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Overview of Environmental Stressors, Avian Diseases, and Contaminants in South American Seabirds

Hunter Boykin

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Hunter Boykin

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Approved:
Capstone Committee

Major Professor: Amy Hirons

Committee Member: David Kerstetter

Committee Member: Mike Adkesson

NOVA SOUTHEASTERN UNIVERSITY
HALMOS COLLEGE OF ARTS AND SCIENCES

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Abstract

Diseases and contaminants found along the South American marine environment are known to impact important seabird species, including the Peruvian pelican (*Pelecanus thagus)*, Humboldt penguin (*Spheniscus humboldti),* Guanay cormorant (*Phalacrocorax bougainvillii),* Peruvian booby (*Sula variegate),* and Inca tern (*Larosterna inca).* These seabirds are primarily found along the coast of Peru where they compete for nest sites and prey. The Punta San Juan guano reserve, where these species are located, is affected by periodic environmental fluctuations such as El Niño and La Niña. These fluctuations cause changes in wind patterns and sea surface temperatures which lead to a reduction in prey availability. Major diseases and viruses have led to reductions in populations. The introduction of Lyme disease, avian malaria, Newcastle disease, and avian influenza A have the potential to greatly affect the local seabirds. Flaviviruses such as West Nile virus and eastern, western, and Venezuelan equine encephalitis affect South American seabirds ranging from Peru to Argentina. Parasites are a common vector for some disease transmission. Ticks and mosquitos are common transmitters of arthropod bourne viruses. Although some of these disease have not been found affecting seabirds in Peru, changing environmental conditions could lead to the introduction of migratory birds that will transmit the disease through infected arthropods and birds. The conditions caused by these diseases include weakness of the body, paralysis, severe respiratory issues, blindness, and possible mortality. Polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), organochlorine pesticides (OCPs), persistent organic pollutants (POPs), and perfluorinated compounds (PFCs) cause internal body damage, leading to population declines. Environmental and anthropogenic stressors increase the effects of the diseases and contaminants. As prey reduction occurs and leads to longer foraging trips, the bodies of the seabirds become weak, which allows the diseases and organic and inorganic contaminants to have a greater impact on their overall health. The combination of environmental stressors, diseases, and contaminants can lead to critical population changes to the endemic species of Punta San Juan.

Key Words: Seabirds, Diseases, Contaminants, Environmental stressors

Introduction

Seabirds are broadly adapted to survive, and thrive, in a variety of marine niches. Seabirds are distinguished from all other birds by foraging in the marine environment. Most species nest and breed in colonies along coastlines where they utilize both the terrestrial and marine environments. Seabirds, specifically the Peruvian pelican (*Pelecanus thagus),* Humboldt penguin (*Spheniscus humboldti),* Guanay cormorant (*Phalacrocorax bougainvillii),* Peruvian booby (*Sula variegate),* and Inca tern (*Larosterna inca),* are attracted to the Punta San Juan region of coastal Peru due to the high production resulting from the large upwelling near the coast that is created by major wind patterns and vertical water movement[5,45,72]. The upwelling brings cold, nutrient-rich waters toward the surface which supports extensive plankton production; this planktonic production in turn attracts major prey items for the seabirds[72]. The nutrient-rich waters create a diverse ecosystem and support a complex food web.

The Peruvian ecosystem is greatly affected by many different disturbances. These disturbances have been known to significantly impact seabird populations as well as create major fluctuations throughout the coastal food web. Environmental changes such as the natural El Niño-Southern Oscillation (ENSO) cycles that occur every 2-7 years are strongly correlated with changes in the numbers of seabirds[41]. Changes due to ENSO events lead to key species, such as the Peruvian anchovy, leaving the area and resulting in nutritional stress for the seabirds and other apex level organisms that prey upon this species[80,94,101]. Seabirds have also faced challenges associated with humans. These anthropogenic impacts include extensive guano harvesting, competition for anchovy, and on rare occasions, bycatch of seabirds by the anchovy fisheries[10,28,105]. The seabirds are also impacted by common seabird diseases and viruses. Mosquito species act as carriers of diseases including avian malaria and West Nile Virus[71,85]. Influenza A is generally transmitted from one bird to another, but can be transmitted to other species[85]. Other issues these seabirds face include competition for resources and pollution. Each of these issues cause changes to the health and population sizes of the endemic seabirds along the coast of Peru.

Punta San Juan, Peru

Punta San Juan is a marine protected area located along Peru's southern coastline that acts as a major habitat for a suite of marine mammals and birds. The site was historically protected as a guano reserve, which is a protected location in which large quantities of bird waste are produced and subsequently mined for fertilizer. Guano harvesting in Punta San Juan is becoming a sustainable practice, allowing the species to survive with less negative anthropogenic impacts[20]. Punta San Juan falls within the sub-tropical zone where highly productive coastal waters attract many different trophic organisms[21,105]. Steep cliffs and rocky beaches line the coastline which creates a protected habitat for seabird nests. Opposite the coastline lies a large, man-made concrete wall that was built to protect the vulnerable seabirds from anthropogenic disturbances and natural predators (Figures 1 and 2)[105]. The Punta San Juan Reserve is home to many seabird species including the Peruvian pelican, the Humboldt penguin, the Guanay cormorant, the Peruvian booby, and the Inca tern as well as important marine mammals[8,10,11,13,28,80]. The Peruvian pelican, Guanay cormorant, and Peruvian booby are major contributors to the guano that is deposited in the reserve[21,105]. The guano (bird fecal matter and uric acid) is a major nutrient source that is not only provided by the seabirds, but is also utilized by the seabirds to create nests and burrows[105].

Terrestrial Environment

The Punta San Juan terrestrial environment falls within the sub-tropical region and consists of a warm, dry climate[105]. This region is dominated by large groups of marine mammals and important, guano-producing seabirds[21]. Guano is a highly important resource created and utilized by the seabirds primarily as a nesting resource[21,105]. Intensive guano harvesting for use in fertilizers in the mid-20th century led to declines in the major guano seabird populations and a terrestrial environment denuded of vegetation[105]. Vegetation patterns have also changed with weather conditions. During strong El Niño events, heavy rainfall increases the herb and shrub coverage[57]. The aggressive guano harvesting has also led to changes in the physical environment by the Peruvian government to protect important species[21]. For example, the Peruvian government built a large concrete wall to protect the seabirds from anthropogenic impacts as well as natural predators. Punta San Juan consists of rocky beaches and steep cliffs near the coast

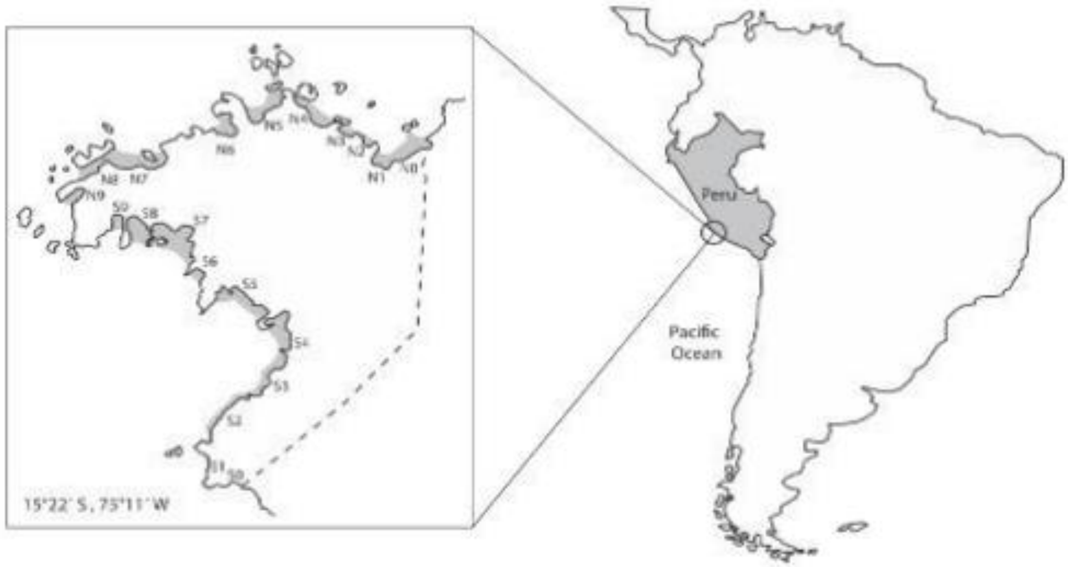

Figure 1: Peru and the Punta San Juan guano reserve along the southern coastline[21].

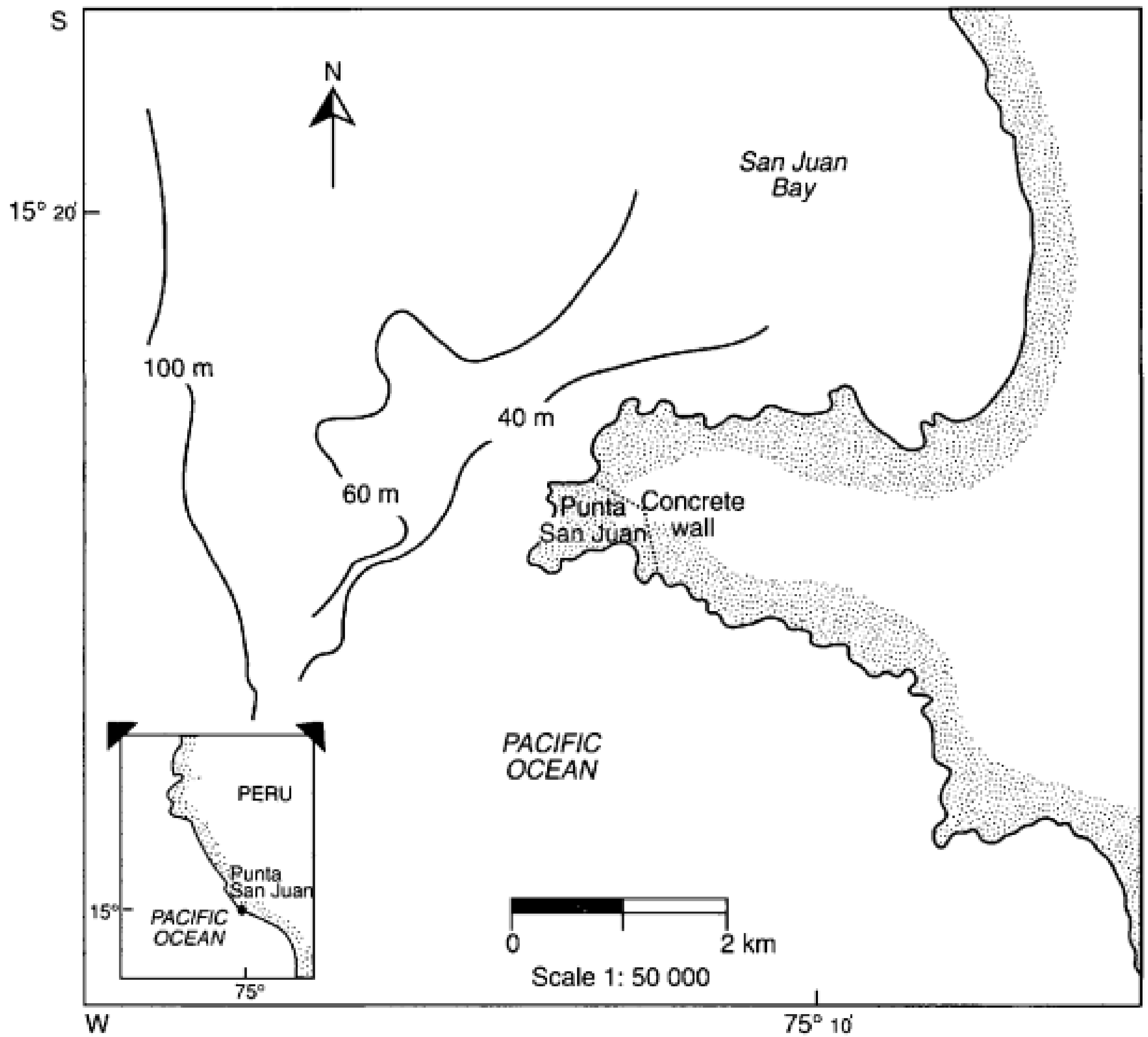

Figure 2: Punta San Juan showing coastal bathymetry and man-made concrete wall[96].

that are utilized as habitat by the dominant seabirds and mammals in the area[21,105]. The seabirds that inhabit this region can be found nesting and breeding in similar locations, leading to competition among species. Certain species will avoid competition by nesting in locations that are unique and further away from other seabirds. Humboldt penguins will dig burrows in the cliffs allowing them to avoid conflict with other seabirds[11,105]. Other seabirds such as the Peruvian booby, actively compete with Peruvian pelicans for the limited nesting space[34].

