RESEARCH ARTICLE

Threats and Vision for the Conservation of Galápagos Birds

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Abstract:

Introduction: Threats that affect the avian diversity on the Galápagos Islands are increasing. We evaluated threats such as climate change and severe weather, human intrusions and disturbance, biological resource use, invasive and other problematic species, genes and diseases, pollution, geological events and loss of genetic diversity in relation with avian species enlisted in both the international and national (Ecuador) IUCN Red List, which can be used as sentinel species of the ecosystem. Here, the status of the threatened species for the next ten years (present time up to 2028), under two scenarios, including the status quo and the avian diversity vision for the species’ conservation, was assessed.

Methods: The conceptual framework of the assessment was envisioned within the existing knowledge and projections of present and future threats to revisit current conservation efforts. Based on this evaluation, a set of management actions coupled with mitigation strategies to address new anthropogenic threats affecting the long-term survival of species in the face of global and regional environmental changes are recommended. Alternative strategies for species conservation, mainly when declining avian populations are susceptible to demographic bottlenecks or risk of extinction and when natural disasters affect ecosystem stability, are also considered.

Results: These results should be envisioned as a guide for the evaluation and management of the avian species in the future to be replicated every decade.

Keywords: Conservation, Climate change, Human instructions, Invasive species, Diseases, Pollution, Geological events, Loss genetic diversity, Sentinel species.

1. INTRODUCTION

The Galápagos Islands are one of the best preserved oceanic archipelagos worldwide despite significant human impact over the last 500 years since their discovery [1]. Human impacts were already likely occurring on the flora and fauna by the time Charles Darwin visited the islands in 1835 [2, 3]. At present, Galápagos has over 1 700 introduced species recorded, more than 30 000 people living on the islands, and more than 200 000 visitors per year [4, 5]. The Galápagos avifauna is regulated by density-dependent (e.g. predation, competition, food shortages, disease, territory) and density-independent factors (El Niño–Southern Oscillation [ENSO] and geological events, e.g. volcanic activity and tsunamis), keeping populations in balance (i.e. population regulation, equilibrium) in the face of large fluctuations. However, human-made activities
from outside and from within Galápagos directly or indirectly affect bird species on the Islands [6-14]. The main threats affecting the Galápagos avifauna (following the IUCN classification) are climate change and severe weather, human intrusions and disturbance, biological resource use (incidental and direct fishing), invasive and other problematic species, genes and diseases, pollution (chemical and biological contamination, solid waste, urban sprawl), geological events and loss of genetic diversity [15].

The categorization of species by the International Union for the Conservation of Nature’s Red List of Threatened Species (the “Red List”) is useful to prioritize efforts and actions regarding species conservation. To date, 172 bird species have been recorded in Galápagos, including endemic (found only in Galápagos), native (occur naturally in Galápagos but also elsewhere), and migratory species. Of these, 32 (18.6%) are listed as threatened (1 Extinct, 4 Critically Endangered, 7 Endangered, 20 Vulnerable) [16]. Of the endemic species, the Least Vermilion Flycatcher (Pyrocephalus dubius) from San Cristóbal Island is considered Extinct, although this needs confirmation as there is an unconfirmed record in 2008 [17, 18]. It is important to note here that the conservation status of a species can change over time due to changes in taxonomy, observed changes in populations, changes in the evaluation system, the discovery of new extant species, and an increase of threats.

Numerous bird studies have been done on the Galápagos during the last two centuries. These studies mainly focused on individual species, contributed a better knowledge on the ecology and evolution of Galápagos avian diversity [7, 9, 10, 16]. However, general bird threats increased during this time in such a manner that it seems to outweigh our understanding of their interaction with bird species likely limiting current management and conservation programs. Therefore, the aim of this study was to evaluate the past and current status of knowledge in regards to the threats in the islands and project scenarios to understand future trends to contribute to the management and overall conservation of the Galápagos avifauna. To accomplish this, potential management actions are proposed under two scenarios (i.e. Status Quo [SQ] and Vision [V]) by assessing and predicting the impacts on species’ population trends.

