have significant impacts. They consume large quantities of plants and grasses, which did not evolve/adapt to their existence. Such plants are typically the food source for many endemic species, weakening them further in competition for food (Schofield, 1989).

Finally, introduced species include pets. With no competitive species, pet species can discover or devise their own niche in the local ecosystem. Natural balances inherent in small locales are disrupted. Dogs, for example, both work for and are enjoyed by human owners. As natural predators, pets have an obvious impact on the local animal populations (Brokie, 1988). Like rats and animals used for farms or transportation, pets are serious invasive predatory species. Whether canine or feline, well fed or not, they chase and catch small endemic species. With regards to birds, they disrupt and often feed upon what they find in nests.

Ecotourism, a combination between tourism and resource protection is a relatively new development in human activity in exotic places such as the Galapagos. People pay to go to places where there is effort to maintain as much of a natural state as possible. Local people may even be paid to preserve, restore, or at least minimize disruption to natural local ecosystems. Ecotourism is one human impact that could effectively both aid as well as damage conservation efforts. Benefits and serious risks are both involved. Among benefits, ecotourism stimulates a local economy as well as encourage locals to help in conservation. Local people and foreign visitors are educated in the unique qualities of an ecosystem, its value, and why it is important to be maintained (Powell and Ham, 2008; DeGroot, 1983; Duffy, 1981).). Of particular importance is traditional hunting or primitive "slash and burn" of natural vegetation to clear land for food crops or commercial farming are displaced. Ecotourism does carry with it human impact, but for conservation purposes it is superior to continuing old techniques of subsistence as well as European/American style profit oriented commercial development.

Even ecotourism, if not managed properly, can have disastrous effects on a local ecosystem. Tourists with money also want comfortable accommodations and good food. Space is already at a premium. More land can be destroyed for housing, even if simple housing like tents, and cooking. Also more human arrivals raise the potential of more invasive species. Tiny insects, capable of becoming dangerous invasives in a "new" environment may be stowaways in clothing, baggage or camera cases. Recently their ability to do so is illustrated even in wealthy, upscale New York hotels with bedbugs. As far as local seabirds are concerned, malaria vector species have recently been discovered on the Galapagos. Avian malaria has drastic implications for bird populations, especially penguins who are extremely susceptible to it. A concept called in tourism is called "regional capacity. Regional capacity has to do with the volume of tourism an area can absorb. The "regional capacity" to cater to tourism is large in Ecuador and western South America. The Galapagos is part of that region. Being that most seabirds are coastal, their habitat is at a premium for tourists, putting more pressure on these islands. Pressure for expanding tourism to the Galapagos is great. Too much tourism based on regional capacity can lead to an abundance of disturbances on the ecosystem. Deliberate conservations efforts cannot take hold or make progress (Powell and Ham 2008).

1.3 ENSO Cycle:

ENSO cycles have had profound impacts on seabird population. Reductions in fish populations due to drastic shifts in water temperature and reduced upwelling. The greater the severity of the cycle, the greater the impact on seabirds and Galapagos penguins and cormorants suffer from high mortality during severe cycles (Jaksic, 2004; Godfrey, 1984). Climate change may be causing a shift towards more drastic cycles, which would have even greater impacts on this region (Sachs and Ladd, 2010).

A profound signal of climate change are the global anomalies known as the ENSO or "El Niño Southern Oscillation (Timmermann et al., 1999; Duffy, 1990). The ENSO cycle is a variable instability causing atmospheric and oceanic changes within the tropical region of the Pacific Ocean (Cane et al., 1986). While ENSO cycles have direct effects on the Galapagos Islands, their broader impacts are global. Originally named by Peruvians, the *El Niño* portion of the cycles is for a Christmas time warming of ocean waters near Peru. Currently the ENSO cycle is determined by a change in sea surface temperatures in the NIÑO3 region of the equatorial Pacific Ocean from 90W-150W, 5S-5N (Figure 3). The cycle's approximate occurrence is every four years, typically occurring every two to seven years. During a "normal" year, the west Pacific warm pool sits around Tahiti.

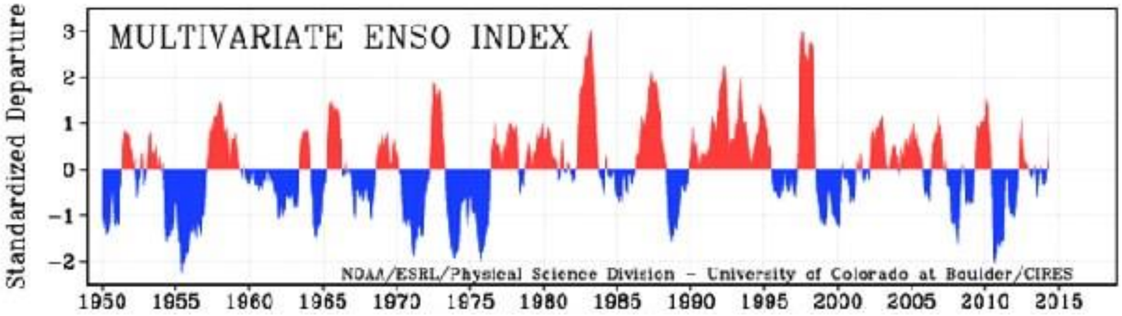

Figure 2: ENSO Index from NOAA (http://www.esrl.noaa.gov/psd/enso/mei/)

During the ENSO cycle, the thermocline in the eastern Pacific is depressed, warming the surface waters across a broad swath of the ocean. This results in a weakening of the prevailing winds coinciding with reduced upwelling of nutrients in ocean currents around the Galapagos Islands. Reduced nutrients lead to less overall biomass and biodiversity in the waters across the whole region (Chavez et al., 1999). In particular, surface dwelling fish species, such as the anchovies and sardines that serve as a primary food source for the penguin and cormorant, decrease in biomass. Opinions differ on how great the impact of climate change will be on ENSO cycles, but there is agreement that climate change will likely alter the present situations. Predictions differ only on how much the cycles will increase in both severity and rates (Cane, 2005).

According to the NINO3 Index (Cane, 2005) the sea temperature in the equatorial Pacific has warmed by 0.4 to 0.8 degrees Celsius over the last forty years. There is an expected increase of 1.0 to 3.0 degrees Celsius in this century. While, since the Industrial Revolution, the region around the Galapagos Islands has experienced little or no change in localized sea surface temperatures, problems there still remain. There is a probability for increasingly drastic ENSO cycles with rising impact on the island seabirds treated in this study and other endemic life (Sachs and Ladd, 2010).

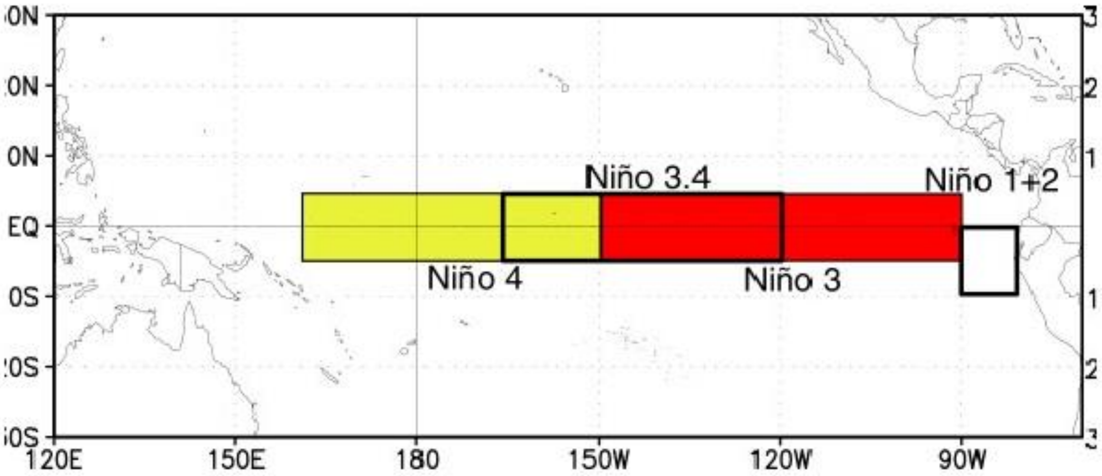

Figure 3: Niño Regions (Photo by: http://orca.rsmas.miami.edu/~melicie/index1.htm)

Between 1965 and 2004, two severe and seven weak *El Niño* cycles were recorded. The two severe ones in 1982-83, and 1997-98 resulted in severe fluctuations of species living on the Galapagos (Vargas et al., 2006). *El Niño* reduces quantities of fish and squid in the waters around the Galapagos and South America. Two possible devastating effects on seabird populations follow: increased mortality from famine, and severe reduction in fecundity among survivors. Additionally, recovery rates for bird population are hampered by human activity in the form of overfishing on already declining ocean stocks. Unfortunately, the Galapagos penguin and the flightless cormorant cannot fly away. Being unable to leave sites of diminishing resources and sustenance, significant mortality losses for the Galapagos penguin may well be the result. Complete reproductive failure is a possibility. The living Cormorant population will be able to sustain itself but it also may suffer reproductive failure (Jaksic, 2004; Godfrey, 1984

1.4 Local Setting:

The Galapagos Islands form an archipelago, or volcanic island, chain located in the Pacific Ocean near the coast of Ecuador (Figure 4). Spanning both sides of the equator, the archipelago includes sixteen main islands, three smaller ones and an array of scattered islets. Here, equatorial waters mix with cooler waters of the Humboldt or Peru Current passing nearby, combining to develop a desert climate. The Humboldt Current itself begins in the Antarctic region (Figure 5). There, with upwelling cold water, a nutrient rich marine environment is developed and flows northward along the South American west coast of Chile and Peru.

Figure 4: Galapagos Islands Photo by http://galapagoslastminutes.com/galapagos-information/island-information/

Upon reaching the Galapagos, Islands the current helps to cool surrounding water temperatures, but distance from Antarctica produces one unfortunate result. Most of the current’s early trove of nutrients has dissipated. Though not very strong, the Equatorial Countercurrent does, however, manage to combine waters with the cool Humboldt to create another upwelling of nutrients. A local problem here rises every seven years or so when *El Niño* cycles hit the islands. Water temperatures rise, breaking down a delicate marine environment, thereby causing subsequent reduction of available nutrients and dependent marine life. (Hess, 2009)

The oceanic region around the Galapagos Islands is, therefore, influenced by alternating combinations of warm waters of the Equator to the north, cooler waters of the Humboldt Current to the southwest plus relatively cooler but nutrient rich upwelled waters from the west. The richest assortment of marine organisms occur around the central Galapagos, especially waters surrounding Isabela Island. Here a rich mixture of cold and warm water biota develops. The cooler upwelled waters produce a large biomass of sardines, thread-herrings, anchovies, pompanos, mackerel, scads, halfbeak and lantern fishes. This biomass feeds higher trophic organisms such as sharks, barracuda, cetaceans, and pinnipeds and, most importantly here, seabirds (Okey et al., 2004).

Figure 5: Galapagos Oceanographic Conditions Galapagos and Currents

Photo by: http://blog.galapagosecolodge.net/2012/09/galapagos-island-geography-and-geology_16.html

Wind induced equatorial upwelling supports development of large quantities of micronutrients such as iron, and macronutrients such as nitrates over the region of the Galapagos. The region of the equatorial Pacific near the Galapagos is strongly controlled by nutrients with higher levels of nitrates but low iron. Iron is a limiting nutrient which causes high nutrients but low chlorophyll. But due to the equatorial countercurrent located on the western side of the Galapagos, phytoplankton can grow. This is attributed to nitrates that come with the upwelling as well as localized iron from the island (Palacios, 2004).

1.5 Galapagos Penguin:

The Galapagos Penguin is the smallest among the four extant penguin species. More significantly, the species is the only tropical member of genus *Spheniscus*, also known as the banded penguins. The next closest related species is the Humboldt Penguin *(Spheniscus humboldti)*. The Galapagos penguin is especially vulnerable to and has long suffered from problems endemic to these islands. Throughout history, there have been multiple bottlenecks of decline in population followed by recovery (Akst et al., 2002). Though this trend continues into their current history, instability increases with concurrently increasing threats to population recovery. Recent and current population censuses show population crashes of as much as 77% because of the severe *El Niño* of 1982-1983 (Vargas et al., 2006). The population typically nests in lava tubes, caves and crevices. Counting penguins is difficult without setting foot ashore, which is not always allowed. With the background of these dramatic population reduction, gaining a more accurate census than presently exists (Vargas et al., 2005; Rosenburg, Harcourt, 1987) by developing a better model to understand future trends is important for the future of the species.