Marine Environment

The marine environment along the coast of Peru is a highly productive region due to the input of cold, nutrient rich water by the Humboldt Current System (HCS)[21,105]. This coastal region is characterized by a narrow continental shelf, less than 10km wide[15]. Upwelling in this region is caused by equatorward trade winds and water transport of surface waters westward across the Pacific basin. This combination of water movement allows for cold, nutrient rich bottom water to reach the surface waters[5,457,72]. The Punta San Juan coast is also located close to the Pacific trench, thereby allowing the upwelling to occur closer to the Peruvian coastline[6]. The HCS provides important nutrients which promotes primary production and subsequently brings an abundance of organisms to the region, leading to the complex food web that exists between the terrestrial and marine environments[28,41].

Marine Production

The Punta San Juan food web relies heavily on the oceanic processes that occur along the coast. Major upwelling from the HCS attracts large quantities of phytoplankton due to the influx of nutrients to the surface waters[27,44]. This increase in phytoplankton greatly increases the amount of primary production in the marine environment. The increase in phytoplankton biomass also leads to an increase in density of zooplankton in the area to prey upon the primary producers[44]. This attracts schooling fish such as the anchovies and sardines which are later followed by large predators such as seabirds and marine mammals[21]. The major oceanic processes in this region allow for a large and complex food web.

The Peruvian anchovy (*Engraulis ringens)* belongs to the family Engraulidae and acts as an integral species to the Peruvian ecosystem[44,80]. This schooling fish has a short lifespan and grows quickly, reaching maturity after one year[80]. The anchovy is relied upon by higher trophic level predators including both seabirds and marine mammals[44]. Sardines (*Sardinops sagax*) are also a common schooling fish found in the HCS. These fish belong to the Cupleidae family and are larger than anchovies[80]. Both the sardine and anchovy are pelagic schooling fish that forage on zooplankton. However, the sardines can be found further offshore occupying waters off the continental shelf when compared to the anchovy, causing availability problems for certain seabird species, such as the Humboldt penguin, which may be unsuccessful in switching from their usual prey[27]. These two fish taxa play a major role in the environment due to their contributions to the food web. Their trophic position allows for many different species to prey upon them (Figure 3). Density of these fish species is often inversely related. During years of high anchovy abundance, the sardine population is much lower (Figure 4)[7]. Populations of anchovy and zooplankton will generally decrease during warmer periods, while sardine populations will increase[94]. This causes a decrease in the number of prey available for the seabirds that rely on the anchovy. The reduced production at these lower trophic levels then leads to a bottom-up effect throughout the food web causing populations of higher trophic level organisms to be reduced as well. Primary and secondary production of the ecosystem leads to changes in seabird populations[27].

Higher trophic level predators such as marine mammals and seabirds can be seen feeding on these lower trophic level fishes, thereby leading to interspecific competition[11,27,72]. This competition among the different bird and marine mammal species illustrates the important role that the schooling fishes play in the HCS food web. However, these apex predators have also been observed foraging together. Marine mammals such as southern sea lions can be seen corralling the schooling fish. Inca terns will follow these mammals and forage on the fishes that have been corralled[8,38]. This cooperation, combined with the large populations of schooling fishes, allows for a relatively stable food web with inter-annual fluctuations due to environmental factors such as El Niño and human interactions[11,27].

Humboldt Current System

The Humboldt Current System (HCS) is an eastern boundary current that flows northward along the western coast of South America supplying Sub-Antarctic surface waters from high latitudes in the southern hemisphere. The HCS results from the circulation of oceanic currents due to the equatorward trade winds[5,22,72]. As the cold surface waters are being

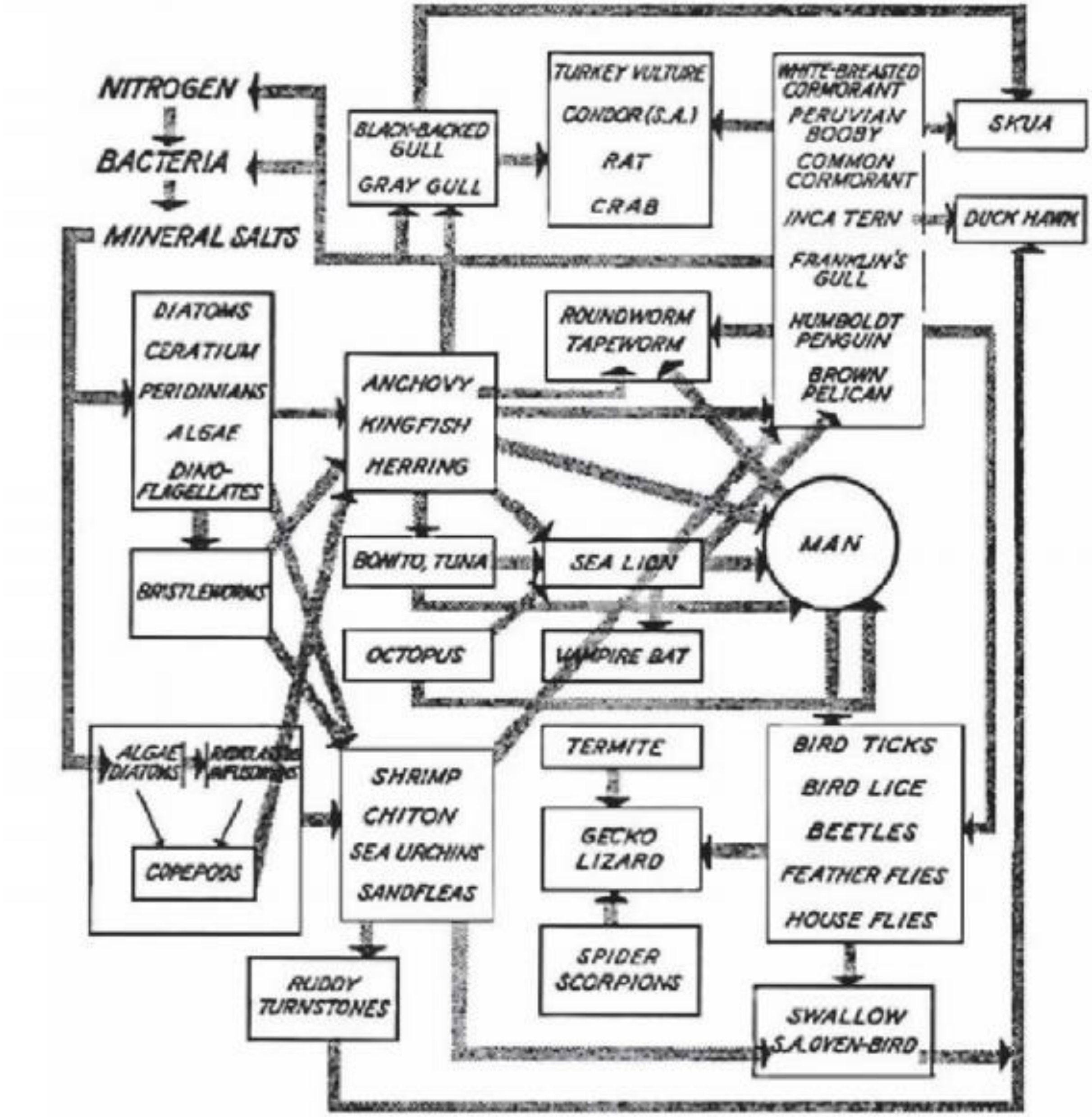

Figure 3: Complex food web of the Humboldt Current System[80].

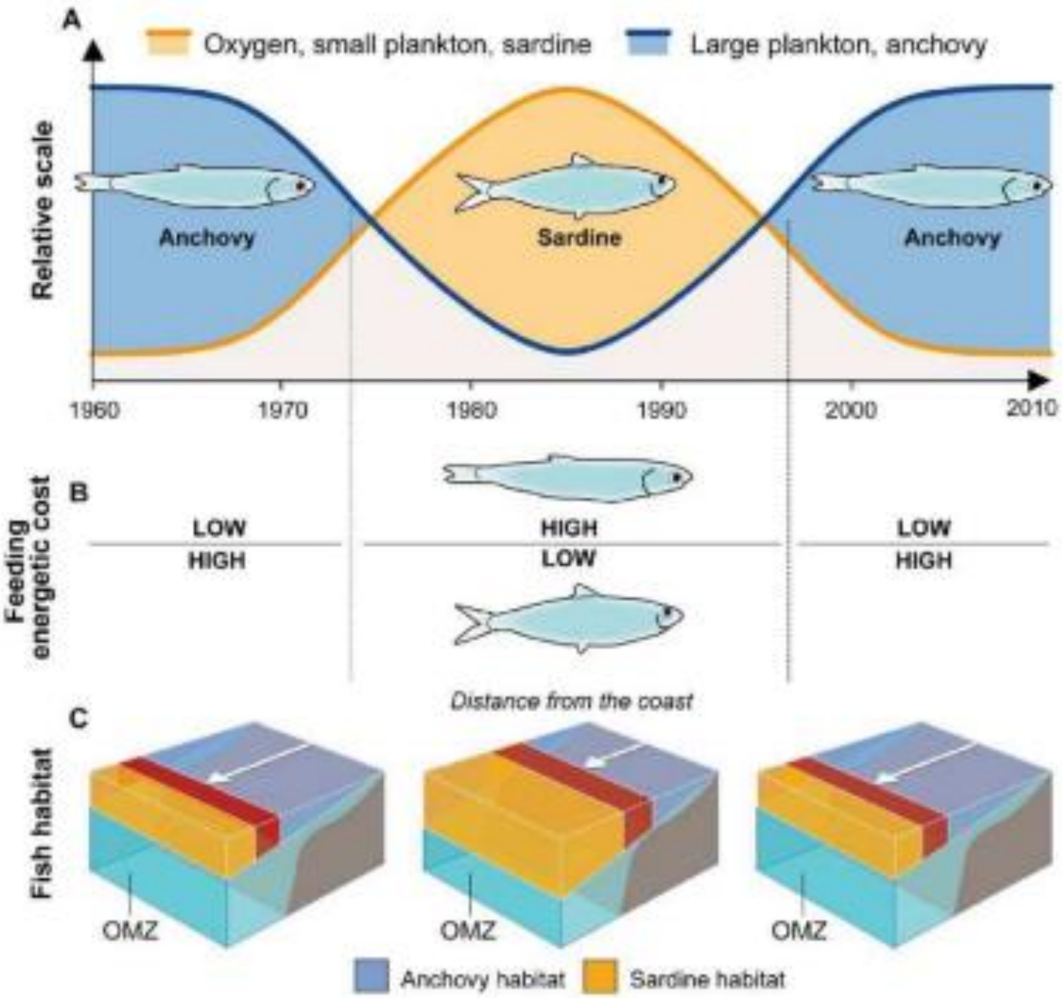

Figure 4: Foraging costs, habitat locations, and relative abundance of the anchovy and sardine[80].

transported northward towards the equator, a countercurrent and undercurrent transport warmer, more saline waters south[72,91]. As the HCS transports water northward, the coastal waters will have a lower salinity and temperature. This may be due to runoff from the terrestrial environment causing the temperature and salinity values to be lower than waters further from shore.