2. METHODS TO ASSESS IMPACTS TO GALÁPAGOS AVIAN DIVERSITY

In Galápagos, 61 avian species are indigenous (i.e. endemic, native) [16]. We choose to work with 20 species registered in the IUCN Red List because these species are the most endangered and upon which conservation efforts and management plans must be prioritized. Furthermore, these species are representative and inhabitants of diverse ecological areas or unique habitats (i.e. marine and coastal habitats, transition zones, and arid and humid habitats) and several species would qualify as sentinel species or bioindicators [7, 15, 19-22]. We evaluated species threats following criteria of the IUCN Red List of Threatened Species, including climate change and severe weather, human intrusions and disturbances, biological resource use (incidental and direct fishing), invasive species, diseases, chemical pollution, geological events and loss of genetic diversity. This assessment included seabirds and aquatic birds Table 1 and land birds Table 2.

We made projections on the future conservation status of the birds over the next ten years up to 2028. This is a conservative and prudent time period to evaluate any changes in management to know the survival of long-lived species based on two scenarios: 1) the Status Quo (SQ) scenario describes possible results based on the assumption that conservation efforts are continued along the current trajectory (i.e. ‘business as usual’) or deteriorates in the next 10 years and 2) the Avian Diversity Vision (V) scenario representing ambitious goals that could be accomplished in the next 10 years if there are improvements in research, management actions, and in extreme cases the implementation of new regulations for conservation efforts in close conjunction with contingency plans.

The Avian Diversity Vision scenario was developed from a workshop, in which we used all available knowledge of Galápagos ecosystems and ecological trends, field experience and the existing scientific literature available, including peer-reviewed papers, grey literature (e.g., technical reports, papers presented in conferences), information from the Check List and Natural History Collection at CDF, and best available expert knowledge (authors). The rationale for this methodology was following the central idea from the “Vision for the biodiversity of the Galápagos Islands” which are based on the guiding principles by Bensted-Smith [6], following an expert workshop on Galápagos conservation developed in 1999, in which two of the co-authors (CAV & HV) participated.

3. THREATS TO GALÁPAGOS AVIAN DIVERSITY

3.1. Climate change and severe weather

The El Niño-Southern Oscillation (ENSO - El Niño [warm] and La Niña [cold] events) has affected the Galápagos Islands for thousands of years and the native species have evolved under its influence [23]. Climate change will likely increase the frequency and intensity of El Niño events [24]. As shown in Table 1, severe El Niño events in 1982-1983 and 1997-1998 caused populations of Galápagos Penguins (Spheniscus mendiculus) to decrease by 80% and 60%, respectively [8, 13, 25, 26]. Reproduction of Waved Albatrosses (Phoebastria irrorata) was affected in 1982-1983 and 2015-2016 ([27], GIU, pers. obs.). In other cases, El Niño affected the habitat by changing the natural ecosystems of lagoons inhabited by aquatic birds and thus affecting threatened species, including the Galápagos American Flamingo (Phoenicopterus ruber glyphorhynchus) [28].

Although the impact of climate change on several large-scale ocean-climatic perturbations (e.g. ENSO episodes) is difficult to predict with certainty, it has been suggested that global climate change may result in continued, more frequent, and intense El Niño events coupled with higher sea-surface temperature, increased precipitation, sea level rise, ocean acidification, and a reduction in upwelling in the Galápagos archipelago [29-31]. Therefore, it is likely that the most significant threat from climate change is its potential to affect the frequency and severity of ENSO events, impacting Galápagos sea-
Table 1. Assessment of threats, current actions and mitigation and management strategies under Status Quo (SQ) and the Vision (V) for the conservation of Galápagos avian diversity: seabirds and aquatic birds, including indigenous species (i.e. endemic and native).