Increased homozygosity of the Galapagos penguin is the clearest sign this species has suffered population bottlenecks. Study of a closely related species, the Magellanic Penguin (*Spheniscus magellanicus)* has found they have a heterozygosity of 46% compared to the significantly lower 3% for the Galapagos penguin (Akst et al., 2002; Nims et al., 2008). Heterozygosity is important because, among other effects, it has impact on a species' susceptibility to disease. High heterozygosity means a greater number of dissimilar pairs of genes for any hereditary characteristic. In the case of disease, the higher the heterozygosity, the greater the probability a plant or animal organism can react successfully against exposure to a disease. It is more likely to have genes adaptable to such circumstances. A low heterozygosity reduces that probability. Vulnerability to the disease is increased. Problems resulting from inbreeding become more relevant because new potentially dangerous diseases have recently been introduced to the Galapagos. Avian malaria is of greatest concern. Casualties are heavy when avian malaria appears among captive penguins within outdoor exhibit areas. Mortality is captivity is as high as 50% per year without treatment (Grant and Duffy, 1994). For a long time this disease has not appeared on the Galapagos. However, in 2001 a known vector mosquito, *Culex quinquefaciatus* was spotted (Miller et al., 2001). The first reported case of malaria in the Galapagos occurred in 2009 (Levin et al., 2009). The Galapagos penguin has, therefore, become a vulnerable species open to impact by a potentially devastating avian disease

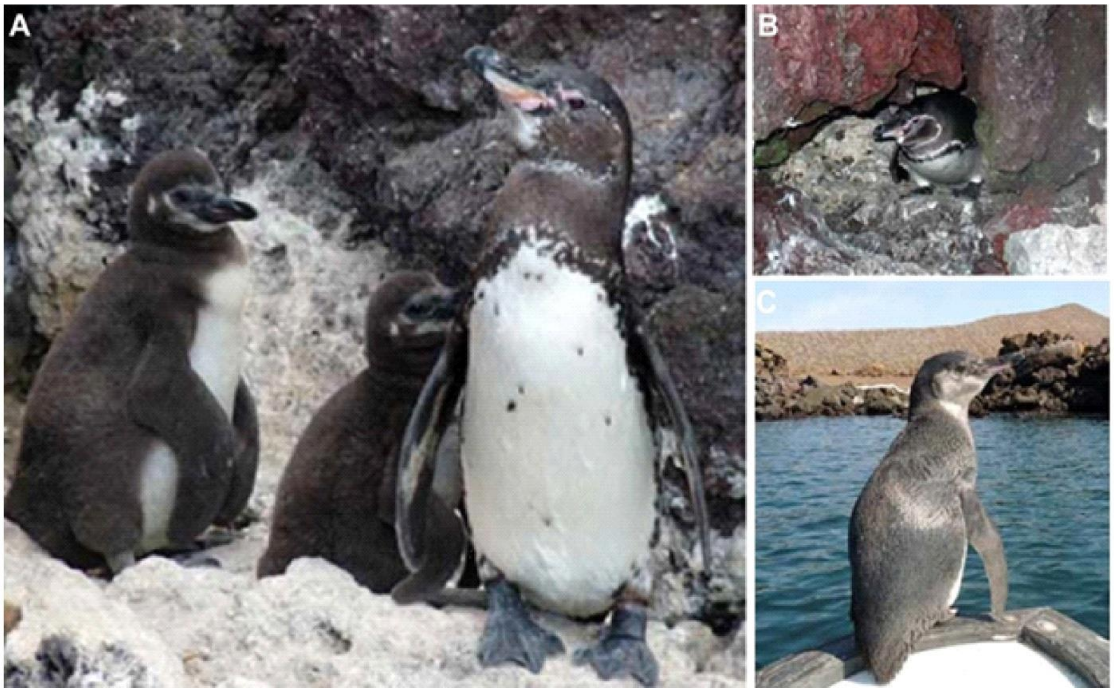

Figure 6: A: Galapagos Penguin Chicks around 3 to 4 weeks old in down. B: Galapagos Penguin nesting in lava crevice C: Juvenile Galapagos Penguin showing gray plumage and lack of facial band. Photos by Dee Boersma

Newly hatched penguin chicks are covered in a grayish brown down. Immature penguins, unlike adults, lack white feathers outlining the cheek on both sides of their heads, nor do they have the dark feather band, hence "banded penguins", around the breast and legs. Fledglings have more blue gray plumage that becomes grayer with age and eventually turns brown. They also lose feathers around the bill by the first molt. Males will sit on the nest first, where typically two eggs are laid three to four days apart. The incubation period is 38-42 days. Chicks are brooded for a few days, and then guarded for a few weeks. They finally fledge at approximately 60 days but will continue to return to the nest site afterwards to continue to beg for food (Borboroglu and Boersma, 2013).

Most breeding occurs during the dry season from May through December. However, they have also been found to breed at any time of year. In a region with high environmental fluctuations it is energetically less expensive to breed and lay eggs than to molt, incubate, and rear chicks. Multiple attempts at breeding are possible and successful egg laying will prepare the population for a good year. Molting is essential for survival, especially in a region of high environmental fluctuation. Therefore, for this species, molting always occurs before breeding (Boersma, 1978; Borboroglu, and Boersma, 2013; Vargas et. al, 2006; 2007).

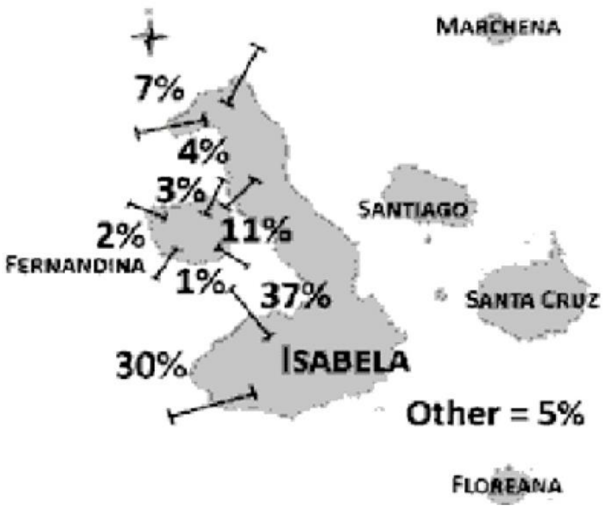

Figure 7: Percentage of Galapagos Penguins located in each of 8 census areas in a 2005 census performed by Vargas et al., 2005

Studies by Vargas 2006; 2007 of Galapagos penguins suggest age is a critical indicator of survival from hatching through adult breeding years. Breeding age begins at about three years. For young penguins, less than one year old, the survival rate is 33%. Survival rate for one to two year old penguins is 75%. For birds three years old and up, typical annual adult survival rates is 90-95% (Vargas et al., 2007). During good years the population should grow by 4.5% per year to carrying capacity, Vargas et al., 2007). During a minor *El Niño* survival remains stable but reproduction drops to almost nothing. In a severe *El Niño* year, adult survival drops to around 23-35% (Vargas et al., 2006; 2007). Juvenile survival rates are worse. The relatively high survival rates of adults clearly indicate that age alters chances of survival. Model predictions suggest that the species has a 30% probability of extinction within the next 100 years (Vargas et al., 2006; 2007).

The overall population is divided into four subpopulations, all restricted to within 400 km of coastline. 95% of the population is distributed between the westernmost islands of Fernandina and Isabela. These are also the most productive oceanic zones located within the Galapagos. The remaining 5% lives on the islands of Floreana, Santiago, and Bartolome (Vargas et al., 2006). An initial census count in 1972 approximated a population of 6000-15000. Errors are likely in that 1972 count (Vargas et al., 2005). A later census compiled in the mid-1990s approximated a wide population range of 1500 to 4700 individuals (Boersma, 1998: Borboroglu, and Boersma 2013).

Increased quality of estimation of the true value of counts will allow for better prediction, which is needed for conservation purposes. Illustrating the need for updated, more reliable models are several additional surveys performed from the 1980's to current times. Assumptions in earlier high census counts were accounted for by inaccuracies in census techniques. One technique criticized by Vargas referred to Boersma's use of flipper tags. Flipper tags can be difficult to see from a distance. Based on these low numbers the calculated population were often overestimated which caused inaccuracies in the census (Vargas et al., 2005).

However, whatever technique used for counting, all count data demonstrate definite patterns related to environmental fluctuations in the ENSO cycle (Boersma, 1998; Nims et al., 2008, Vargas et al, 2005, 2006, 2007). Whether a severe cycle or a mild one, implications for many Galapagos species are important. Population drops as high as 77% have occurred during severe ENSO cycles. These drops also initiate population bottlenecks (Boersma, 1998; Nims et al., 2008; Vargas et al, 2005; 2006; 2007). Weaker cycles occurring more frequently and have variable impacts and usually do not cause severe reductions in adult survival. Most adults do fine during these years. However, infant survival, chick survival, and adult fecundity drop to near-zero. In the 1971 light *La Nina* year, penguins appeared heavy and healthy. Birds averaged a 15% weight loss in the more severe 1972 *El Niño* year that followed (Boersma, 1998). The bottleneck effect takes effect in one longer-term impact. The rate at which the species can recover is reduced as numbers goes down. Cascading through the years, the reduced numbers of individual leaves them far more vulnerable during a later, more severe cycle. This trend is observed by all the census techniques. Lacking a clear population recovery, because of lower populations between each severe cycle, brings the species closer to extinction (Rosenburg and Harcourt, 1994; Vargas et al., 2006; Vargas et al., 2007).

Should conservation efforts be proposed, and, if so, how should they be carried out? One possible conservation option with a high likelihood of success is captive breeding or captive rehabilitation programs. For the three related species of the Galapagos penguin, there are captive breeding programs. In whatever case or circumstances, other species of *Spheniscus* penguins are generally much stronger in the wild as opposed to the Galapagos penguin. Galapagos penguin population numbers suffer most during the frequent minor *El Niño* events. As indicated above, during minor ENSO events, there is high survival of adults. At the beginning of the ENSO cycle, breeding seems to be successful since many eggs are laid. However, two variables change as an ENSO cycle begins. One is adults tend to neglect incubating eggs. Second, of chicks hatched, their survival rate is very low. Likely these occurrences are due to limited prey in low nutrient warm waters brought in by the ENSO cycle (Boersma, 1998, Borboroglu and Boersma, 2013). It is possible a variation of the captive breeding or rescue programs used by the Southern Africa Foundation for Conservation of Coastal Birds (SANCCOB), described below, might mitigate how severe population loss would be.

Environmental pollution impact, especially in oil spills, on penguins has been researched. Most such research has been performed on African penguins. These have frequently suffered devastating oil spills, most often responded to by the Southern African Foundation for Conservation of Coastal Birds (SANCCOB), which is dedicated to saving African penguins and other threatened seabirds. Its work spreads from the Indian Ocean to Southern Africa, the Antarctic and "Sub-Antarctic". SANCCOB is also a leader in seabird disease research. A facility connected to SANCCOB was set up to help rehabilitate and save stranded adults plus rescue abandoned nests and chicks which suffer oil spills. During one major spill in 1994, more than 10,000 adults were stranded and rescued. 5,213 were ultimately released. 2,652 were observed at breeding sites within 2 years (Underhill et al., 1999). Magellanic Penguins have also seen good pre and post-release survival after oiling, demonstrating possibilities in rehabilitation of adults (Ruoppolo et al., 2012).

However, this is only dealing with birds previously stranded and injured by oil. Rescued chicks and eggs seem to return to the wild in much better shape. Following an oil spill in 2000, hand-reared and re-released chicks displayed comparable survival and breeding rates to chicks raised in a more natural, non-impacted environment. Such comparative results mean that 1000 hand raised chicks will produce 1,220 chicks in their lifetime when natural fecundity of African Penguins is 1.63, and natural death rates are used. Because this may go a long way towards returning a population from a crash, there are additional advantages to proper hand rearing. These chicks have the potential of developing a larger body mass, as well as being better swimmers than their naturally raised counterparts. The only major drawback is high probability of introduced disease to naturally raised chicks (Barham et al., 2008). This drawback can be overcome by potentially protecting wild populations from disease. There was a tested vaccine trial performed in the Baltimore Zoo. By vaccinating only 50% of their bird population, the infection rate for avian malaria went from 50% to only 17% (Grim et al., 2004). This leaves an overall decent chance of success with a captive breeding program for the Galapagos Penguin. This type of program could strongly increase their chances of survival.