Major upwelling zones along the western South American coast increase the nutrients present in the water[28]. The HCS is characterized by three upwelling subsystems. These include 1) a productive, seasonal, upwelling system found in the south/central region off the coast of Chile, 2) a highly productive, localized, upwelling that occurs year round in Peru, and 3) an upwelling system characterized by lower production along the northern extent of Chile and the southern reaches of Peru (Figures 5 and 6)[72]. The increase in nutrients due to upwelling along the coast leads to trophic enhancements in these regions. This creates a biologically diverse and productive ecosystem within the HCS which supports food webs of small and large pelagic fish and cephalopods, followed by seabirds and mammals[28,72,101].

Due to the high importance of the HCS to the South American neritic waters, changes in the oceanic processes can cause significant fluctuations in the region. Environmental phenomena such as El Niño and La Niña create major reductions or enhancements in the available nutrients to the environment, respectively. Large upwelling in this current system is greatly reduced due to El Niño events which lead to warmer surface waters and a decline in the number of species in the region[5,101]. La Niña events provide the opposite effect of El Niño. This phenomenon is associated with colder surface waters and allows for an enriched upwelling region. This leads to an abundance of nutrients supporting large populations of zooplankton, fishes, and seabirds[5]. Both phenomena cause important changes to the HCS and the species that primarily rely on the HCS for food.

El Niño Southern Oscillation

The Humboldt Current System and resultant upwelling support the food webs of the Punta San Juan Reserve. The major influx of nutrients allows for many different species to survive in a region that is influenced by anthropogenic and environmental factors. The HCS experiences changes inter-annually due to fluctuations in the atmosphere. These perturbations

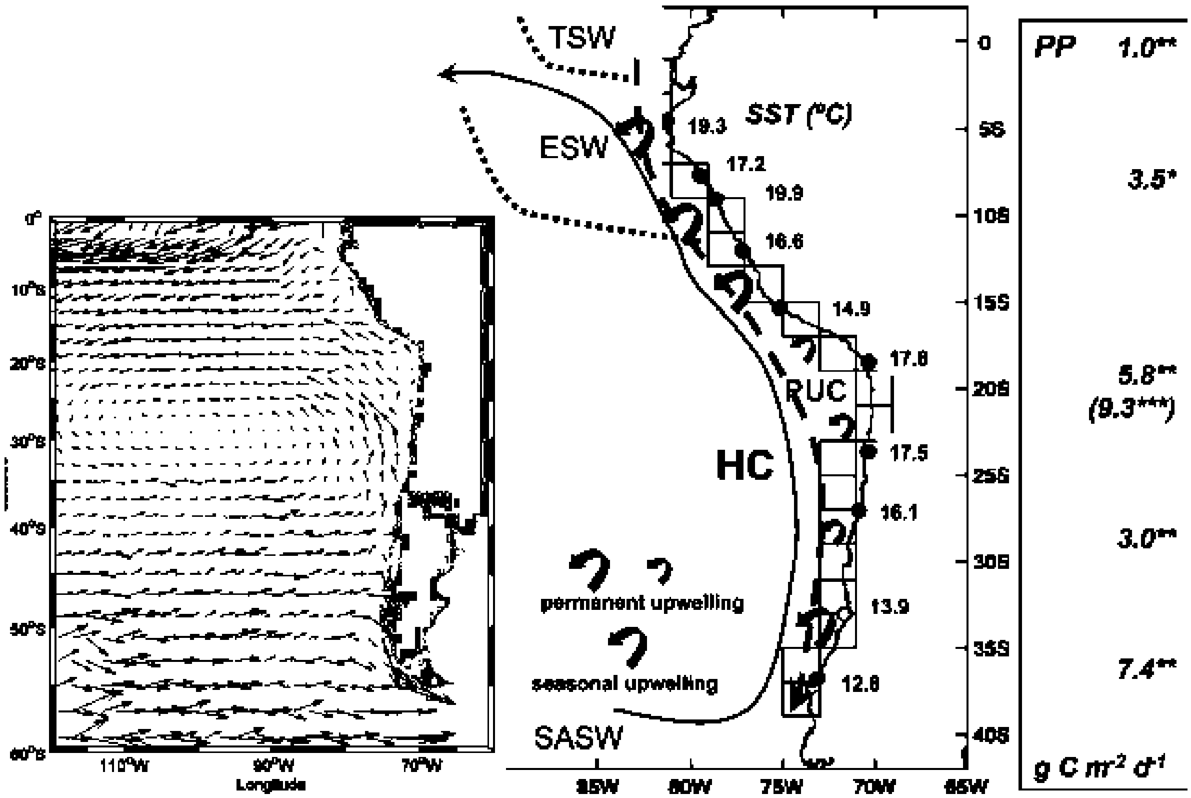

Figure 5: Model of the Humboldt Current System including wind patterns (left), upwelling locations, water masses, and sea surface temperatures (center), and primary production values including the mean, maximum, and gross daily amounts (right)[72].

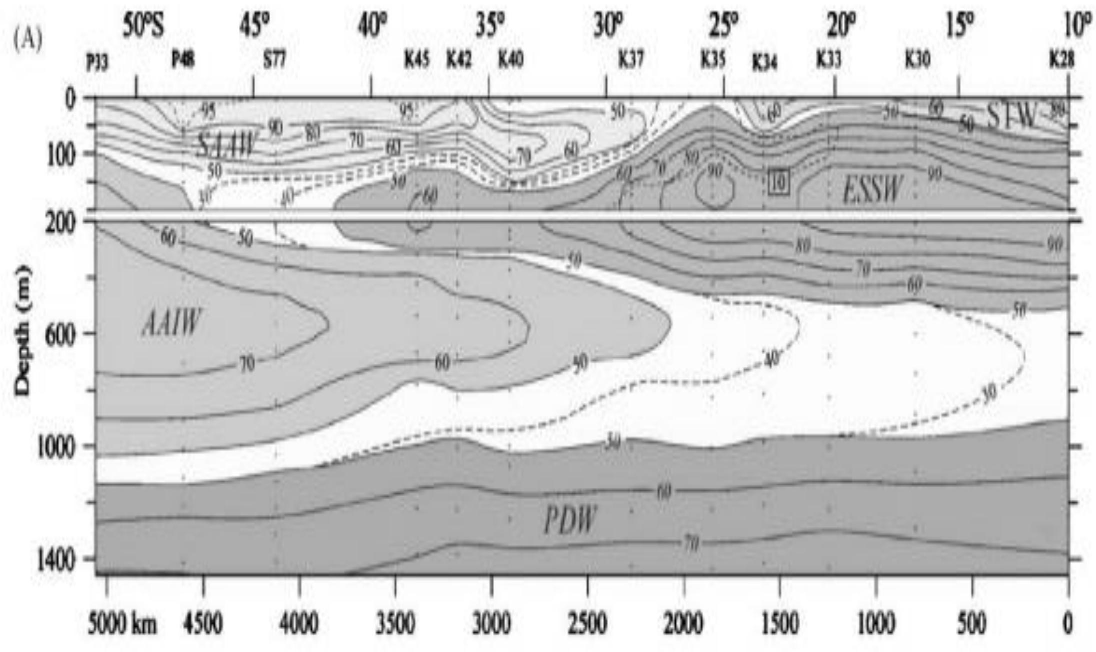

Figure 6: Distribution of water masses off Peru and Chile. A representation of the difference in water masses being transported by the trade winds and undercurrents[91].

occur every 2-7 years and cause significant changes to the Peruvian ecosystem[41]. These fluctuations occur due to a phenomenon known as El Niño Southern Oscillation (ENSO) which is associated with increased sea surface temperatures and changes in wind patterns[47,54]. El Niño is the warm phase of ENSO where the equatorward trade winds and westerlies are greatly reduced[41,57]. The reduction in these wind patterns causes coastal upwelling to cease, allowing for warm, nutrient-poor tropical waters from the western Pacific Ocean to move toward South America[35,41,48]. These major environmental changes then cause fluctuations in the coastal food webs. La Niña in turn results in cooler surface waters supporting high primary and secondary production and an increase in the breeding and body conditions of the seabirds (Figure 7). During El Niño years, reductions in the populations of seabirds will occur and become worse as the El Niño years strengthen La Niña occurrences allow for the populations to rebound and increase from the previous declines; however, reductions in the frequency of La Niña years can lead to the inability of seabird populations to recover from ENSO events[14].

Environmental changes caused by El Niño are often associated with bottom-up effects in coastal food webs. Increases in sea surface temperatures and the reduction in upwelling leads to the influx of nutrient-poor waters and an increase in the oxygen minimum zone[5,40,41,47]. These conditions cause popular schooling fish such as the anchovy to move to deeper waters or leave the area[80,94,101]. This dispersal of important species strongly affects the seabirds that are found along the coast. Once the schooling fishes leave, the seabirds must leave their nests for longer periods and travel farther distances in order to find their prey[54,57]. The seabirds will leave their eggs and young in order to find food, often leading to major population declines[35,54]. Adult seabirds that cannot find food will also succumb to starvation and chicks will starve[35].

El Niño is also associated with large amounts of rainfall. This rainfall increases the terrestrial vegetation of Peru and areas along the coast while also potentially leading to reproductive declines in the seabirds. Large amounts of precipitation and extreme conditions caused by El Niño lead to difficulties for the seabirds to reproduce[57]. Droughts in the years following El Niño further lead to seabird population declines. These declines lead to changes in other species by fluctuations in species in higher trophic levels (Figure 8). Strong El Niño events provide extreme conditions for some seabirds, causing subsequent populations to be unable to

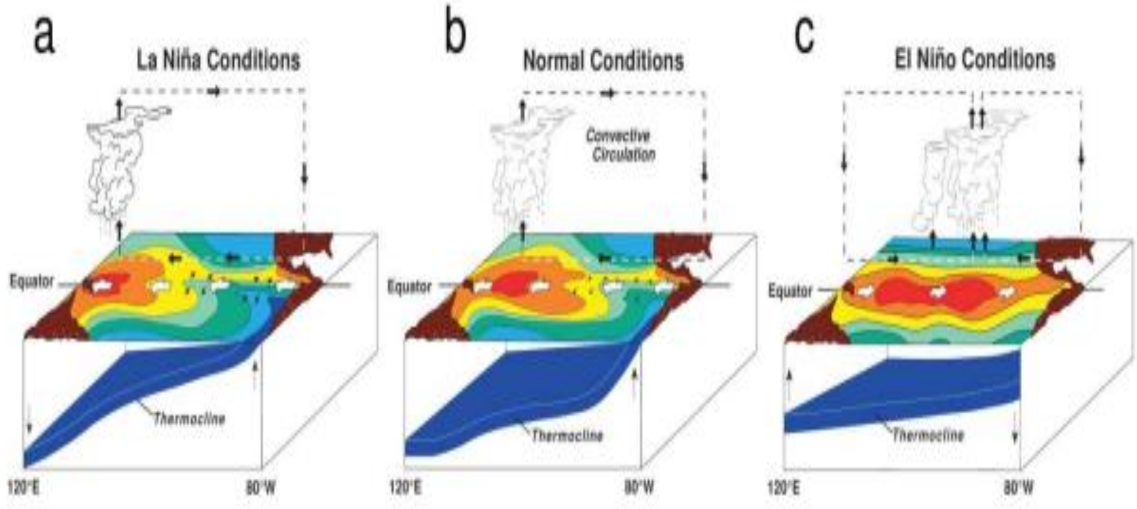

Figure 7: Sea surface conditions during El Niño and La Niña periods with reference to normal sea surface conditions in the Pacific Ocean[80].