<table>
<thead>
<tr>
<th>Species</th>
<th>Scenarios</th>
<th>Climate Change and Severe Weather</th>
<th>Human Intrusions and Disturbance</th>
<th>Biological Resource Use</th>
<th>Invasive Species</th>
<th>Diseases</th>
<th>Pollution</th>
<th>Geological Events</th>
<th>Loss Genetic Diversity</th>
<th>Population Trends</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galápagos Penguin</td>
<td>2018</td>
<td>Populations affected by ENSO. Decreased 80% and 60% in 1982-83 and 1997-1998. No reproduction in 2015</td>
<td>Some collisions and disturbance in breeding areas by motorboats</td>
<td>Fisheries affect some individuals</td>
<td>Cat, rats on eggs and chicks</td>
<td>Plasmodium sp. recorded.</td>
<td>Heavy metals assessed</td>
<td>Tsunamis, volcanic eruptions, higher tide levels affected nests near the coast</td>
<td>-</td>
<td>Declining</td>
<td>1, 7, 8, 9, 12, 13, 14, 25, 26, 42, 44, 49, 55, 72, 79</td>
</tr>
<tr>
<td>Spheniscus mendiculus</td>
<td>SQ</td>
<td>Population affected same percentage. ENSO is strongest and frequently</td>
<td>More collisions and disturbance in breeding areas by motorboats</td>
<td>New methods in fisheries affected individuals</td>
<td>Minimum control of cat, rats</td>
<td>Enter to GPS emergent diseases</td>
<td>Oil spills, mercury, POPs (e.g. DDT)</td>
<td>Same as above</td>
<td>-</td>
<td>Declining</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Population affected. ENSO stronger and more frequent</td>
<td>Control increasing tourism and populated bays and implement propeller protector on motorboats</td>
<td>Exclusion of longline and drifting fish aggregating device in the GMR without the need of experimental fishing trial and field studies, following the precautionary principle</td>
<td>Aggressive control on cats and rats in the coast</td>
<td>Control vectors and ABG has better management.</td>
<td>Continue the prohibition of entry of bunker-tanker boats; outside of GMR; improve preparedness and response plan to mitigate and control oil spills and releases of hazardous substances from ships within and outside of the GMR</td>
<td>Same as above</td>
<td>50/500 rule for a minimum viable population, develop a breeding center</td>
<td>Stable</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>- 2018</td>
<td>Populations affected by ENSO. Decreased 50% and 25% in 1982-83 and 1997-1998</td>
<td>Disturbance in breeding areas</td>
<td>-</td>
<td>Cat, rats on eggs and chicks</td>
<td>Plasmodium sp. recorded.</td>
<td>Parasites recorded</td>
<td>Heavy metals assessed, oil spills, POPs (e.g. DDT)</td>
<td>Tsunamis, volcanic eruptions, higher tide levels affected nests near the coast</td>
<td>-</td>
<td>Declining</td>
</tr>
<tr>
<td>Species</td>
<td>Scenarios</td>
<td>Climate Change and Severe Weather</td>
<td>Human Intrusions and Disturbance</td>
<td>Biological Resource Use</td>
<td>Invasive Species</td>
<td>Diseases</td>
<td>Pollution</td>
<td>Geological Events</td>
<td>Loss Genetic Diversity</td>
<td>Population Trends</td>
<td>Source</td>
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</tr>
<tr>
<td>Flightless Cormorant Phalacrocorax harrisi</td>
<td>SQ</td>
<td>Population affected same percentage. ENSO it stronger and more frequent</td>
<td>More disturbances in breeding grounds</td>
<td>-</td>
<td>Minimum control of cat, rats</td>
<td>Entry into Galápagos by emergent diseases</td>
<td>Oil spills, POPs (e.g. DDT)</td>
<td>Same as above</td>
<td>-</td>
<td>Declining</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Population affected. ENSO it stronger and more frequent.</td>
<td>Control increasing tourism and populated bays and implement propeller protector on motorboats</td>
<td>Exclusion of longline and drifting fish aggregating device in the GMR without the need of experimental fishing trial and field studies, following the precautionary principle</td>
<td>Aggressive control on cats and rats in the coast</td>
<td>Control of vectors and ABG has better management</td>
<td>Continue the prohibition of entry of bunker-tanker boats; outside of GMR; improve preparedness and response plan to mitigate and control oil spills and releases of hazardous substances from ships within and outside of the GMR</td>
<td>Same as above</td>
<td>Data collected and known</td>
<td>Increased</td>
<td>-</td>
</tr>
<tr>
<td>Galápagos Petrel Pterodroma phaeopygia</td>
<td>2018</td>
<td>Cinchona pubescens and Rubus sp. affect colonies</td>
<td>Original natural areas lost for agricultural activities</td>
<td>Fisheries Unknown impact</td>
<td>Cat, rats?, pigs, cattle affected nests</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>-</td>
<td>Declining</td>
<td>7, 9</td>
</tr>
<tr>
<td></td>
<td>SQ</td>
<td>Invasive plants on colonies</td>
<td>-</td>
<td>Fisheries Unknown impact</td>
<td>Minimum control of cat, rats</td>
<td>Unknown</td>
<td>Unknown, oil spills</td>
<td>-</td>
<td>-</td>
<td>Stable</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Introduced plants eradicated from colonies</td>
<td>Reforesting breeding areas in GNP, and in agricultural areas (gulch) with the collaboration of farmers</td>
<td>Data collected and analyzed</td>
<td>Aggressive control of feral species</td>
<td>Data collected and known</td>
<td>Continue the prohibition of entry of bunker-tanker boats. Data collected and known outside of GMR; improve preparedness and response plan to mitigate and control oil spills and releases of hazardous substances from ships within and outside of the GMR</td>
<td>-</td>
<td>Data collected and known</td>
<td>Increased</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>2018</td>
<td>Nil reproduction in 1982-83</td>
<td>Few human interaction on island</td>
<td>Fisheries impact</td>
<td>Mosquitoes</td>
<td>Few diseases recorded</td>
<td>Heavy metals assessed, oil spills</td>
<td>-</td>
<td>-</td>
<td>Declining</td>
</tr>
</tbody>
</table>