1.6 Flightless Cormorants:

Figure 8: Flightless Cormorant with chicks. Photo by http://www.lizworld.com/galapagos/isabela2.htm

The Galapagos or flightless cormorant *(Phalacrocrax harrisi*) has a set of circumstances and problems very different from the Galapagos penguin. First, the total population of cormorants is only around 1,000 at its maximum. The entire population is split up into several subpopulations or colonies located within a narrow range on two islands. Evidence suggests that each colony is distinct genetically. While some researchers suggest that each colony should be studied separately (e.g., Duffie et al., 2009), others regard these separate cormorants as a whole population (e.g., Valle, 1995). The entire population is distributed among less than 400km of coastal land divided between the islands of Isabella and Fernandina. The majority is located on the western side of Isabella and eastern Fernandina. They are resident breeders, remaining at the breeding ground year round. They do travel between colonies, but normally only by swimming. Swimming works better because walking long distances is very difficult for them, plus they cannot fly (Duffie et al., 2009).

Genetically, the closest related species are the Double-crested cormorant (*Phalacrocorax auritus*) and the Neotropical Cormorant (*Phalacrocorax brasilianus*). However, the Galapagos cormorant is unique from all other cormorants in the world due to its clear inability to fly (Kennedy et al., 2009). As elsewhere, evolutionary adaptation brings both benefits and risk. The loss of the ability to fly removes constraints that come with heavier body mass. By having a body mass twice that of other cormorant species, the loss of flight is made up by advantages of more efficient and effective diving for fish. Being heavier and unable to fly also makes the flightless cormorant more vulnerable to predators (Wilson et al., 2008).

Unlike the Galapagos penguin, the cormorant seems to have a small but stable population. Despite drastic fluctuations that so impacted the penguins over the last three decades, the cormorant has seen no extreme change in population numbers. This has allowed the species to move from being listed as endangered to vulnerable (Jimenez et al., 2011). Clutches and juveniles raised are positively associated with cold water. They typically breed more than once a year. Females appear to frequently switch mates, meaning males invest more time than they do in raising the young. Individual colonies are separated from others by 7-45 km. 76.1% of nests typically contain 3 eggs and have a mean clutch size of 1.7. Most eggs are laid between March and October. However, during *El Niño* years, few to no eggs are laid. First year survival is 50%, while the annual survival rate for following ages is 85.7%. Juvenile production per adult is 0.22 during normal years and 0.02 during ENSO years (Tindle et al., 2013; Trillmich et al., 1983). Only reproduction is affecting from changing climates and not adult survival. This is in contrast to the penguin whose recovery of numbers after population crashes are hampered due to absence of reproduction during mild years (Valle, 1995).

A 1970-1971 count came up with a population of 700-800 pairs. They also found a total of 653 nests. Fewer nests were counted the following year (Harris, 1974). Small populations ranging from 700 to 1900 have been observed during the last three decades. Maximum age is unknown. Banding identification, however, revealed one individual reaching 17.2 years. It remains unknown whether this is the norm.

2 Methods:

A stage-based population viability model was built to aid our understanding of population fluctuations among two seabirds of the Galapagos Islands. The Galapagos penguin and flightless cormorant are our subjects. Earlier models and studies have already suggested how ENSO cycles impact shorebirds (Merlen, 1984; Vargas et al., 2007). Population crashes have occurred during these cycles followed by variations in rates of population recovery or lack thereof (Rosenburg and Harcourt, 1987). Climate change, therefore, can be expected to impact population fluctuations with increasing severity and effects of ENSO cycles. Figures and tables below, as products of the population viability model, will bear these trends out. Species survival of these two flightless shorebirds is of real concern.

Population Viability Analysis (PVA) is a quantitative method of predicting future populations of a species. As much as possible, indicators should include current and historical census data for a species in question, their important or critical vital rates, locations, habitat, situations and circumstances. Most important among these indicators are the "vital rates," such as the fecundity and survival probabilities at the specific life stages. All rates are shown below in Table 3.

A modified Leslie matrix model variant called an Usher matrix (Owen-Smith, 2007) was used for these analyses. A Leslie matrix shows each stage of growth based on probability of survival each year all the way to death. Many species have stable and fairly constant survival once mature. Instead of creating a large matrix with repetitive survival an Usher matrix cleans it up by taking adult survival and loops it in the last column. It will produce similar results to a Leslie matrix and allows the matrix to look simpler on paper. (Owen-Smith, 2007).

Below is a life cycle graph of a species' survival and growth. These values are shown in decimals, all values are probabilities and therefore will range from 0.0 to 1.0. Juvenile fecundity is the amount of offspring produced by the juvenile proportion of the population per year, as adult fecundity refers to the proportion produced by adults. Here the fecundity value can go from below 1.0 to well above.

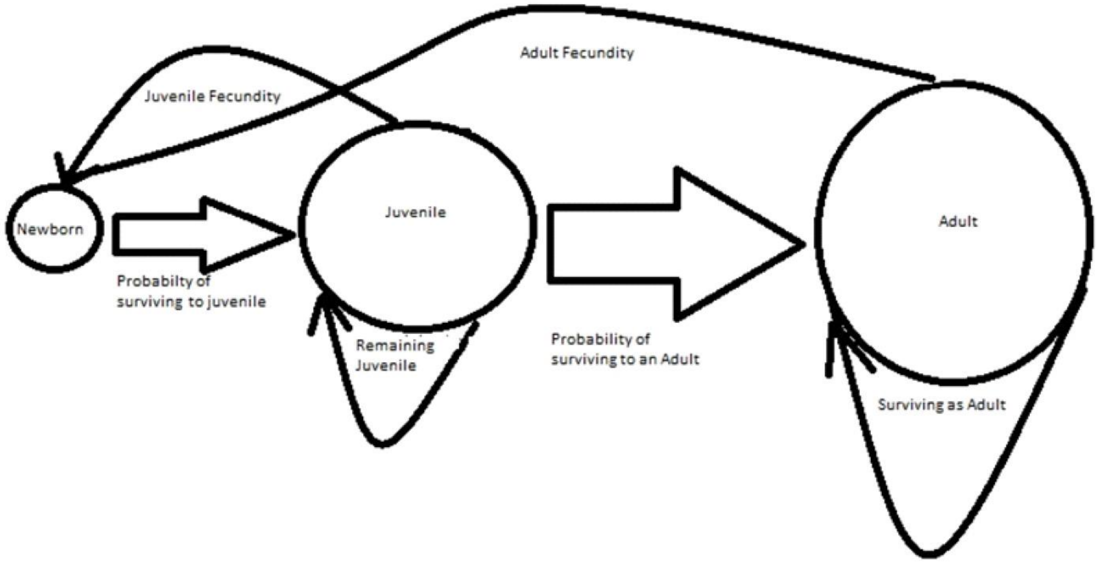

Figure 9: Life Cycle Graph

The data for the PVA is then used to create a matrix with the same data. The following table designates how and where each value from the life cycle graph fits into such a matrix.

Table 1: Sample Life Matrix

	Juvenile Fecundity	Adult Fecundity
Newborn surviving to Juvenile	Juvenile remaining a Juvenile	
	Juvenile surviving to Adult	Adult surviving and remaining an Adult

This matrix then is multiplied by a vector of census data. A vector is a single column with several rows, though it must match the amount of rows in the matrix, in this example that would be 3.

Table 2: Sample Census Vector

Census of Newborns for current year
Census of Juveniles for current year
Census of Adults for current year

Once these tables are built, matrix multiplication is performed. In this particular case, we take a matrix and multiply it by a vector. Figure 10 (shows how matrix calculations are performed. The result of multiplying a matrix by a vector is a new vector of the same amount of rows of the original, again being three in this example. In the PVA, this resulting vector is a prediction of census numbers for the following year's possible census data collection. However, at this point, unpredictable occurrences are not taken into account, since the original matrix stays the same at each step. Unpredictable occurrences may be a tidal wave, an oil spill, extreme storms and/or exposure to invasive, infectious disease. The original matrix cannot take these random factors into account. Effects of any unpredictable nature would be difficult to predict in the model, as would how great might be the negative impact upon the population. This newly calculated census vector is then again multiplied by the original matrix activating yet another vector of the population for the second year. This method can be performed for however many years in the future a prediction is needed for. It must be borne in mind that such a projection assumes stable rates. Therefore if any impacts are to be modeled, the matrix of survival probability must be varied. Thus, a matrix each for good years and for bad years needs development.

For the PVA analyses of the Galapagos penguin and flightless cormorant populations, previous census data from 1970 were used to start the model. Starting there was meant to determine if a level of demonstrated predictability existed in how my calculations matched census data collected in later years. The model also uses several matrices based on different climatic conditions as represented by the recurring ENSO cycle. This PVA of the Galapagos penguin and Flightless cormorant cannot be complete without inclusion of the Pacific Ocean's recurring ENSO cycles. ENSO cycles affect population sizes of both species although has a stronger impact on penguins. In order to build the model, a table of sea surface temperature was built. Using this table determined which matrix to use (good year versus bad year). For this model, a rise in sea surface temperature of 0.5 ºC indicated a mild ENSO cycle (mild year), and a rise of 2 ºC indicated a major ENSO event (severe year) according to ENSO listing such as the multivariate ENSO index (Vargas et al., 2006).

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} ax + by \\ cx + dy \end{bmatrix}$$

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} ax + by + c \\ dx + ey + f \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} ax + by + cz \\ dx + ey + fz \\ gx + hy + iz \end{bmatrix}$$

$$\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} ax + by + cz + d \\ ex + fy + gz + h \\ ix + jy + kz + l \\ 1 \end{bmatrix}$$

Figure 10: Matrix Multiplication Sample: Photo by http://www.cjump.com/bcc/common/Talk3/Math/Matrices/Matrices.html#W01_0040_matrix_and_vector_mat

To help analyze the data further, each matrix requires running a sensitivity and elasticity analysis. Such an analysis allows evaluation how potential changes in each value of the matrix might affects the total growth rate (Owen Smith, 2007). It looks at each arrow located on the life cycle graph and the importance of them to the whole population. The sensitivity analysis indicates how changes in each value of the matrix by a change of a finite number such as 0.1, affect the eigenvalue or eigenvector. Sensitivity analysis evaluates the effect of a change by any value. The elasticity analysis on the other hand shows how each value of the matrix is affecting by an equal percentage change, say 10% (Stevens, 2009).

After the model was built, I then used the data collected to compare to general ENSO data collected by Florida State University in combination with NOAA found on (http://coaps.fsu.edu/jma). These data were used to calculate the likelihood of severe ENSO cycles, mild cycles, and normal years which include La Nina years. Using the R programming language with the R package of *popbio* (http://cran.r-project.org/web/packages/popbio/index.html; Stubben and Milligan, 2007) based on Morris and Doak (2002),census data was multiplied by random combinations of three matrices (good year, mild year, severe year) determined by the percentages based on the ENSO data collected. It then runs the test 100 times giving a histogram of the total population at year 50. Then a final analysis was run showing the likelihood of reaching a quasi-extinction point. The quasi-extinction point is the state where population size cannot recover from losses. The species may survive for a long time but its numbers will never rebound. At such low population sizes, demographic and environmental stochasticity become key factors to survival. The analysis again runs against the same statistics for each type of cycle and shows the likelihood of reaching this point in 100 years.

From possible future transitions, two other samples were run with slightly altered climate data: first, by increasing the likelihood of mild cycles by 10%, and second, by increasing the severe cycle by two cycles in 50 years. If local climatic conditions are altered due to global climate change, these increases in severity of ENSO cycles could occur.