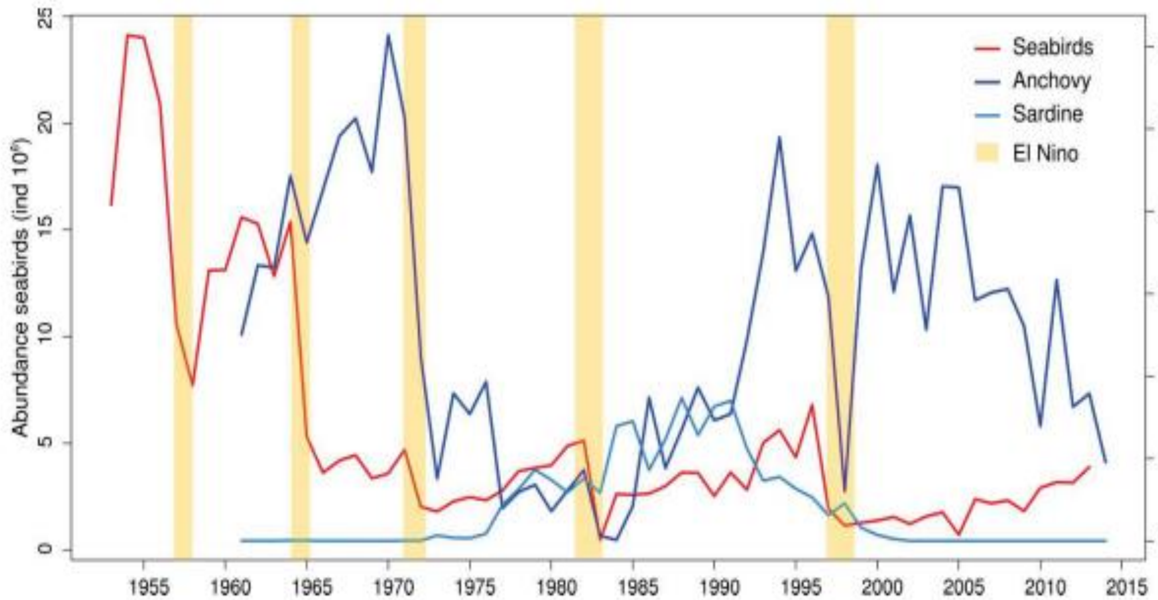

Figure 8: The abundance of Peruvian boobies, pelicans, and Guanay cormorants, as well as the number of sardines and anchovies caught between the years of 1952-2014. Vertical yellow bars represent El Niño events[80].

recover[27]. These extreme conditions will likely have stronger effects on the endemic species due to the smaller population sizes and limited region.

Seabirds

Peruvian Pelican

The Peruvian pelican (*Pelecanus thagus*) of the family Pelecanidae is found along the western coast of South America with populations stretching from southern Ecuador to most of the Chilean coast[10,80]. Populations of this pelican species have been estimated between 100,000 to 1,000,000 individuals with an estimated 500,000 mature individuals. These birds can be found living in coastal locations including sandy and rocky shorelines and extending to rocky cliffs and offshore islands[10]. They can be seen nesting in warm, flat surfaces on the ground in comparison to other seabird species in the area. These pelicans have shown aggression toward Peruvian boobies that attempt to nest in similar locations, but they will generally lose nesting space to the boobies during periods of increased human interaction[34,80]. The Peruvian pelican is most closely related to the brown pelican; however, there are many different morphological features that help distinguish between the species (Figure 9)[61]. The Peruvian pelican is an important contributor to the production of guano in the Peruvian region. This guano that is produced is utilized by other coastal seabirds, including the Humboldt penguin, primarily as a nesting resource, as well as by humans for fertilizer[21,80].

Peruvian pelicans are piscivorous, feeding on common schooling fishes such as anchovy and sardines that are attracted to the coastal waters due to the major upwelling[10]. The anchovy makes up approximately 80% of the overall diet of the regional pelicans[80]. Capturing prey by these pelicans is also unique in comparison to the other seabirds in the region. They participate in a capture method known as surface-plunge diving and surface-seizing which can occur up to 2m in depth. They only forage in the surface waters at night when anchovies move to shallower depths[59,80]. These birds are also kleptoparasites and steal fish from other foraging seabirds. The aggression of these birds can also extend to feeding on pelican chicks if necessary[80]. The Peruvian pelican is a near-threatened endemic species to the Humboldt Current System[10,80]. Populations are attracted to the western coast of South America due to the major upwelling zones along the coast. Because these upwelling zones are responsible for bringing their prey to the

Figure 9: Peruvian pelican[80].

region, changes to this may cause drastic population declines to the seabirds. El Niño events that occur every few years have caused chick and egg mortality as these seabirds leave the nests for longer periods than normal in search of food. Due to the frequency of the El Niño events, population sizes do not generally change drastically; however, more severe El Niño events have been known to cause major, periodic declines in the pelican populations (e.g. 1998)[10,39]. This pelican species is listed as near-threatened with a stable, possibly increasing population[10].

Humboldt Penguin

The Humboldt penguin (*Spheniscus humboldti*) of the family Spheniscidae is an endemic penguin species to the Humboldt Current System that are distributed along the coastlines of both Chile and Peru[11,29]. Many breeding colonies of the Humboldt penguin can be found throughout coastal Chile while few key breeding colonies are found in Peru. One major population of Humboldt penguins nest in the Punta San Juan guano reserve[11,29,105]. Recent population studies found approximately 33,000 Humboldt penguins in Chile while Peruvian populations consist of approximately 11,000-13,000 individuals[11,65,67]. The penguins found at Punta San Juan nest in guano burrows and sea caves and along cliff ledges and crevices[11,19,81,105]. The penguins that choose to nest in the flat, open areas of the reserve must survive higher humidities and temperatures, intense winds, and predators[105]. This penguin species also prefers to breed in high elevations where guano is more prevalent. Once they have created burrows in the guano deposits, they will breed in the spring and fall months[11]. Humboldt penguins are medium-sized penguins, standing approximately 65cm tall, and are identified by their black, gray head with a white chin and a white stripe that extends from their beak down their body (Figure 10)[11,29]. Many ecological similarities occur between Humboldt penguins and species found in the same genus. Magellanic penguins occur in overlapping areas along the coast of Chile. This species of penguin is affected by similar environmental and anthropogenic conditions. They are affected by ENSO events, habitat disruptions, and similar diseases[97]. African penguins live in a location that is very similar to Humboldt penguins. They experience population declines due to prey reduction as well as certain diseases, particularly avian influenza. Outbreaks of diseases on these penguins could signify major problems for the ecologically similar Humboldt penguin species

Figure 10: Humboldt penguin at Punta San Juan, Peru[29].

The diet of the Humboldt penguin consists of popular schooling fishes including the Peruvian anchovy (*Engraulis ringens*), Araucanian herring (*Strangomera bentincki*), sardines (*Sardinops sagas*) and the silverside (*Odontesthes regia*)[11,48,66,67]. These schooling fishes supported by the coastal upwelling that occurs along the coast of Peru[28]. This trophic variety allows the penguins to change their diving patterns to find the appropriate fishes that may be available. During these dives, these penguins will perform two different dive behaviors that include shallow dives occurring within about 1m of water, or bounce dives, where the penguin dives directly to the seafloor then back to the surface[103]. Humboldt penguins dive patterns include V, W, or U-shaped dives[66]. Many Humboldt penguins also forage within 25km from their colony and follow their prey close to shore (Figure 11)[15].

The Humboldt penguin is a vulnerable species consisting of low population sizes and appears to have not yet recovered from the major catastrophes that have affected them over the past century[11,29,51]. This penguin species is endemic to the western coast of South America which suggests their susceptibility to environmental and anthropogenic effects. Threats over the past century have included population disturbance due to guano harvesting, overfishing of their prey, and destruction of their habitats[29,67,105]. Guano harvesting in the mid-19th century has caused major disruptions in the penguins' habitats. The penguins use the guano that is produced by other seabirds as breeding and nesting locations. Reductions in these guano deposits may lead to less protection from predators. Magellanic penguins also occupy a geographically close and overlapping habitat to the Humboldt penguin. This penguin species experiences similar threats to their populations including changes in the climate, prey availability, and diseases[12].

El Niño events have led to abandoned nests as the birds search for prey resulting in chick mortality[11]. Human overfishing of their prey has also led to population declines due to the starvation of the seabirds. Massive reductions in their prey also leads to similar impacts observed during El Niño; adults will leave their nests for long periods in search of prey which leads to chick mortality[29,48,54]. During periods when prey availability is very low, these penguins will suspend breeding[49]. Along with environmental and anthropogenic threats, some penguin colonies must also face the threat of one another. Though this only occurs on rare occasions and in small numbers, male aggression has been observed. These males will intrude on the nests, kill the chicks, and attempt to mate with the females[96].

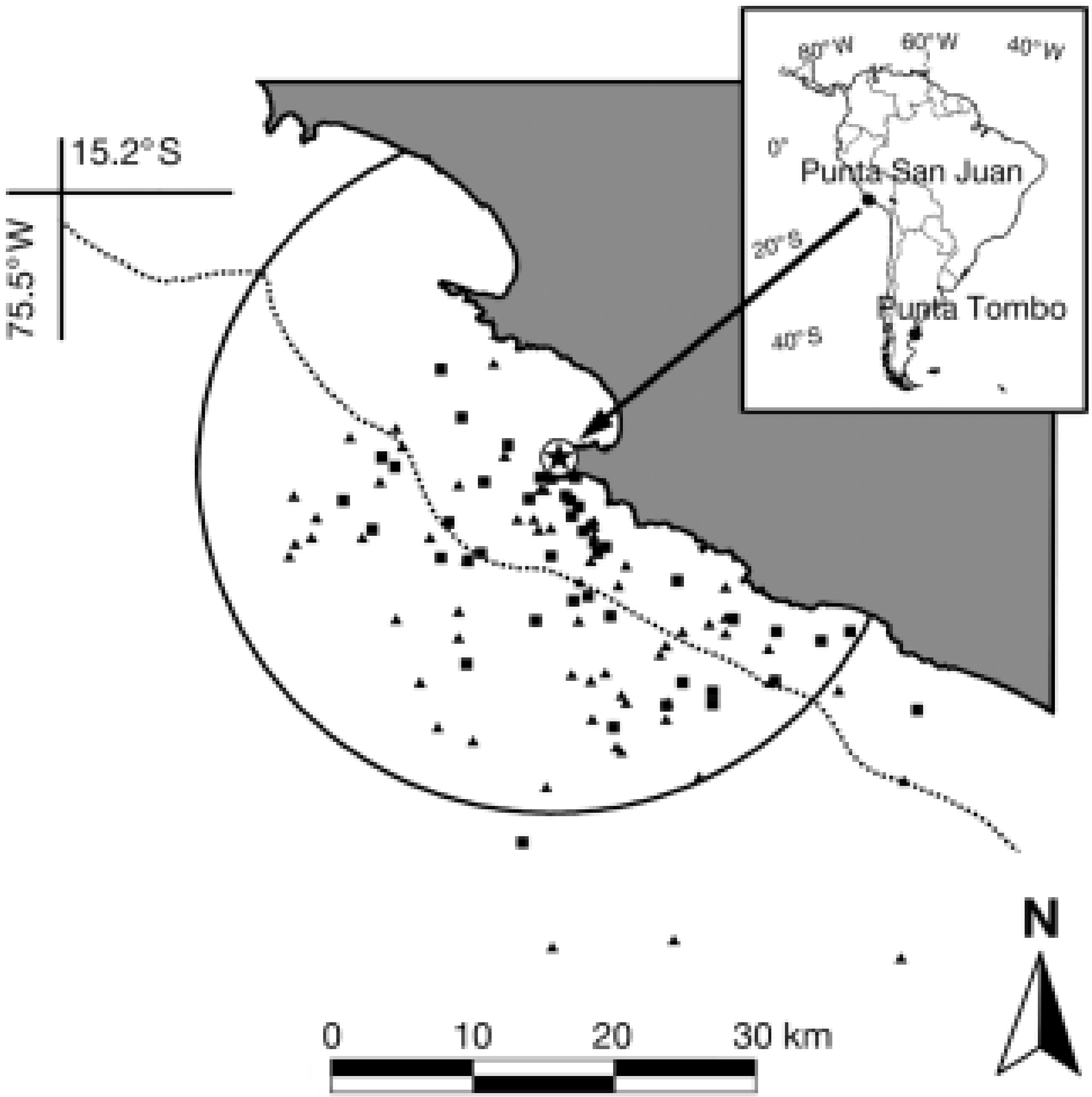

Figure 11: Foraging distances of Humboldt penguins relative to their colony. Solid line represents the 25km distance from the colony. The colony of Humboldt penguins at Punta San Juan is represented by the star. The triangles and squares represent the forage locations of two females of the colony in Punta San Juan[15].

Guanay Cormorant

The Guanay cormorant (*Phalacrocorax bougainvillii*), of the family Phalacrocoracidae, is a common seabird species found along the coast of Peru and Chile[9,96]. This specific seabird, like a few other endemic species to the Humboldt Current System, is a major contributor to the production of guano[80]. Populations of Guanay cormorants have been estimated to decline to between 2.5 million to 5 million individuals from approximately 21 million individuals in 1955[9,96]. These large population sizes mean environmental changes impact their species success less than the more vulnerable seabirds in this region. As an adult, the Guanay cormorant is characterized by having a very dark blue-green coloration on their back and neck, white underbelly and a distinctive red coloration surrounding their eyes (Figure 12)[9,80].

Guanay cormorants create nests from guano deposits, feathers, and even other debris along considerably steep slopes. These secluded nesting sites mean less competition with other local seabirds. In situations where nesting locations are difficult to find, the cormorants lose out on many locations to the pelicans and boobies in the same region. Guanay cormorants preferred nesting locations that were much cooler than the flat and hot locations chosen by the pelicans[34].

The diet of this endemic seabird consists mainly of the popular schooling fish, the Peruvian anchovy; however, they have been known to prey upon Peruvian silverside and mote sculpin as well[9,96]. The cormorants feed solely during the day and will generally spend 2 hours or less foraging, indicating high prey availability. Foraging trips that last more than approximately 6 hours could represent periods of low prey availability or increased difficulty finding food[96]. The cormorant dives are usually shallow (<8m); they will follow their prey to the benthos[102,96]. The majority of foraging trips off the coast of Punta San Juan occurred within 3km from the shoreline and reached depths of up to 50m when following prey[96].

The Guanay cormorant is near threatened due to consistent population declines, from approximately 21 million individuals to approximately 4 million individuals, throughout Peru and Chile[9]. These massive declines have resulted from guano harvesting disturbance and El Niño. Guano harvesting has contributed to habitat destruction and noise pollution to the area which forces the cormorants to leave and abandon their nests, uprooting whole colonies. This could then lead to possible competition in nearby locations for nesting and prey. Periodic

Figure 12: Morphological features of the Guanay Cormorant[80].

environmental fluctuations account for the rise and fall of population sizes; however, strong El Niño effects cause changes in prey availability and upwelling. These changes can then lead to major issues such as reproductive failure or even death. Minor issues include competition for food with coastal fisheries and, on rare occasions, as bycatch by these fisheries[9].

Other cormorant species found in South America exhibit similar habitats and behaviors compared to the guanay cormorant. The red-legged cormorant nests on steep, rocky cliffs which correlate strongly to the nesting preferences of the guanay cormorant[43]. Neotropic cormorants occupy a range of habitats including both freshwater and marine environments. This cormorant will forage similar to the guanay cormorant by plunge diving from higher elevations in order to prey on fish[84]. Similarities among these individual species represent important ecological aspects of these seabirds.

Peruvian Booby

The Peruvian booby (*Sula variegate*) of the family Sulidae, is also found along the western coast of South America[13]. These seabirds have similar population sizes to the Guanay cormorant, with recent estimates of 1-1.2 million individuals[13,36]. The booby is found nesting on cliffs, slopes, and flat sandy regions. For these birds, slopes and cliffs, less steep than those favored by cormorants, are preferred for nesting whereas the sandy flats are preferred for breeding[33,80]. Pelicans in the region have been known to show aggression to these birds over nesting space; however, these boobies were able to utilize cliff edges to avoid much of the aggression[34]. Nests consist of debris and nearby pebbles[80].

The Peruvian booby is closely related to the blue-footed booby. These two species share similar habitats and an overlap in their distribution. The species can be distinguished by different morphologies. The Peruvian booby has a distinct white head and neck, darker back feathers, and a white underbelly. Their beaks are generally a purple-blue color and their legs and feet are grayer than other boobies (Figure 13)[80]. These are distinctive morphological differences than the closely related blue-footed booby. Blue-footed boobies have a brown head and neck with blue feet and legs[95]. The Peruvian booby utilizes the HCS as a major source of environmental input such as food and nutrients. This differs from the blue-footed booby which is found in coastal

Figure 13: Peruvian booby[80].

environments ranging from the Gulf of California to Peru. The highly productive HCS likely could have acted as a barrier leading to a divergence from other booby species[82].

The diet of the Peruvian booby consists mainly of the Peruvian anchovy, comprising approximately 80% of their overall diet[80]. The population sizes of this seabird are strongly associated with the availability of anchovies[26]. These seabirds also feed on other schooling fish such as the sardine and can change their diet to other fishes and squid if necessary[13,80]. The Peruvian booby will generally feed close to shore where they can benefit from the coastal upwelling and in close proximity to their colony[13]. The boobies plunge dive from heights of about 30-40m in either large or small groups into schools of anchovy[13,33,64,80]. This foraging process allows for momentum to assist in prey capture.

The Peruvian booby is one of the major seabirds on the western coast of South America. This species is categorized as least concern due to their large population sizes and relatively stable population trends[13]. Due to the large quantities of guano that these seabirds produce, they provide nest materials and habitats to the other seabirds along the coast. Although large numbers of Peruvian boobies are present in the wild, strong El Niño impacts and anthropogenic guano harvesting have caused fluctuations in their population sizes. Due to the reliance on anchovies, major El Niño effects can lead to reductions in the number of breeding pairs. Previous guano harvesting has also affected these birds. Similar to the Guanay cormorant, the guano harvesting in the area acts as a major disturbance; however, it is not believed to cause massive changes to booby populations[13].

Inca Tern

The Inca tern (*Larosterna inca*) of the family Laridae is also endemic along the western coast of Peru and most of Chile[8]. The number of Inca terns is approximately 150,000 individuals[8,36]. These terns nest in sea caves, fissures, and even burrow which may have been previous nesting locations of Humboldt penguins[8,98,106]. The Inca tern has been observed breeding in crevices and other cavities along the rocky coastline, safely away from predators[8,98]. The terns are small to medium sized birds, standing approximately 41cm tall, and can be identified by their orange beaks and legs, gray feathers, and white underbelly (Figure 14)[8].


Figure 14: Inca Tern[80].

The Inca tern has a diet similar to the Guanay cormorant, feeding on Peruvian anchovy, but also other species such as mote sculpin and silversides. Plunge diving for these fishes is a common technique used by these terns[8]. Foraging on the zooplankton is very common during periods of low anchovy abundance, generally in the austral spring. These seabirds will also forage among sea lions; the sea lions will chase the fish towards the surface allowing the seabirds to easily forage[38]. This technique is important because the birds retain more of their body energy.

The small population sizes and recent declines have resulted in the near threatened status of the tern. They are highly susceptible to changes to their environment. Previous guano harvesting resulted in significant declines in the tern populations, from millions of individuals to approximately 150,000 tern[8]. Recent regulations on the harvesting of guano from the Peruvian region have allowed time for the terns to adapt to what is now considered a minor disruption rather than a reason for population declines. El Niño is another major factor to the survival of these terns. Previous strong El Niño impacts have caused a large reduction in their reproductive success. The Inca tern is capable of recovering from these environmental anomalies if there is enough time between major disturbances in the region[8]. Predation is also a common threat for this seabird species. Inca terns are commonly preyed upon by peregrine falcons. Chicks were easily attacked by these falcons and the gull species of the region. The eggs are primarily scavenged on by turkey vultures[98].

Population Diseases and Risks

By understanding the interactions between these seabirds and their environment, it can lead to more information on disease transmission and risks. Many of these seabirds breed and nest in colonies and can be found foraging in the same area for the same prey. This abundance of species and individuals in small areas allows for pathogen transfer from bird to bird. This is significant because these seabirds are endemic to the HCS and occupy a limited habitat range. This limited range and tight groupings makes them highly susceptible to disease transmission and potential mortality events[79].

To study these diseases, biological samples and data are collected and analyzed. Blood collection is a major source of information on the health status of seabirds. Blood collection through venipuncture can occur in different places on the bird's body. In Humboldt penguins the brachial or ulnar vein can be used to collect blood samples; however, the jugular vein is the preferred location for most seabirds[51,79,99]. Serum samples are tested and studied to collect information on complete blood counts and plasma biochemistry[97,100]. The serum samples are also used to test for avian pathogens including different flaviviruses and avian influenza[100].

Seabirds are affected by many different types of diseases which can lead to serious health problems and possible death. Certain viruses are highly contagious and can spread easily in locations where seabirds are nesting and breeding in close proximity to one another. For example, avian influenza affects the gastrointestinal tract of seabirds and can lead to pneumonia, conjunctivitis, and possible mortality[62,74,85]. Avian malaria can cause mortality by damaging internal organs and leading to blockages in blood vessels[87]. Symptoms of this disease can often be subtle and unnoticed before being researched, and can be fatal[93]. Lyme disease is transmitted by a vector, such as mosquitos, that feed on the blood of their host[71,78].

Parasitic Diseases

The seabirds along the coast of Peru are endemic to the HCS. Therefore, understanding how they are affected by pathogenic parasites provides important information on the transferal of diseases and viruses and the effects these diseases have on the seabirds. Ticks are major ectoparasites that can be found on seabirds around the world, feeding on blood and acting as carriers of viral diseases[23]. Ticks can be found distributed throughout the world as both hard (Ixodidae family) and soft (Argasidae family) species. Different tick species are known to affect seabird taxa in specific locations[31]. Seabirds are a very popular host for ticks due to large seabird colonies; ticks are far more likely to find a suitable host as well as food[24,31,76]. For the seabirds found in Peru, guano-rich habitat attracts these parasites to the area. The Ornithodoros tick is found within the guano burrows of the Humboldt penguin found in the Punta San Juan reserve and on nearby seabirds[50].