Population statistics and biological data are incorporated into the population viability model. Vital rates are drawn from journal articles and published census data (Table 3). Among other variables, these vital rates include survival probability by stage, fecundity, and population carrying capacity. Such data are limited for the Galapagos penguin and flightless cormorant. Much is missing and more biological data is needed to provide reliable predictions of their population growth or contraction. Species closely related to the Galapagos penguin and flightless cormorant are represented in several wild and captive populations. From the pool of biological and genetic data they provide, gaps in collected data for the specifically Galapagos flightless birds may be extracted. One problem needing further investigation is extraction of such data from the flightless cormorant. Genetic and biological differences to others of its genus may make the usefulness of data from other species dubious.

Table 3: Collected Vital Rate Data for Galapagos Penguins and Flightless Cormorant

Vital rate evaluated	**Value in literature**	**Value used in model**	**Citation**
Galapagos Penguin			
Severe ENSO Cycle Adult Survival	0.25-0.35	0.33	Vargas et al., (2006)
	0.23 to 0.55		Vargas et al., (2007)
	0.23		Boersma, 1998
Severe ENSO Cycle Juvenile Survival	0.0 to 0.3	0.2	Vargas et al., (2007)
Severe ENSO Cycle Chick Survival	Extremely poor to none	0.01	Boersma, 1998
	Poor to none		Vargas et al., (2006)
	0.01		Vargas et al., (2007)
Severe ENSO Cycle Fecundity	Low to none	0.01	Vargas et al., (2006)
Mild ENSO Cycle Adult Survival	0.95	0.9	Vargas et al., (2007)
Mild ENSO Cycle Juvenile Survival	0.33	0.78	Vargas et al., (2007)
	Low		Boersma, 1998
Mild ENSO Cycle Chick Survival	Very poor to none	0.01	Boersma, 1998

Mild ENSO Cycle Fecundity	Little to none	0.01	Boersma, 1998
Good year Adult Survival	0.95	0.9	Vargas et al., (2007)
Good year Juvenile Survival	0.75	0.78	Vargas et al., (2007)
Good year Chick Survival	0.33	0.33	Vargas et al., (2007)
Good year Fecundity	56.7% of mature females breed per season/ in 2003 33.5% of breeding females had 1 chick, 46.4% had 2, 12.4 had 3 ad 7.7%	1.6	Vargas et al., (2007)
	2% lay eggs 3 times/ year, 57% twice a year, 41% once a year		Steinfurth, 2008
	74% laid eggs twice, 24% laid eggs three times		Boersma, 1977
Carrying Capacity	4200	4200	Vargas et al., (2007)
<u>Flightless Cormorant</u>			
Adult Survival	0.92		Tindle et al., 2013
Fecundity Good year	0.8		Tindle et al., 2013
Fecundity Bad Year	0.3		Tindle et al., 2013
Adult Survival	0.904		Tindle et al., 2013
Chick Survival	0.5 to .857		Tindle et al., 2013
Juvenile survival	.857		Tindle et al., 2013

Together with these biological variables are other data requirements, including weather patterns (such as the periodic ENSO cycles), variable conditions of surrounding waters, climate and climate change. For example, surface water temperatures in waters surrounding the Galapagos Islands are only one set of variables among other ever-shifting weather/climate variables. Recorded surface water temperatures were used as predictor of ENSO cycles. As already suggested in the introduction (section 1.3), severe and mild

ENSO cycles do impact bird food supplies, fecundity, along with both adult and chick survival. Therefore, ENSO cycles provide a reliable predictor for future population success or decline. Overfishing and pollution are still more variables. Any time they occur they will have short-term to ongoing impact on all endemic population groups, not just seabirds. Ultimately, all these variables affect population growth or contraction.

Variable conditions on land also require attention. Availability of appropriate or desirable species-specific nesting sites is only one. How safe these nesting sites are from invasive species, such as already mentioned rats and dogs, is another problem. The population variation model will be used to seek these variables out, offer predictability on population and suggest where future data collection and research efforts should be concentrated.

Sea surface temperature data from 1965 to the present are included in Figure 11 below. This data, was collected by the Darwin Foundation, was recorded around the island of Puerto Ayora in the Galapagos (http://www.darwinfoundation.org/datazone/climate). Sea temperatures were used as a past predictor of the severity of ENSO cycles. Seeking possible correlations, sea surface water temperatures recorded for roughly fifty years around the Galapagos Islands are matched to subsequent ENSO cycles.

Data in the tables following Figure 11 trace subsequent impact of the ENSO cycles on the survival of penguins and cormorants. A temperature variation from average at about 0.5 ºC is indicative of initiation of a minor ENSO cycle. A variation from average greater than 2.0 ºC indicates more drastic weather events with subsequent consequences in population fluctuations. Use of current data on frequencies of ENSO cycles therefore should aid in determining future populations and fluctuations for penguin and cormorant.

Considered in the model are data gathered from the National Oceanic and Atmospheric Administration or NOAA as well as the Florida State University (http://coaps.fsu.edu/jma). They suggest outlooks for possible increases in frequency and severity of the ENSO cycles are assumed to be part of climate change. In the model they were used to make assumptions on percentages of ENSO cycles with current climatic conditions

2.2 Galapagos Penguin Predictions:

Vital rates found for this species are variable depending on the severity of the ENSO cycle. Decreases in population by as much as 77% occurred during a severe variations in sea surface temperature in both 1983 and 1998. Such losses, even in small variations, potentially could create an unrecoverable state for this population. Figure 15 will show that since the 1970s, this species has not been able to recover to previously reported historical numbers (>4000 individuals). Survival rates are relatively high (~90%) for adults during most years. Fecundity rates are also high but sensitivities in vital portions of their life stages have made them more vulnerable to climatic variation. This poor outlook becomes even more problematic when one investigates an increasing risk of temperature variations with climate change in the future. Possibilities of disease also affect their situation.

Captive rehabilitation information may also be modeled in order to assess possible changes brought about by conservation efforts. Data from rehabilitation programs on African penguins, as well as others, may be used to determine success rates and breeding statistics for rehabilitated birds.

2.3 Flightless Cormorant model:

As already indicated, the flightless cormorant does not suffer similar catastrophic crashes, as does the Galapagos penguin. Therefore, with a high rate of survival, defined as minimal to no loss during even drastic temperature changes, a cormorant population may remain relatively stable. Breeding is the only issue that suffers during fluctuations in temperature. Due to this, when population loss does occur, it will take relatively little time to recover its earlier numbers. Cormorants, however, are not free of potential problems. Though the population does not typically suffer from the same crashes experienced by penguins, it's extremely small size (<1000) increases cormorant sensitivity to changes. Climate change with all its complexities makes determining probabilities difficult. In any case, even moderate drops in numbers could bring the population very close to extinction. Proper monitoring and accuracy of cormorant population counts are essential to keeping populations of this seabird successful.

3 Results:

3.1 Galapagos ENSO cycle

Figure 11 below records the ENSO cycle for the Galapagos from 1965-2013. Anything from 0.5 to 2.0 degrees Celsius above the average sea surface temperature is indicative of a coming minor *El Niño* cycle (yellow region). More than 2.0 degrees above Celsius is indicative of a severe *El Niño* (red region). Data was collected by the Darwin foundation at Puerto Ayora in the Galapagos. (http://www.darwinfoundation.org/datazone/climate/). The graph clearly shows two severe cycles corresponding with severe cycles of 1983, and 1998. However several others are getting close. If temperatures were to warm slightly, these cycles could increase the rate of severe cycles.

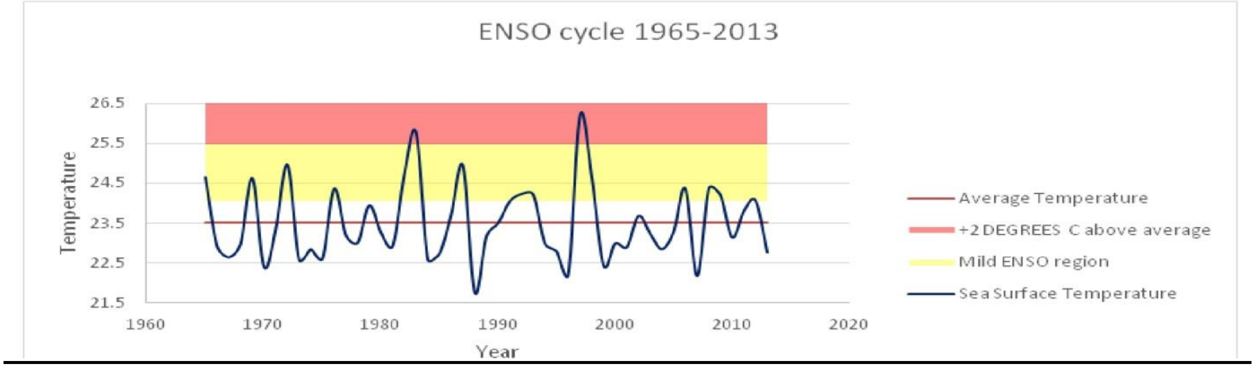

Figure 11: ENSO Cycle for Galapagos 1965-2013

3.2 Galapagos Penguin:

Table 4 below shows the population projection matrix for severe *El Niño* cycles. For the penguin, adult survival is severely impacted. Major die-offs occur with survival rates as low as 33%. Fecundity is also drastically impacted. Reproduction approaches zero during these years. Elasticity and sensitivity analysis (Tables 5 and 6) performed on the matrix were then calculated for the bad year matrix. Adult survival is shown to be most important with a value of (0.998), which is typical of long-lived species. All other values are the same. Sensitivity in Table 6 shows similar results. However, with the provision of being significantly lower, adult fecundity (0.018) and newborn survival rate (0.018) are the second highest values. These are areas where conservation efforts would be applicable to help maintain or restore earlier population numbers. The matrices for the Galapagos penguin are from data collected from a variety of journal sources.

Table 4: Penguin Severe Year Life Matrix

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	0.01
Fledgling	0.01	0	0	0
Juvenile	0	0.2	0	0
Adult	0	0	0.33	0.33

Table 5: Penguin Severe Year Elasticity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	0.00055
Fledgling	0.000554	0	0	0
Juvenile	0	0.0005544	0	0
Adult	0	0	0.000554	0.99778

Table 6: Penguin Severe Year Sensitivity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0.000554	1.68E-05	1.02E-05	0.018304
Fledgling	0.018304	5.54E-04	3.36E-04	0.604381
Juvenile	0.030219	9.15E-04	5.54E-04	0.997783
Adult	0.030236	9.16E-04	5.55E-04	0.998337

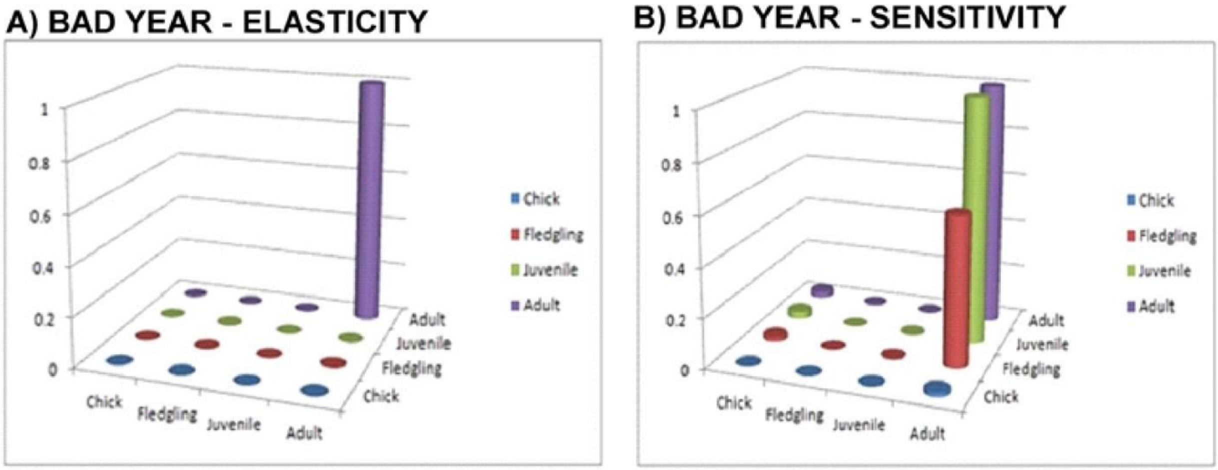

Figure 12: Bar Chart of A: Elasticity B: Sensitivity for the penguin severe year matrix. The size of the bars represents the numerical value of the influence of any respective matrix entry on the Eigenvalue.