Parasite feeding is generally based on the breeding periods of the seabirds. Large numbers of seabirds will create nests and form large groupings which allow for the hungry ticks to find a host[31,76]. Upon finding this host, the ticks will engorge on the blood of the seabirds[31]. If the tick is a carrier of a viral pathogen, it will be transmitted to the seabird. Viruses that may be transmitted include Lyme disease, Huacho virus, and Punta Salinas virus[31,37,78]. Lyme disease has not been discovered in Peru; however, the introduction of tick species can create a major problem for the seabirds of Punta San Juan. Although it is unclear if Huacho virus and Punta Salinas virus cause disease in the seabirds, they are associated with the tick species found affecting Inca terns[31]. These arthropod-bourne viruses, also known as arboviruses, are generally transmitted by the blood-sucking arthropod that is carrying the bacterium[76]. After feeding ceases, the ticks will then fall off the host and will begin to molt or oviposit. This period of the tick's life is very long as they will generally wait in the seabird nests until the following breeding season. Some species will not leave their nests after breeding season which allows the tick to complete their feeding and molting cycle year round (Figure 15)[31].

Mosquitos will transmit different viruses and diseases via the blood to seabirds[23,71]. Mosquitos act as a vector, transmitting viruses such as eastern and western equine encephalitis virus, Venezuelan equine encephalitis virus, West Nile virus, and avian malaria to seabirds and mammals[23,52,53,71]. These viruses are associated with symptoms such as paralysis, fever, and possible mortality[52,53]. The close nesting preferences of seabirds allows for the increase in transmission of each of these diseases and viruses.

Parasites are not restricted to ticks and mosquitos, however. Endoparasites such as trematodes, nematodes, and cestodes have been found affecting juvenile seabirds, leading to gastrointestinal and liver issues and eventually mortality[23]. The trematode species *Ichthyocotylurus erraticus* affect certain seabirds including the Inca tern. This trematode has caused mortality in many Inca terns; an infestation that causes severe colon and intestinal problems for the seabird, leading to constipation, hemorrhaging, and eventual mortality[83].

Viral and Bacterial Diseases

Lyme Disease

Lyme disease is a vector borne, spirochete-caused disease that is generally transmitted by *Ixodes* sp. ticks[78]. The spirochete that causes Lyme disease is *Borrelia burgdorferi*[23,78]. Seabirds in Peru have not been shown to be host species for the hard ticks carrying the spirochete to date. However, fluctuating climatic conditions could prompt the arrival of a migratory bird species carrying the infected ticks to Peru. Many migratory and ground-dwelling birds act as a reservoir for Lyme disease[78]. Introduced ticks to the region would need to survive in the reservoir

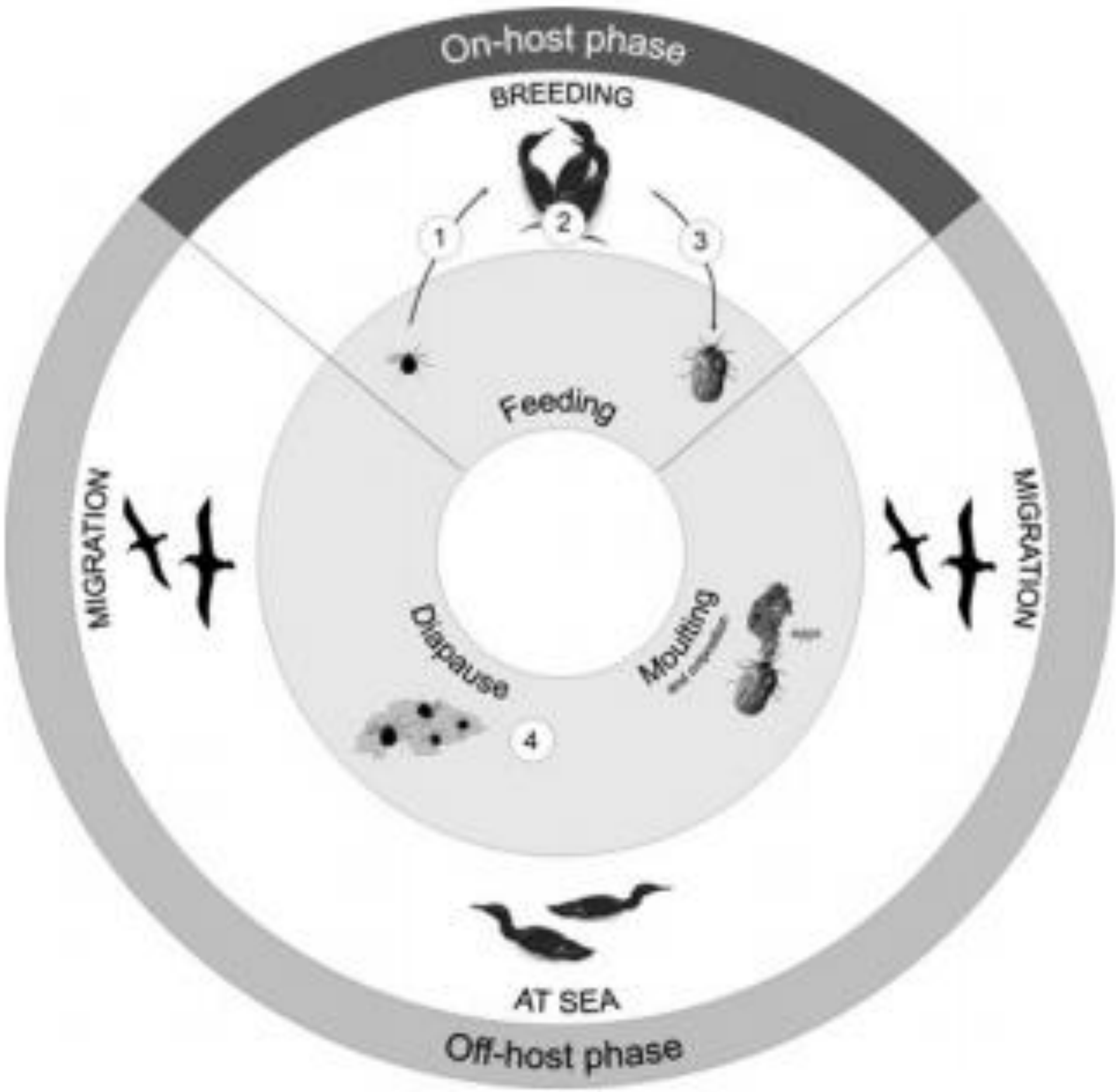

Figure 15: Life cycle of the ticks due to the migration of the host seabirds[31].

seabirds. The infected tick will feed on the blood of the birds causing the *Borrelia* species spirochete to be transmitted into the body of the bird[85]. Antibodies to this spirochete have been found in the king penguin[23,39]. This shows that the penguins may be exposed to Lyme disease agents. This spirochete has been found globally infecting many different species of terrestrial and marine birds.

Lyme disease infections of seabirds have been found in both the northern and southern hemispheres. This is believed due to the migration of birds that have hard ticks attached to their bodies[31,85]. The hard tick species that have been commonly found infected by the *Borrelia* spirochete will generally feed on the bird for approximately 1-2 days before falling off their host. If they are attached to a highly migratory bird species, then the tick could travel great distances before falling off and infecting other individuals[85]. This is significant in many areas where Lyme disease may not be prevalent.

Avian Malaria

Avian malaria is one of the major causes of death in many captive penguins. Avian malaria is transmitted to seabirds through a mosquito vector; specifically, *Plasmodium* is the infecting agent of avian malaria transmitted by mosquitos[71,93]. This presents a problem for all seabirds that are commonly afflicted by mosquitos. Different species of *Plasmodium* have been discovered in many different seabirds, including two different *Plasmodium* agents affecting penguins[71,93]. *Plasmodium elongatum* and *Plasmodium relictum* have been found in Humboldt penguins and African black-footed penguins, respectively. Humboldt penguins are a very common penguin species found in captivity[1]. Captive species that have an open exhibit as well as most wild species can easily acquire avian malaria from the infected mosquitos. Avian malaria has impacted many penguin species around the world, causing death in a large percentage of both juvenile and adult species. Signs of avian malaria are often subtle and unnoticeable and generally include regurgitation, anorexia, and depressive actions as well as respiratory distress. Each of these issues will eventually lead to higher mortality rates if the disease is undetected and untreated[71,93]. Treatments for avian malaria are still being developed and studied in order to reduce the numbers of birds affected by this deadly disease.

Avian malaria could have significant impacts on the endemic seabirds of the Humboldt Current System, however, it has not been observed in the wild populations of Humboldt penguins at the Punta San Juan Reserve. This means that for now, blood parasites such as the possible malaria-infected mosquitos, were not present. However, the penguins may be infected by avian malaria and the clinical signs remain dormant, only exhibited when the penguins are stressed such as during El Niño years[87]. Numerous studies of the effects of avian malaria have been performed on penguins in comparison to other seabirds. Although avian malaria has not become a major factor affecting the wild populations at the Punta San Juan Reserve, the introduction of mosquitos and the malaria disease could cause drastic changes to each of the affected bird populations[92]. Populations of penguins in the Galapagos Islands were also tested for avian malaria. These birds were found unaffected; however, the endemic nature of the species causes them to be at a greater risk to the introduction of this disease.

Newcastle Disease

Newcastle disease (ND) is caused by a virulent viral strain known as avian paramyxovirus serotype-1 (APMV-1) from the family *Paramyxoviridae*[4,30,32]. It is highly contagious and known to affect many different bird species around the world[30,32]. Newcastle disease can be characterized by the strain virulence: velogenic, mesogenic, or lentogenic[4,30,32]. Velogenic strains are highly virulent and can be further characterized as viscerotropic or neurotropic depending on the location of the affected area[4,30]. Viscerotropic velogenic strains are generally associated with hemorrhagic lesions of the intestines, whereas neurotropic strains are associated with neurological and respiratory issues[4,30]. Velogenic strains usually cause high mortality rates and are more common in cormorants and pigeons[4,32]. Mesogenic strains are moderately virulent, causing respiratory and neurologic issues, but are often associated with lower mortality rates[4,30]. This strain has also infected large numbers of cormorants and pigeons[32]. Lentogenic strains are mildly virulent, causing infections to the respiratory tract of the affected birds[4,30]. This mild strain of APMV-1 can be found commonly affecting shorebirds, gulls, and wild waterfowl. Many of these strains can also be associated with lower egg production[32]. This disease could have severe ramifications for the populations of endemic seabirds in Peru.

Along with its highly contagious nature, Newcastle disease is associated with high mortality rates. Mortality generally affects younger, juvenile birds, whereas the adults are more resistant, but still show effects of the disease. Newcastle disease is associated with many symptoms including blindness, head tremors, ataxia, and even paralysis of the wings and legs[30].

Even if a bird survives the infection, the lingering symptoms may render the bird unable to forage and find food, breed, or escape predators.

This disease is highly contagious, leaving large groups formed by the seabirds for nesting and breeding particularly susceptible. Affected birds have been observed in many countries ranging from Asia, Africa, Central America, South America, and North America[4]. This presents the potential for major problems for the seabirds that are endemic to the Humboldt Current System. This strain represents an impending problem for the Guanay cormorant due to their large population size and limited habitat locations if an outbreak occurs. Newcastle disease can also be transmitted from domestic to wild birds. Infected domesticated chickens can pass the virulent strain APMV-1 to wild birds such as gulls, pigeons, and cormorants[30,32]. This process occurs due to their inhalation or ingestion, therefore allowing many possible paths for transmission to occur[32].