Table 7 suggests that a mild *El Niño* affects only adult survival. All other survival rates are virtually unchanged. The elasticity as well as the sensitivity analysis (Tables 8 and 9) suggest adult survival to be most important. However, sensitivity analysis shows fecundity (0.27) as the second highest value and significantly higher than that of the severe cycle. Chick survival (0.08) is the next highest value. This shows that both adult survival as well as population fecundity (including both fertility and chick survival) suffer in such years. Again, this may hint at possibilities for successful conservation efforts to sustain or restore earlier higher population numbers.

Table 7: Penguin Mild Year Life Matrix

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	0.01
Fledgling	0.33	0	0	0
Juvenile	0	0.78	0	0
Adult	0	0	0.78	0.9

Table 8: Penguin Mild Year Elasticity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	0.002996
Fledgling	0.002996	0	0	0
Juvenile	0	0.0029961	0	0
Adult	0	0	0.002996	0.988016

Table 9: Penguin Mild Year Sensitivity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0.002996	0.00109524	0.000946	0.270464
Fledgling	0.008196	0.00299607	0.002589	0.739866
Juvenile	0.009485	0.00346749	0.002996	0.85628
Adult	0.010978	0.00401308	0.003467	0.991012

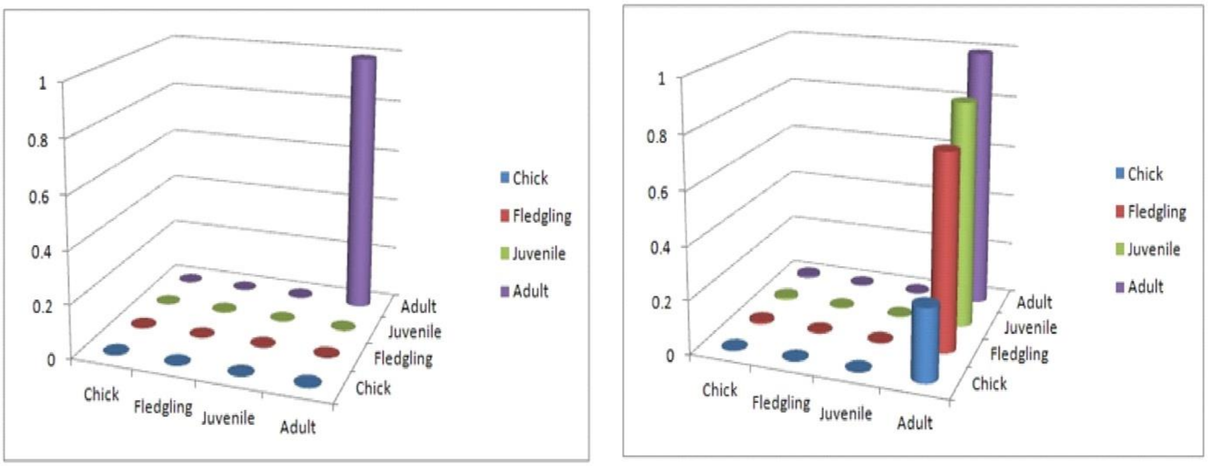

Figure 13: Bar Chart of A: Elasticity B: Sensitivity for the penguin mild year matrix. The size of the bars represents the numerical value of the influence of any respective matrix entry on the Eigenvalue.

During *La Nina* years or even during normal years, fecundity and survival are high (Table 10). According to the data found, there is no recorded difference in fecundity and survival between a normal year and *La Nina* years. The breeding rate is similar to that of a species with high fecundity, suggesting a possible strong rebound of the population. Adult survival (0.62) is shown as most important and chick survival (0.42) is a strong second. Here it is even higher than during both ENSO phases. It clearly shows how chick survival is vital during this phase to keep the population growing. If something were to happen, such as a major environmental catastrophe and wipe out the chick population, it would cause the population to be significantly impacted. This stage class occurs during the majority of years and shows which groups are vital.

Table 10: Penguin Good Year Life Matrix

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	1.6
Fledgling	0.33	0	0	0
Juvenile	0	0.78	0	0
Adult	0	0	0.78	0.9

Table 11: Penguin Good Year Elasticity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0	0	0	0.125106
Fledgling	0.125106	0	0	0
Juvenile	0	0.1251064	0	0
Adult	0	0	0.125106	0.499575

Table 12: Penguin Good Year Sensitivity Analysis

	Chick	Fledgling	Juvenile	Adult
Chick	0.125106	0.03668537	0.025427	0.087995
Fledgling	0.426644	0.12510638	0.086711	0.300087
Juvenile	0.615562	0.18050337	0.125106	0.432965
Adult	0.888132	0.26043011	0.180503	0.624681

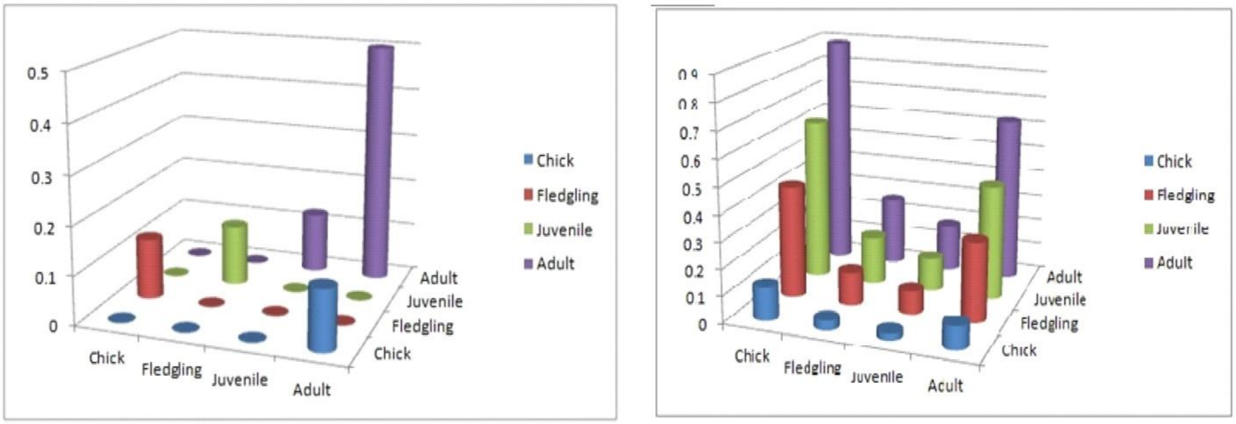

Figure 14: Bar Chart of A: Elasticity B: Sensitivity for the penguin good year matrix. The size of the bars represents the numerical value of the influence of any respective matrix entry on the Eigenvalue.

Using the matrices built above (Tables 4, 7, and 10), as well as sea surface temperature data from 1970 to 2013, the model shown in Figure 15 was built for the Galapagos penguin. The green line is the calculated population based on census data from several journal articles. The blue line is the model that was constructed based on survival data and fecundity from the journal articles and placed into the matrices provided above. As shown, two sharp declines in the population coincided with the two severe ENSO cycles of 1983, and 1998. These two sharp declines have created a situation where, even with a high fecundity rate, the population has declined to a point well below its size in the 1970's. This creates a situation of increasing risk to the population from other risk factors, including pollution, diseases, invasive species, and continuing human interference. If not given some type of strong conservation effort, the population could continue to decline. An even worse prospect would be an increased rate of mild to severe ENSO cycles due to developing climate change. Without proper monitoring and conservation, the species will likely continue to decline.

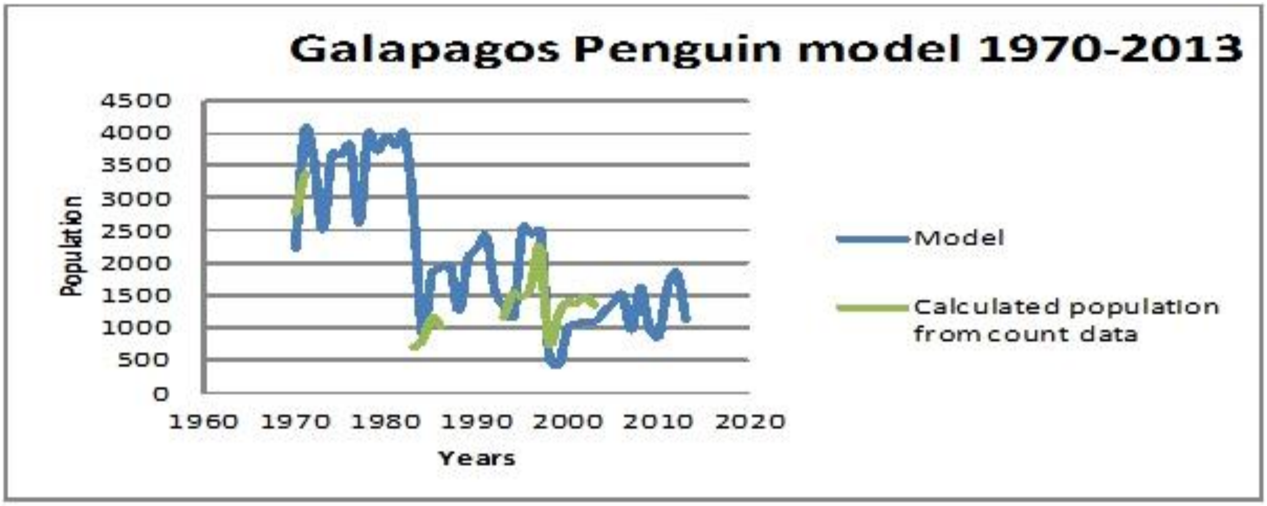

Figure 15: Galapagos Penguin Model 1970-2013 (Blue line is predicted values, Green is census data)

3.3 Flightless Cormorant Projections:

The flightless cormorant does not suffer the same severe drops in population level during ENSO events that the Galapagos penguin does. As shown with the following matrix for severe ENSO cycles, survival is still good for adults and juveniles. However fecundity, like in the penguin models, drops to almost nothing - a value of 0.01. Though not as severe as in penguins, such fecundity reductions cause drastic drops in the population of cormorants. Elasticity and sensitivity analysis suggest adult survival (0.99) to be most important to the species. This also is similar to the penguin upon which both have a similar life structure.

Table 13: Galapagos Cormorant Severe Year Life Matrix

	Chick	Juvenile	Adult
Chick	0.00E+00	0	0.01
Juvenile	1.00E-04	0	0
Adult	0.00E+00	0.5	0.5

Table 14: Galapagos Cormorant Severe Year Elasticity Analysis

	Chick	Juvenile	Adult
Chick	0.00E+00	0.00E+00	4.00E-06
Juvenile	4.00E-06	0.00E+00	0.00E+00
Adult	0.00E+00	4.00E-06	1.00E+00

Table 15: Galapagos Cormorant Severe Year Sensitivity Analysis

	Chick	Juvenile	Adult
Chick	4.00E-06	8.00E-10	0.0002
Juvenile	2.00E-02	4.00E-06	0.999988
Adult	2.00E-02	4.00E-06	0.999992

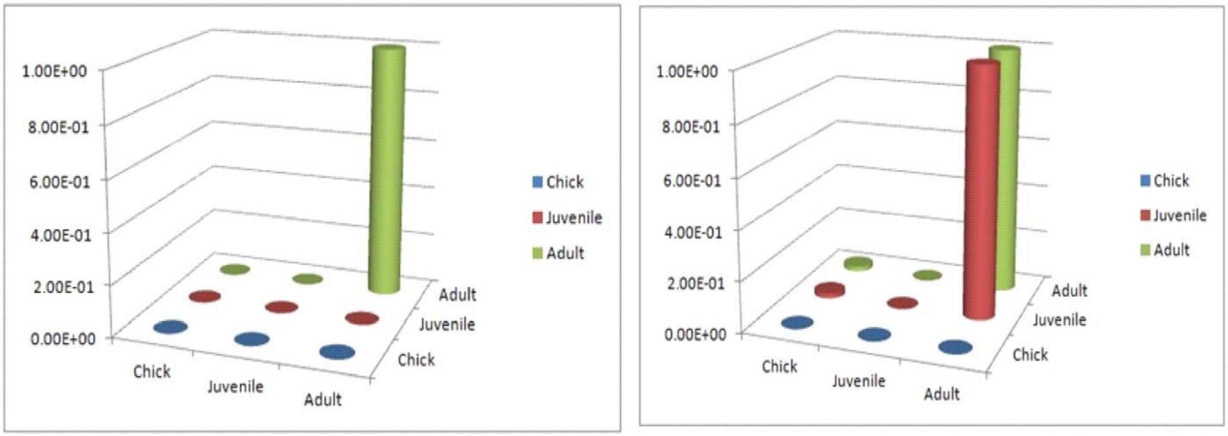

Figure 16: Bar Chart of A: Elasticity B: Sensitivity for the Cormorant severe year matrix. The size of the bars represents the numerical value of the influence of any respective matrix entry on the Eigenvalue.

With mild ENSO cycles and good years, adult fecundity is relatively high (1.7) and survival is excellent. The species may recover from any drops in the population during bad years. If not bothered by invasives or disease the population will stabilize even though the numbers remain relatively low. Sensitivity analysis also indicates adult survival is most important (0.61), while chick survival is a close second to species survival (0.51). The implication is that juvenile survival during these years forestalls the population from crashing.

Table 16: Galapagos Cormorant Good Year Life Matrix

	Chick	Juvenile	Adult
Chick	0	0	1.7
Juvenile	0.5	0	0
Adult	0	0.857	0.904

Table 17: Galapagos Cormorant Good Year Elasticity Analysis

	Chick	Juvenile	Adult
Chick	0	0	0.193556
Juvenile	0.193556	0	0
Adult	0	0.193556	0.4193321

Table 18: Galapagos Cormorant Good Year Sensitivity Analysis

	Chick	Juvenile	Adult
Chick	0.193556	0.0732462	0.1504351
Juvenile	0.5114792	0.193556	0.3975306
Adult	0.7885671	0.2984126	0.6128881

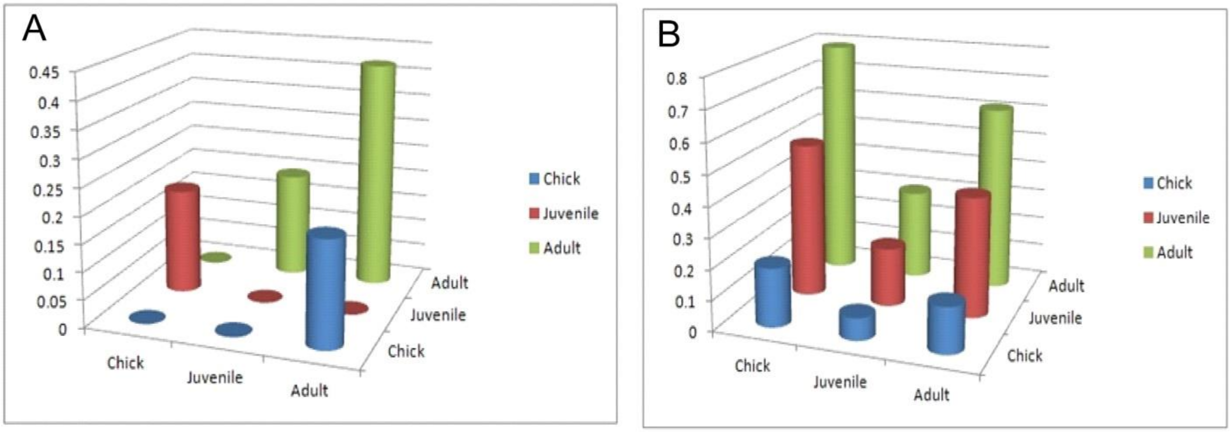

Figure 17: Bar Chart of A: Elasticity B: Sensitivity for the Cormorant good year matrix. The size of the bars represents the numerical value of the influence of any respective matrix entry on the Eigenvalue.

Also for the cormorant, a population simulation was attempted based on the vital rates. This was compared to the very sporadic census data, and broad agreement could be achieved. In Figure 18, the red reveals the limited quantity of available census data. Using these available data in the population viability model produced the blue line in Figure 18. The pattern suggests, minus other external impacts such as introduced disease or other human impact that the population will recover from any crash. Noted are the two major crashes in the population coinciding with the severe cycles of 1983, and 1998.

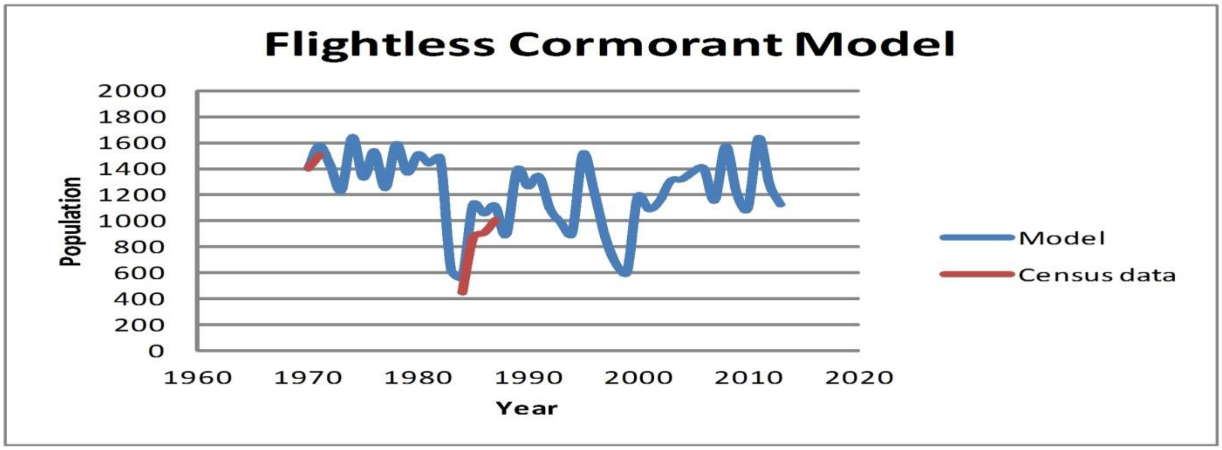

Figure 18: Galapagos Cormorant Model 1970-2013 (Blue Line is predicted model, Red is the available census data)

3.4 Using the models to make predictions:

A sensitivity/elasticity analysis performed found fecundity and chick survival to be important, albeit not the most important factors. However, here a good conservation effort can be applied and focused. If conservation efforts had been started back in the 1970s, an increase in fecundity of just 0.6 from 0.1 for both mild and severe ENSO cycles, the model shown in Figure 19 suggests that a remarkable increase in penguin numbers likely would have occurred. Figure 19 is an edit of the original model shown in Figure 15 with a higher fecundity rate for mild and severe ENSO cycles. This, however, is still a smaller value than what occurs during good years. From census data, eggs were seen during both mild and severe cycles.

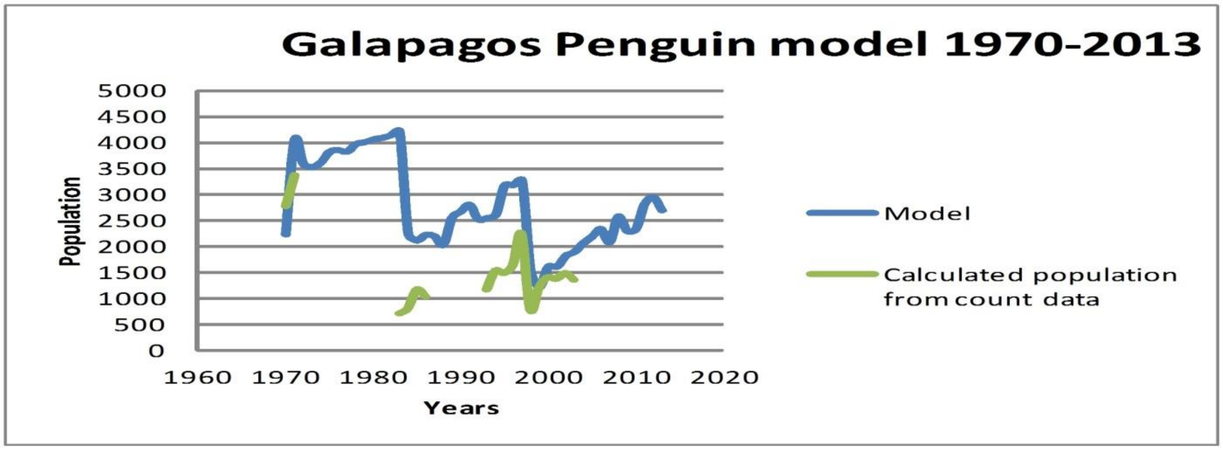

Figure 19: Galapagos Penguin Model with increased Fecundity from 0.01 to 0.6 for mild and severe years for 1970-2013

Population predictions created in a population viability analysis (PVA) and appearing in Figure 20 below used R programming as detailed in the methods. Frequencies of the total population after 50 years are shown. This prediction is based on the Florida State University database of ENSO events from 1950 to 2013. This ENSO data were calculated for the percentage of each type of year. From this a 6.3% chance of a severe cycle occurring is calculated. There is a 28.6% chance of mild ENSO cycle, and a 65.1% chance of a good year. As seen the population ends up very close to zero almost 20% of the time. Large stable populations are less likely than small populations. As is shown there is almost a 20% chance of less than 100 penguins. It is almost another 20% for 100-300 individuals being left at the end of the 50-year cycle. There is only a 10% frequency that the population could grow back up to the population cap of 4300.

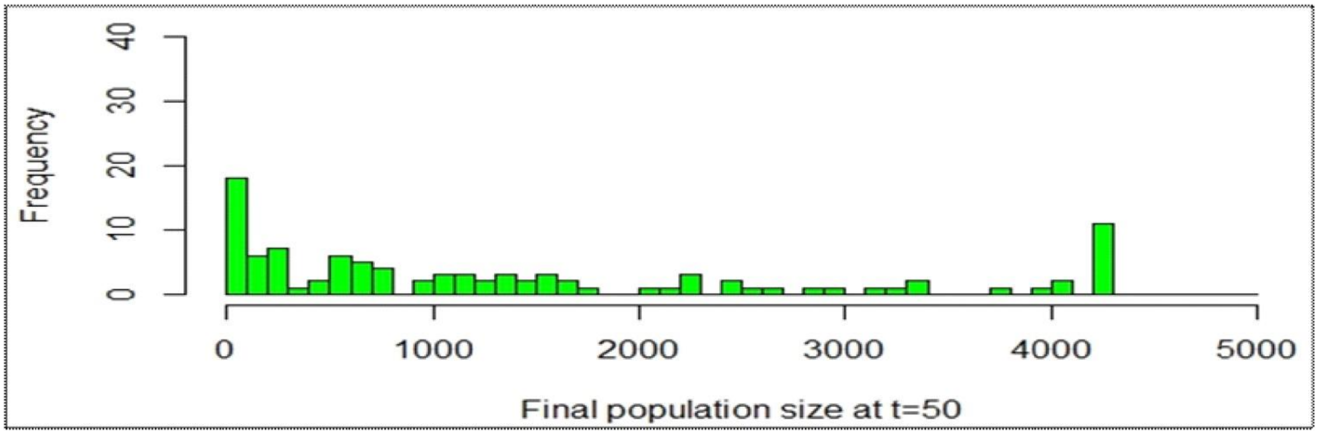

Figure 20: Galapagos Penguin Population Projection with possible populations at year 50

In order to calculate a probability of reaching a quasi-extinction threshold, requires a small enough population that chance of rebound becomes likely impossible. For this using a hypothetical population of 20 was applied and demonstrated below in figure 21. Figure 21 indicates that the probability a population of 20 has a 90% chance of remaining 20 with current environmental conditions. With the Galapagos Penguin being split into three sub-populations this population would be extremely susceptible to disease, pollution, predation, and any other catastrophe that could occur. This 90% probability of remaining at a population of 20 does not take into account any of these occurrences.