Avipox

Avian pox, also called avipox, is a double-stranded DNA virus caused by Avipoxvirus. This virus consists of a common form and a rarer form, diphtheritic pox[60,75]. Mortality from avipox is uncommon, but higher mortality rates are associated with diphtheritic pox. Avipoxvirus affects many different wild birds around the world, but there is less information on the impact on wild seabirds. However, this virus has affected multiple different penguin species; particularly the Magellanic penguin and Humboldt penguin[60]. Magellanic penguins share a geographically similar habitat to Humboldt penguins. The similar and partial overlap of habitats indicates a potential for infection and population changes.

Transmission of avian pox occurs through direct and indirect contact. Direct transmission occurs through broken skin contact amongst birds and by contact of the conjunctiva with infected particles[60,75]. Indirect transmission occurs through arthropod vectors. After becoming infected with this virus, the birds will begin to show symptoms. These symptoms commonly include wart-like lesions on the beak and around the eyes, as well as loss of feathers on the skin[60]. In the diphtheritic form of the avian pox, problems including lesions on the digestive and respiratory tracts lead to difficulty breathing and swallowing. These problems can lead to possible mortality[60,75]. Avipoxvirus presents a concern for the populations of Humboldt penguins in Punta San Juan. This virus can be easily transmitted from Magellanic penguins that share a similar habitat. The close proximity of the penguins can lead to an increase in the number of infected birds.

Influenza A Virus

The influenza A virus is widely recognized and acts as a major threat to many seabirds. This virus is highly pathogenic, is capable of infecting many different organisms around the world, and leads to the avian influenza disease[58,62]. Seabirds play a major role in the virus' propagation, acting as an important reservoir and host for the influenza A virus[63,85]. The avian influenza virus is more commonly found in flying birds and has been found in seabirds such as the Peruvian pelican, Inca tern, and the occasional Humboldt penguin[23,58,63]. Seabirds are asymptomatic during the infection process and can, therefore, infect many different bird species[85]. Studies have shown that the influenza virus is less common in penguins due to the prevalence of serum antibodies in certain species. These antibodies were found during serum data analyses that were performed to better understand the transmission and host properties of the virus in penguins[23,73]. Although the influenza virus is less common, a recent outbreak in southern Africa led to a mass mortality event of African penguins[97]. This shows that an outbreak in Peru could lead to a similar outcome to the African penguins.

As hosts for the virus, seabirds are greatly impacted and able to impact other species. The virus can replicate in the intestinal tract of the host bird where it can later be transmitted to other species leading to severe respiratory issues for many of these different animals[58,85,86]. Seabirds transmit the disease by direct contact, such as predation and feeding on the seabirds, or indirect contact, such as contact with contaminated water or feces left by the birds. Another process of transmission of the disease may include airborne particles that are released into the environment by the seabirds (Figure 16)[86]. Once transmitted, health problems include pneumonia, conjunctivitis, and possible mortality, even in mammals including humans[62,85]. The transmission of the disease shows the importance of the seabirds as host and how they easily transfer the virus to other species. This is important when understanding the impact that birds have on nearby species particularly along the coast of Punta San Juan. Punta San Juan is a host to rookeries of South American sea lions and the vulnerable Peruvian fur seals; whose populations may be affected by the virus if transmitted from the seabirds[56].

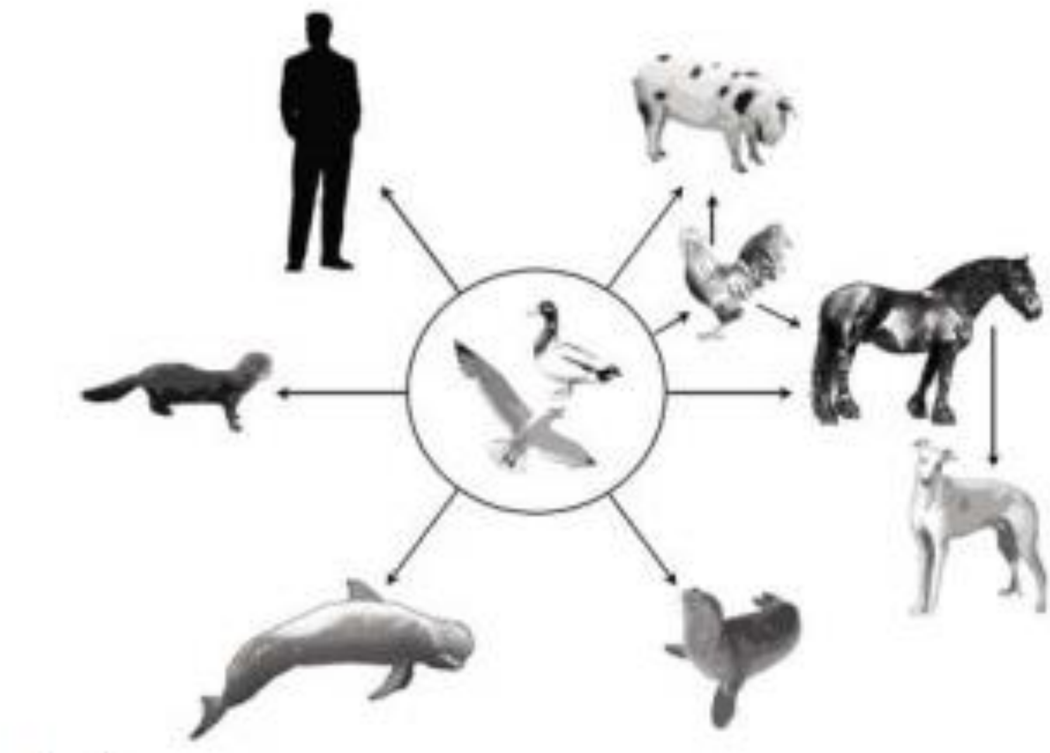

Figure 16: Influenza A virus transmission to terrestrial and marine mammals[86].

Flaviviruses

Flaviviruses, of the family *Flaviviridae*, is a grouping of over 70 different viruses. Flaviviruses are arboviruses, meaning that they are transmitted through arthropod vectors. These vectors include mosquitos and multiple tick species. Important flaviviruses include West Nile virus (WNV), Eastern equine encephalitis virus (EEE), Western equine encephalitis virus WEEV), and Venezuelan equine encephalitis virus (VEEV)[52,53].

West Nile virus is transmitted through an arthropod vector such as moquitos. WNV is infectious to over 60 different vectors which allows for a greater potential for the virus to spread. Seabirds are an important host for WNV and the close proximity of their nests will lead to an increase in the number infections. Once infected with WNV, seabirds are able to transmit the virus to other birds and mammals, including humans. Symptoms associated with WNV include asymptomatic infections and possible encephalitis[52].

Eastern equine encephalitis virus (EEEV) is another important flavivirus. EEEV is transmitted through mosquito vectors which will feed on birds and mammals. This particular virus will infect wild seabirds found in Peru and Brazil. Seabirds are popular hosts for this virus. Mosquitos that are not infected with EEEV will feed on the infected seabirds causing the transmission to other species. Mosquitos will transmit this virus to horses leading to many different health issues. Symptoms of EEEV in birds and horses will include fever, paralysis, and death. Outbreaks of EEEV have occurred in northern Brazil and infected over 50 different species of birds[52].

Western equine encephalitis virus (WEEV) is similar to EEEV due to their transmission and host species. WEEV is transmitted by arthropod vectors which are primarily mosquitos. The mosquitos will feed on birds and other mammals which act as a host for this virus. Symptoms of WEEV include fever, fatigue, changes in limb movement, and possible mortality. Mortality rates are lower in birds infected with WEEV in comparison to EEEV[52].

Venezuelan equine encephalitis virus (VEEV) is also transmitted by an arthropod vector. Birds are occasionally hosts for this virus which is unique when compared to other flaviviruses. Symptoms of this virus include high fever, convulsions, and death. Major outbreaks of this virus have occurred in Columbia and Venezuela leading to mass mortality of many horses. If seabirds become a major host for this virus, Peruvian species can greatly amplify this virus leading to future outbreaks and mortality events[52].

Coastal farming practices are popular in Peru. Due to the nesting preferences of seabirds in Peru, the amplification of these different flaviviruses could increase. This could be a great concern for transmission. Mosquitos that feed on infected birds can transmit the viruses to other species leading to major health issues and possible mortality. Due to the amplified transmission, Peruvian farming could be strongly impacted by these viruses.

Contaminants

Alongside the different diseases and viruses impacting seabirds, contaminants are also a significant factor to their health. Due to the abundance of chemicals released into the environment, seabirds, in general, are exposed to different chemicals and pollutants by direct contact, inhalation and ingestion[18]. Increasing human populations and industrialization in nearby regions around Punta San Juan increase the likelihood of seabird exposure to a suite of chemicals[3]. It is believed that due to human input, in the form of open-pit iron ore and copper mines, seabirds are accumulating large amounts of different elements that lead to toxic conditions. These mines release chemical wastes into the marine environment which are incorporated into the regional food web and are transferred to all trophic members[2,3]. These contaminants can also be released into the environment through natural sources such as volcanic activity. Dominant contaminants introduced into the environment that affect these seabirds include persistent organic pollutants (POPs) and perfluorinated compounds (PFCs). POPs include certain contaminants such as polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and organochlorine pesticides (OCPs)[3,16]. These contaminants are known to cause problems such as disruptions to the function of internal body systems, reduced reproduction success, and eggshell thinning, all contributing to population declines[3]. Due to the biomagnification of these contaminants throughout the food chain, seabirds are at great risk of being affected. Ingestion of materials such as plastics leads to an increase of PCBs and OCPs compounds found in seabird tissues[25]. Using seabirds to study the accumulation of these contaminants in the marine environment is often very useful. Seabirds are sensitive to environmental changes including the introduction of chemicals[18,70]. Seabirds are found globally and in regions where contaminants are easily spread throughout the terrestrial and marine environments[18].

Seabirds can be used as indicators or monitors of the health of the environment. Pollutants and chemicals ranging from oil spills to heavy metals and their effects on seabirds and the environment can be assessed by studying their impacts on seabird health. The accumulation of certain heavy metals may be due to an increase in the prey of the seabirds and can be associated with feeding habits. Additionally, water, air, and soil are sources of metals (Figure 17)[18]. These contaminants can affect the environment and cause seabirds to leave or prove to be fatal in many different species[43].

To study these concentrations, rates of contamination, and effect in seabirds, different body tissues are collected and analyzed, particularly feathers and blood[18,70]. Mercury is a major component of many anthropogenic sources, such as mines and petroleum refining, and it can contaminate many trophic levels in food webs in both the inorganic and methylated forms[2]. Mercury has been found in many of the seabird species along the coast of Peru and can be associated with their prey items such as anchovy found in the Humboldt Current. Mercury biomagnifies throughout the food web[2,77]. Mercury exposure and accumulation can have a variety of different health effects on seabirds, including survivability and reproduction, behavioral changes, and nervous system issues[2,18]. Mercury and other heavy metals have also shown to affect the eggs of different seabirds, particularly eggshell thinning. Seabird eggs are highly important in contamination studies because they can reflect the concentration of metals present in the maternal tissues[3,88]. Seabirds such as penguins are highly sensitive to these changes and over time population declines can occur if there is continual input of contaminants into the Peruvian environment[16,88].