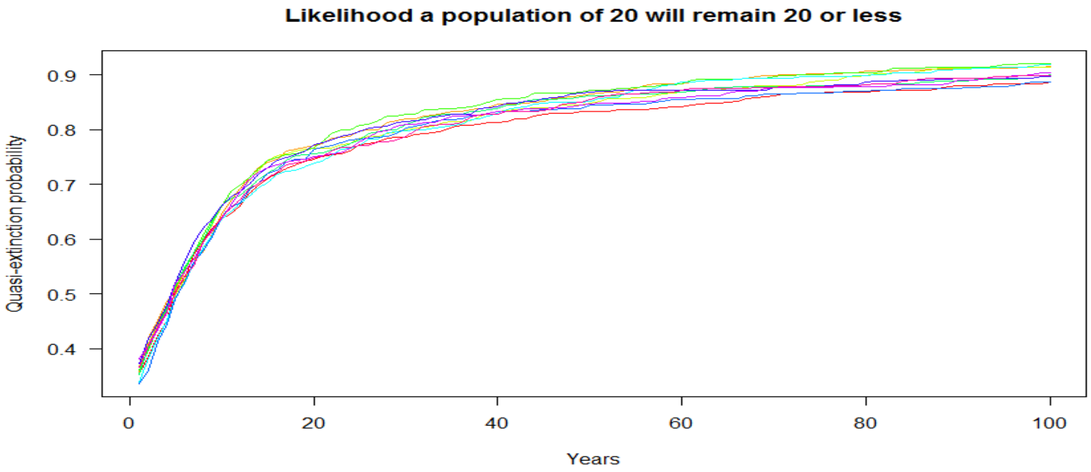

Figure 21: Calculated probability that a population of 20 will remain 20 over the next 100 years using current environmental conditions.

Figure 22 shows probability of reaching a quasi-extinction point of 20. The species persist for a long period after reaching the quasi-extinction point, however, I picked a small population, which would likely not allow the population to recover. Over the next 100 years there is almost a 20% chance of reaching the quasi extinction threshold.

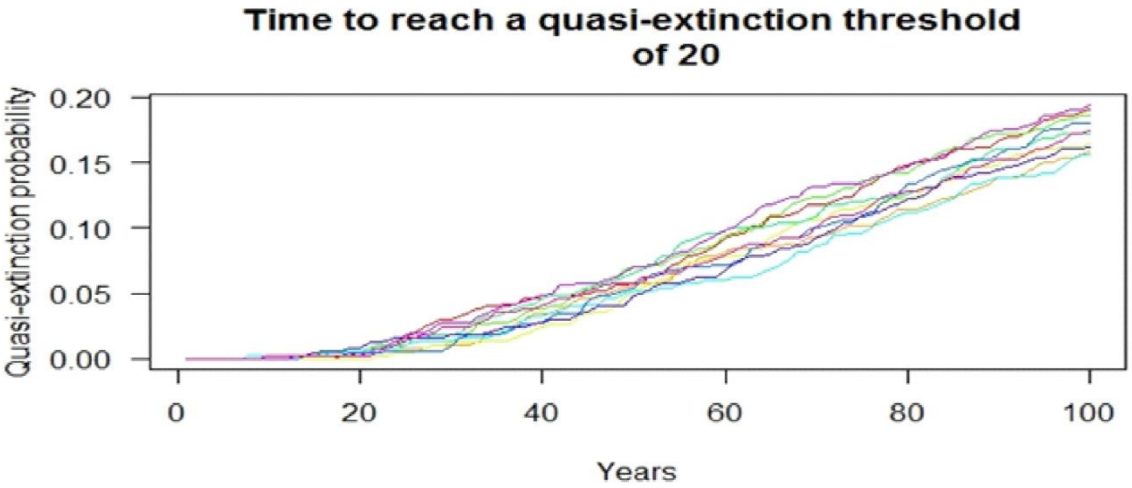

Figure 22: Galapagos Penguin probability of reaching an assumed Quasi Extinction Threshold of 20 animals

With climate change being an issue, there is an increased likelihood of faster recurrence rate of *El Niño* cycles, specifically mild cycles. The following charts, Figure 23 show population projections with a 10% increase in mild *El Niño* cycles. It shows an increase in the probability of the populations only achieving small sizes. With an over 20% frequency, populations of less than 100 are likely to be encountered.

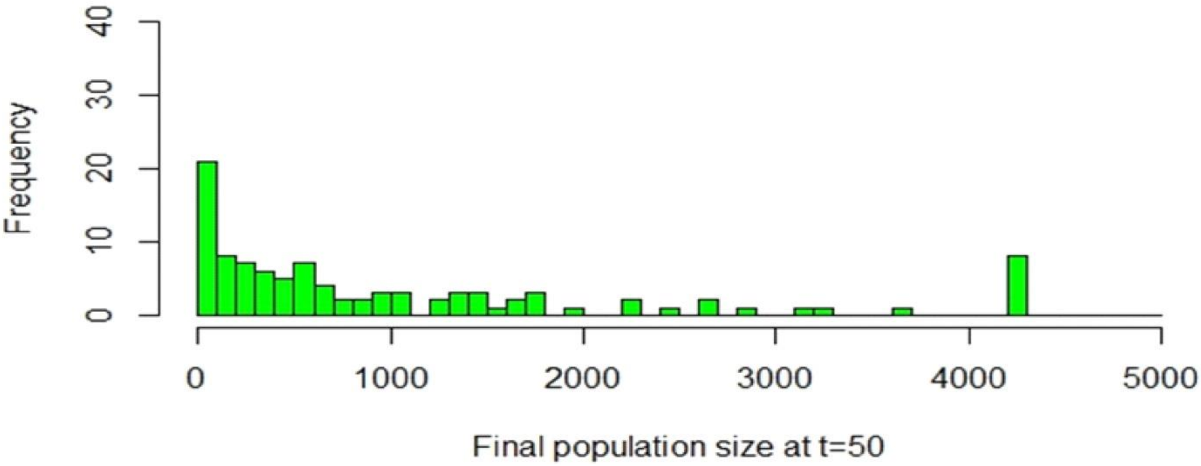

Figure 23: Galapagos Penguin Population Projection with possible populations at year 50 with an increase in mild ENSO cycles by 10%

With the increase in mild *El Niño* cycles of 10% the chance of reaching the quasi extinction point of 20 individuals reaches just over 20% over the next 100 years (Figure 24).

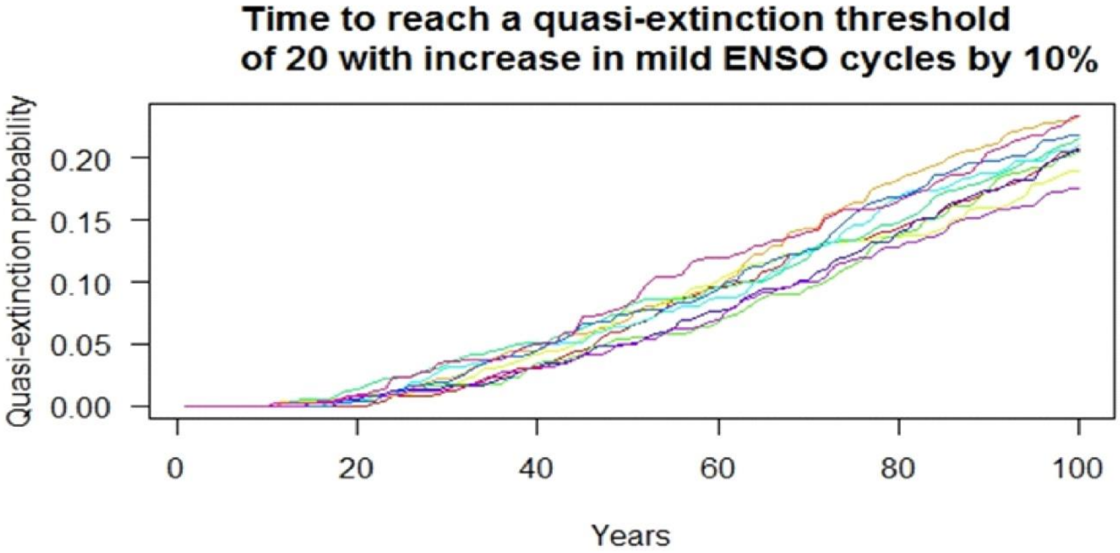

Figure 24: Galapagos Penguin Probability of reaching an assumed quasi extinction threshold of 20 animals with an increase in mild ENSO cycles by 10%

Again with increasing chances of changing climate applied, there is also increased risk of mild cycles becoming severe cycles. An increase of only two severe *El Niño* events over a 60-year period would show the population projections portrayed below (Figure 25). Smaller populations are clearly shown. There is almost a 35% chance of a population of less than 100 penguins in the next 50 years.

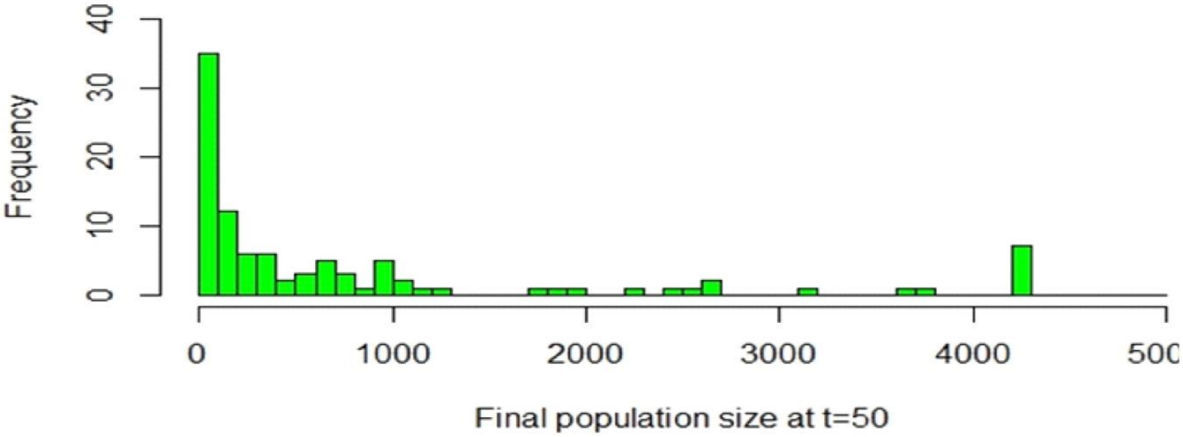

Figure 25: Galapagos Penguin Population Projection with possible populations at year 50 with an increase in mild ENSO Cycles by 10%

All indications are that the probability of small populations will increase in the next 50 years. With this likelihood, reaching the quasi extinction threshold of 20 individuals reaches an almost 60% probability over the next 100 years. This increase would not include an increased likelihood of mild cycles. Figure 26 suggests how drastic the increase in severe cycles could impact the Penguin with increased probability of extinction.

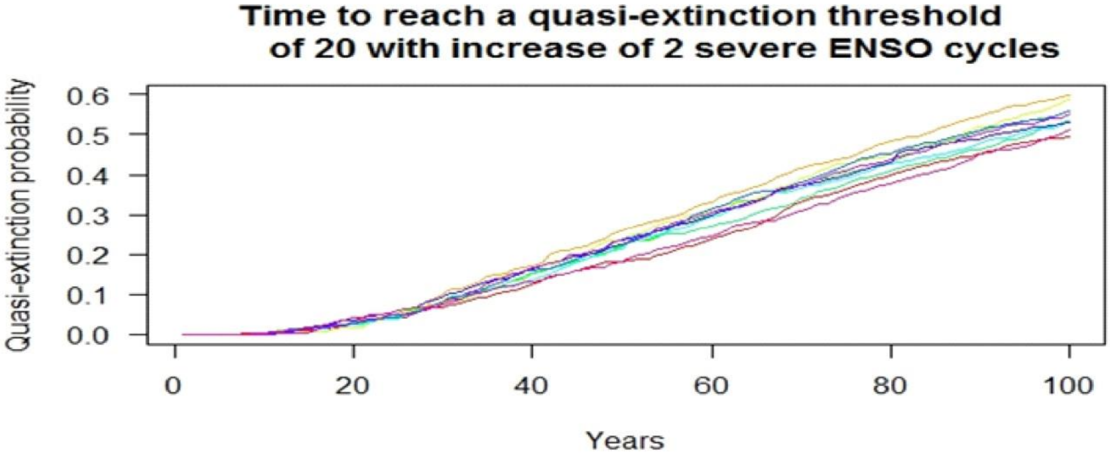

Figure 26: Galapagos Penguin probability of reaching an assumed quasi extinction threshold of 20 animals with an increase of 2 severe ENSO cycles

4: Discussion

ENSO cycles from 1965-2013, as illustrated in Fig. 11, primarily relate to surface ocean temperatures at or near the Equatorial Pacific Ocean. *El Niño* and *La Nina* events occur as average surface water temperatures rise or fall of a few degrees. An *El Niño* event may have nearly global implications on weather thousands of miles away, but upon Galapagos Islands' indigenous species such as the Galapagos penguin and flightless cormorant, implications are profound.

Due to Pacific Ocean ENSO cycles occurring every three to seven years, climatic conditions around the Galapagos bring with them widely variable weather. Figure 11 above illustrates ENSO cycles and by how much they vary in severity. While some cycles are mild with little change in oceanic conditions, others alter weather events enough to negatively impact marine food sources for the Galapagos penguin and cormorant. The results are die-offs of penguins and cormorants.

Observing the severe uptick of the 1983 and 1998 ENSO cycles in the graph above and note how the models shown below compare to the ENSO cycle (Figure 27). Collected census data as well as the model demonstrate that these drastic cycles are involved in extreme population crashes of the Galapagos penguin as well as the flightless cormorant. The cormorant however quickly recovers from these drastic crashes as long as external factors such as locally introduced predators and diseases do not impact the species.

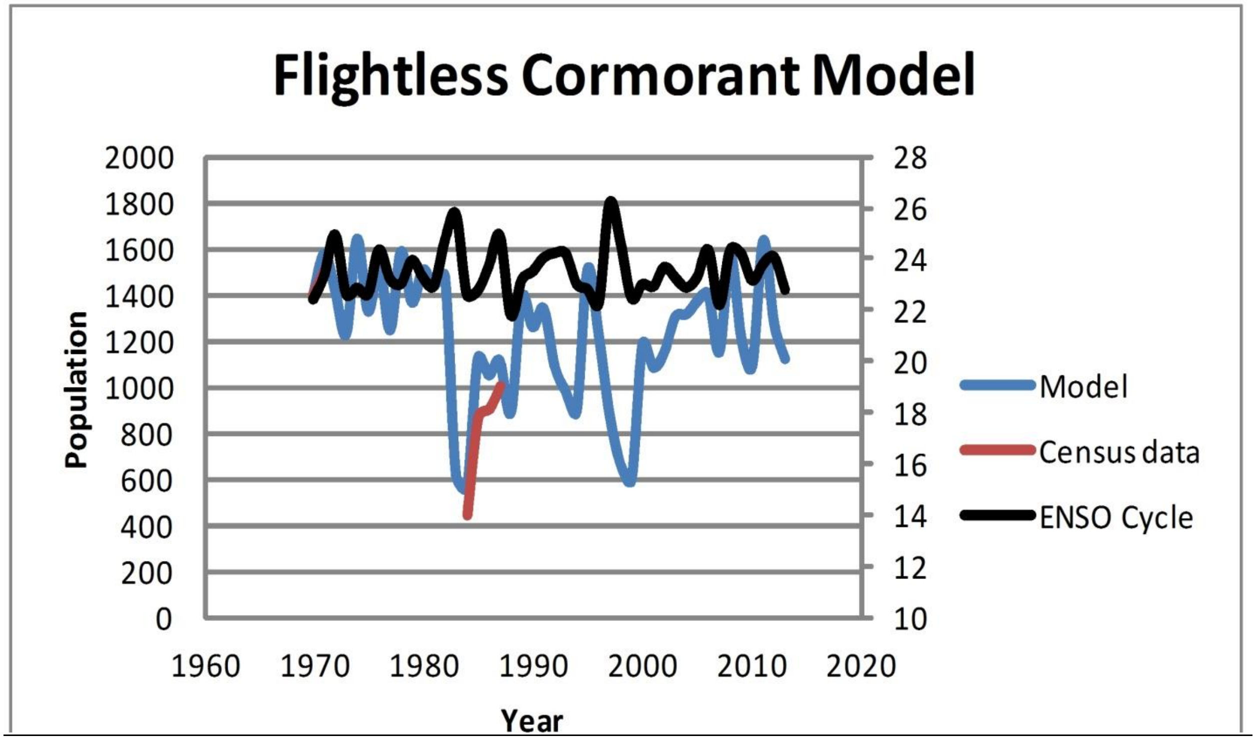

Figure 27: Galapagos Cormorant model vs. ENSO Cycle

Despite its high growth rate and long life span, the Galapagos penguin does not, or cannot, fully recover from these crashes as found by Boersma, 1998, Vargas et al., 2005, as well as supported by my own model. Decreased rates for recovery are caused by the frequent impacts of mild ENSO cycles. They cause significantly smaller crashes in addition to slowing recovery from severe cycles. With enough years between severe cycles, the population would recover as it has in the past. Albeit slow, the model reveals a steady increase during the frequent repetition of mild cycles. Unfortunately, recent decades have seen increasing frequency of severe ENSO cycles, each of which could have major impacts for the future growth of the population.

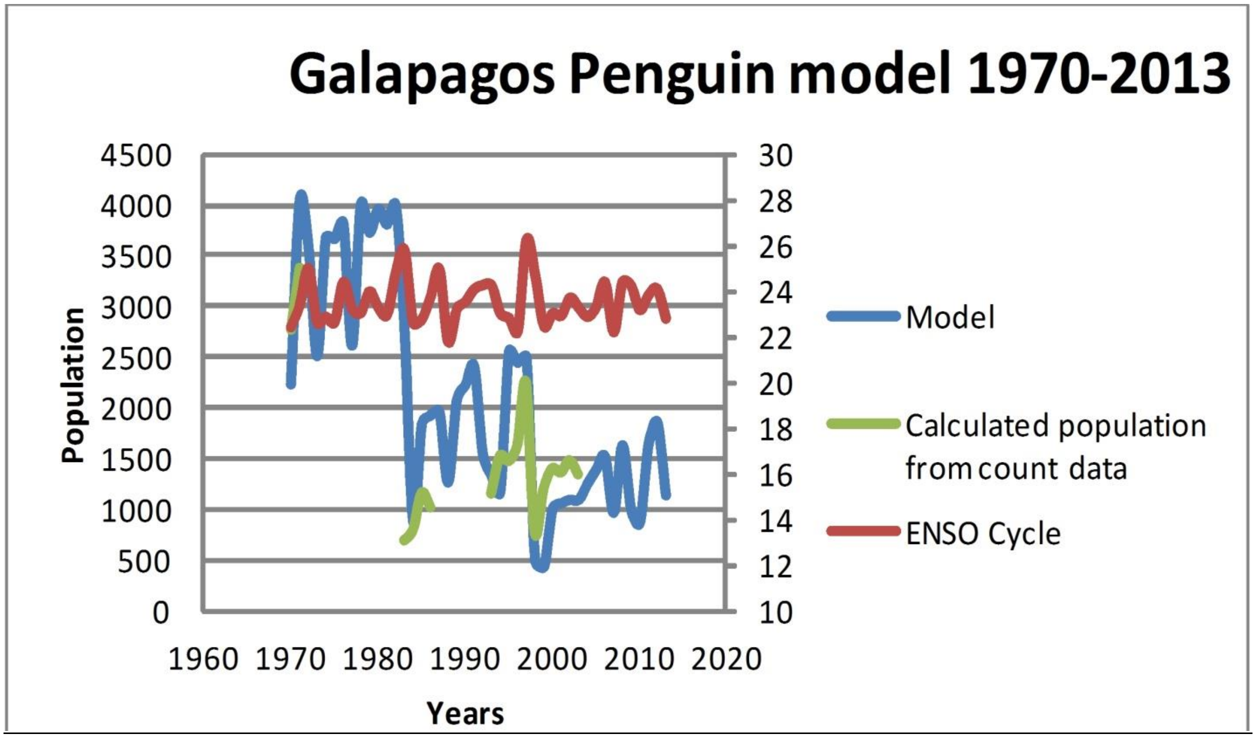

Figure 28: Galapagos Penguin model vs. ENSO cycle

Using collected vital statistics, the model shows the population crashing two times from 1970 to 2013. These two crashes coincide with the two severe ENSO cycles during this period. Each time a severe cycle occurs, it bumps the population down to a new lower state. Though the population seems to grow at a high rate, the increasing numbers are not enough to cause the population to recover to historical levels.

The PVA model closely mirrors the census data. This demonstrates the model as a reasonably reliable predictor for future populations. Follow-up predictions have been calculated. Their results are repeated below. This PVA model provides an additional tool to monitor both population trends and needs plus aid efforts in ongoing and proposed conservation programs.

An important concern when calculating probability of future populations is extinction- potential. This PVA model provides for one measure of probability: the “Quasi-Extinction Threshold” extending over the next one hundred years. For the discussion below, refer back to the following three graphs using three variables for reaching a quasi-extinction threshold of 20 birds or less (Figures 21, 23, and 25).

Using the model, future projections for the Galapagos Penguin indicate a 20% chance of reaching an assumed quasi extinction point in the next 100 years if the current pattern of ENSO cycles continues. With slight changes to the current pattern of mild ENSO cycles, this 20% chance of reaching the quasi extinction point will also increase. However, ongoing global climate change may increase the frequency of severe cycles (Sachs and Ladd, 2010), leaving up to a 60% increase in reaching the quasi extinction point over the next 100 years. Observe the pattern of sea surface temperature around the Galapagos in Figure 28. The probability of increasing severe cycles is clear in that several mild cycles reach a point coming close to a severe pattern.

Numerous other variables not shown in these graphs have had and will have serious negative impacts. The recent introduction of a vector species of mosquito increases the probability of reaching the assumed quasi extinction point within one hundred years. This possibility becomes even more likely when considering the low genetic diversity in the population (Akst, 2002). Earlier human impacts, as in the introduction of dog, cat and rat predators have already negatively impacted the Galapagos penguin's likelihood of population recovery. These species pushed the penguins off some of their original breeding grounds, putting a further strain on the species. Though these introduced species have been removed from the islands to some extent, they do demonstrate how Galapagos seabird species are in a precarious survival state in need of effective and ongoing protection and monitoring.

Species survivability may also be considered with a "sensitivity analysis." Proportionally, how important is the birth or hatchling survival rate compared to the adult population? "Chick survival" in birds is a similar concept to "infant mortality" in humans. One way to consider it is the percentage or proportion of the young hatched or birthed surviving a first year of life. How many or what proportion of them then survive life stages to early reproductive years and finally develop adult fecundity? When environmental conditions turn adverse, such as in weather, disease or invasive species, what proportions of each of these stages survive to reproduce? Which of all these stages or conditions allow for the most successful "recovery" from lost numbers to some approximation of earlier population size? Sensitivity analysis shown in Figure 29 below clearly shows that the most important stage for the survival of the Galapagos penguin is adult survival. As seen, however, adult fecundity and chick survival are secondarily important. It is this stage that a strong focus should be placed on. Captive breeding programs have been shown to be highly successful in their ability to care for and release penguins back into the wild. African penguin chicks released into the wild after being cared for have been shown to be healthier and stronger when released, at least if cared for at a facility with a large pool to learn strong swimming skills (Barham et al., 2008).

Research done on related species, where eggs and chicks were taken into captivity and raised, had positive results. Survival rates from African Penguin rehabilitated showed equal survival and breeding rates to wild born and raised penguins. Despite a smaller fecundity rate below than during normal good years, what is demonstrated, indicates that even a small conservation effort produces strong impact.

Conclusion:

Reviewing existing census data and developing new demographic models, the following dynamics are demonstrated. The Galapagos cormorant experiences losses in reproduction during severe ENSO cycles. Usually, a quick recovery during other years restores the population to its earlier level. Over time, the population remains small, but stable. Introduced predators and disease are its greatest threats. Curtailment of these threats should aid restoration of population stability.

In contrast, the Galapagos penguin experiences drastic reproduction and survival losses during severe ENSO cycles. Increasing frequency of severe cycles over the last fifty years has resulted in diminished capacity for survival and recovery. Losses in reproduction also occur during mild cycles. Other threats to penguin population include invasive predators and introduced diseases. Malaria, introduced by invasive mosquitos, is a high probability threat to the species' survival. Increasing climate change is an additional threat, possibly resulting in extinction.

Interventions such as captive breeding programs could mitigate these threats. Without some form or a mix of types of intervention, the penguin's chances of extinction are 20% over the next 100 years. That is if current conditions continue. Climate change alone could increase that probability to 60%.

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