Food Restrictions and Growth

Seabirds provide information on the health of the environment and any changes that may be occurring. Because of this, seabirds act as indicators, or sentinels, for the environment that they inhabit[20,43,70]. Prey availability and food restrictions can provide important information on the survival and growth of seabirds[68]. Conditions that lead to limitations in prey availability can cause several issues for seabirds. These will generally include adult seabirds leaving their nests for longer periods to find food, reduction in breeding, and reduced food for chicks which later

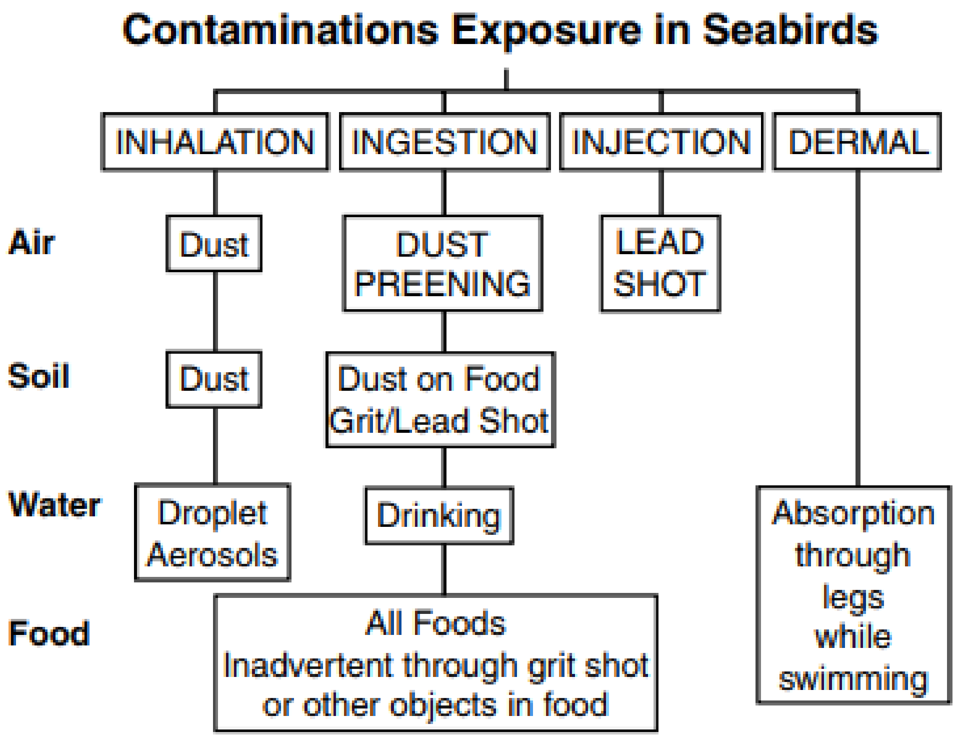

Figure 17: Intake of contaminants through different mediums by seabirds[18].

leads to lower growth rates of the young birds[20,29,68]. Longer foraging periods can be seen in species such as the Humboldt penguin and Guanay cormorant during periods of El Niño, where their prey leave the Peruvian waters to escape the higher than normal sea surface temperatures and leads to reduced production[9,29]. Tern chicks that are subjected to food restrictions have shown significant differences in the growth patterns when compared to non-food restricted chicks. Smaller head and bill sizes, and wing chord sizes were recorded for species that were limited in food[68].

Competition Restrictions

Competition restrictions focus on the competition among species for food. Each of the five seabirds reviewed are endemic to the western coast of South America. This means that they are found in a limited region and have the ability to greatly affect one another with regards to prey availability. These seabirds feed at the same trophic level, primarily on popular schooling fishes such as the anchovy and sardine[8,29,80]. Many of these seabirds will feed on different species when necessary; however, they may spend a large amount of time foraging for their prey. Guanay cormorants will generally forage for shorter periods of time when their prey is easily accessible, but they have also been observed searching for more than 6 hours in order to find food[96]. This extended time from their nests could lead to predation on eggs and chicks as well as less nutrients for the young seabirds. Common in these seabirds is the reduction in growth size due to the lower availability of prey[68]. Competition restrictions can also include pressures such as overfishing caused by humans[54,89]. The overfishing of these important fish species leads to greater intra- and interspecific competition due to the large reduction in the available species.

Environmental Restrictions

Environmental restrictions are associated mostly with inter-annual conditions that may cause prey species to leave the area or die-off. Frequent environmental conditions may not affect the survivability of the seabirds; however, major anomalies such as ENSO can cause changes in the availability of prey and the health of seabirds. El Niño occurs every 2-7 years and causes increased sea surface temperatures and a reduction in the coastal primary production[41]. This then leads to a nutrient-poor marine environment for the seabirds and their prey[40,41,47]. Changes to the marine environment cause the large populations of schooling fishes to leave the region or move to deeper waters[80,94,101]. The seabirds are forced to either follow their prey farther distances or change their prey during these periods. Longer foraging strategies have been observed; however, they may lead to abandoned nests and chick mortality due to predation or chick starvation[96]. Food shortages also lead to changes in breeding patterns. Scarce food supplies require seabirds to prioritize foraging over breeding, leading to fewer chicks in the following years. The energy expended by seabirds during foraging is a major indication of food shortages. Seabird activity greatly increases as food becomes scarce, causing stress for adults attempting to find food[20]. Strong environmental anomalies can cause lasting effects which may lead to seabird populations being unable to recover in subsequent years.

Anthropogenic Restrictions

Human interactions with the Peruvian environment have caused many problems for the seabirds. Many of the seabirds found in the Punta San Juan Reserve are known as guano birds due to their production of large amounts of guano (bird fecal matter and uric acid)[105]. Guano is a highly important resource utilized by Humboldt penguins and Inca terns for nesting burrows[8,11,98,106]. Commercial guano harvesting for fertilizer began in the mid-19th century when the seabird populations were flourishing; populations consisted of hundreds of thousands of individuals[105]. Periods of aggressive harvests has led to nesting site lost by Humboldt penguins and some Inca terns and habitat destruction and disturbance for many of the other seabirds[8,9,11]. The destruction of habitat leads to higher mortality rate due to abandoned eggs and young seabirds. Reduced nesting materials also resulted in greater susceptibility to predation[105]. The introduction of humans to this environment has also led to the introduction of invasive species such as chickens, that bring new diseases, and dogs, that act as invasive predators[29].

These impacts are not limited to the guano harvesting of the region. Major fisheries along the coast increase the competition for food. Because of the highly productive coastal waters of Peru, a large anchovy fishery is supported[69]. The anchovy fishery has become the largest fishery in the world, capturing between 2 and 12 million metric tons (mt) between 1960 and 1970 and reaching more than 12 million by 1972[17,54,90]. Recent capture numbers between years 2000-2008 shows a steady harvest amount anywhere from 6 to 9 million mt[90]. Large-scale changes to the anchovy populations can be drastic for the seabirds, particularly enhanced during El Niño years[35,54]. Day and night commercial fishing for anchovies has led to increases of seabird bycatch. Between the years of 1991 and 1996, bycatch was a major issue for the Humboldt penguin. Approximately 1,500 penguins were caught in drifting gill nets which led to a major decrease in their population[29]. Fishers will also change their gear and fishing areas depending on the species that are being followed[29,69]. This then leads to different and possibly more seabirds being caught in the drifting nets.

Many anthropogenic impacts have also decreased over time. Certain efforts have been enforced to promote the survival of different endemic and vulnerable seabirds found in Peru. The creation of the wall in the Punta San Juan Reserve provides the seabirds with protection from natural predators as well as humans that may attempt to enter the reserve[105]. The formation of the Guano Administration Company led to a reduction in the guano harvest in the Punta San Juan Reserve. This protects the resources for the seabirds and provides a more natural habitat[21]. The fisheries are also being regulated to reduce the bycatch of the seabirds while also sustainably harvesting the anchovies[90]. The environment is also being tested for contaminants to better understand and reduce the introduced amounts. This will overall lead to healthier seabird populations for the future.

Conclusions

Punta San Juan, Peru is a guano reserve which is home to five major endemic seabird species. The Peruvian coastline is located along a highly productive current system, the Humboldt Current System (HCS). The HCS is an area of strong upwelling creating a very diverse and complex food chain and attracting a very important prey fish, the Peruvian anchovy[28,72,101]. The Peruvian anchovy (*Engraulis ringens*) is the main prey item for each of the endemic seabirds located in the guano reserve[44,80]. Changes in the populations of this particular prey species has shown to cause behavioral changes in the seabirds. Longer foraging trips and reductions in breeding have occurred due to prey availability[96]. Movement away from the Peruvian coastline by these anchovies is primarily related to environmental fluctuations that occur periodically.

El Niño Southern Oscillation (ENSO) is a phenomenon which causes increased sea surface temperatures and wind pattern changes[47,54]. Changes to the wind patterns decrease the upwelling that occurs in the HCS along the Peruvian coast. The reduction in the upwelling leads to a less productive environment, which along with the increased sea surface temperatures, causes the prey species to leave the region[5,40,41,47]. This leads to an increase of stress on the seabirds to find food and feed their chicks. ENSO events occur periodically, approximately every 2-7 years, and have been associated with population declines in each of the studied seabirds[41].

Environmental stressors are only some of the major issues that these seabirds must overcome. Diseases such as Lyme disease, avian malaria, Newcastle disease, and avian influenza A have the potential to cause significant health issues. Severe respiratory problems, paralysis, changes in appetite, blindness, head tremors, and mortality have been associated with these particular diseases[1,30,58,85,86]. Viruses such as eastern, western, and Venezuelan equine encephalitis virus, and West Nile virus can also lead to a high fever, paralysis, and possible mortality[52]. Environmental and anthropogenic stressors, such as aggressive guano harvesting, can increase the potential of infection by these different diseases by increasing birds' stress levels. Increased time away from the nest due to longer foraging trips can lead to exhaustion. This condition, when accompanied by a lack of food, can lead to weakness in the bodies of the seabirds[20,68]. Seabirds affected by the diseases have symptoms that will cause them to be unable to leave the nest in order to forage for food, leading to mortality[30].

Contaminants are also a major factor that contributes to the health of seabirds. Persistent organic pollutants (POPs), which include polybrominated diphenyl ethers (PBDEs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs), as well as perfluorinated compounds (PFCs), are known to cause disruptions to internal body systems and reduced reproduction success leading to population declines[3,16]. Heavy metals introduced into the environment through anthropogenic sources such as mines are able to biomagnify quickly throughout the food chain[2,25,77]. Heavy metals cause problems that range from disruptions to the seabirds' internal body systems to reductions in their reproductive success. These major issues cause drastic population declines[3].

Many of these issues have an additive impact on the populations. The clustering of seabirds at Punta San Juan and other sites may cause them to be at an increased health risk. Due to clustering of nests in different locations as well as smaller population sizes, combinations of disease and environmental conditions can cause major complications for the survivability of the species. The clustering of these species causes them to become more concentrated in certain areas leading to an increase in their susceptibility to these conditions. During ENSO years, healthy seabirds are strongly affected by the environmental stressors that occur. The birds that contract certain diseases have weaker immune systems causing them to be affected by these environmental events at a greater degree. Contaminants will cause major disruptions to the body's organ functions as they bioaccumulate in the tissues. During ENSO periods, the environmental conditions will cause prey availability to change[5,40,41,47]. This can lead to a potential decrease in the contaminant accumulation in the food web or introduce new ones as the birds are forced to forage on different prey and/or in different forage grounds. The biomagnification of contaminants in the food web could be reduced leading to reduced contamination levels in seabirds. This could potentially help to counteract the impact of the environmental disease stressors that the seabirds are facing. The environmental and anthropogenic stressors, contaminants, and disease issues each lead to major health problems for the seabirds but, combined, create a convoluted web of stress responses.

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