(Table 1 continued...)
<table>
<thead>
<tr>
<th>Species</th>
<th>Scenarios</th>
<th>Climate Change and Severe Weather</th>
<th>Human Intrusions and Disturbance</th>
<th>Biological Resource Use</th>
<th>Invasive Species</th>
<th>Diseases</th>
<th>Pollution</th>
<th>Geological Events</th>
<th>Loss Genetic Diversity</th>
<th>Population Trends</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waved Albatross</td>
<td>SQ</td>
<td>Nil reproduction with ENSO in GPS</td>
<td>More human interaction on island</td>
<td>More fisheries impacts outside of GMR</td>
<td>Mosquitos and other introduced species recorded on Española</td>
<td>New and emergent diseases</td>
<td>Oil spills, POPs</td>
<td>-</td>
<td>-</td>
<td>Declining</td>
<td>-</td>
</tr>
<tr>
<td>Phoebastria irrorata</td>
<td>V</td>
<td>Nil reproduction when ENSO in GPS</td>
<td>Restrict daily tours</td>
<td>Continue the ACAP Plan</td>
<td>Better biosecurity control to visit the islands</td>
<td>Not emergent diseases Data collected</td>
<td>Continue study; outside of GMR; improve preparedness and response plan to mitigate and control oil spills and releases of hazardous substances from ships within and outside of the GMR</td>
<td>-</td>
<td>Data collected and known</td>
<td>Stable</td>
<td>-</td>
</tr>
<tr>
<td>Galápagos American Flamingo</td>
<td>2018 ENSO affected lagoons</td>
<td>ENSO affected lagoons</td>
<td>Loss of lagoons in Isabela. Disturbance in breeding areas</td>
<td>-</td>
<td>Dogs, pigs affected individuals and nest</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Tsunamis, higher tide levels affected nests near the coast</td>
<td>Unknown</td>
<td>Declining</td>
<td>7, 9, 25, 28</td>
</tr>
<tr>
<td>Phoenicopterus ruber</td>
<td>SQ</td>
<td>ENSO affected lagoons more frequently</td>
<td>More loss of lagoons in Isabela. Disturbance in breeding areas</td>
<td>-</td>
<td>Minimum control of cat, rats, dogs, pigs</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Same as above</td>
<td>Unknown</td>
<td>Declining</td>
<td>-</td>
</tr>
<tr>
<td>glyphorhynchus</td>
<td>V</td>
<td>ENSO affected lagoons</td>
<td>Recovery of lagoons. Educational program and environmental outreach to reduce disturbance in habitat areas</td>
<td>-</td>
<td>Aggressive control of feral species</td>
<td>Data collected and known</td>
<td>Data collected and known</td>
<td>Dunes and rocky habitats affected before by tsunami, sea level rise and flooding recovered</td>
<td>Data collected and known</td>
<td>Stable / uncertain</td>
<td>-</td>
</tr>
<tr>
<td>Lava Gull</td>
<td>2018 -</td>
<td>Loss of habitat Disturbance on breeding areas</td>
<td>Fisheries unknown impact</td>
<td>Dogs, cats, rats affected individuals</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>-</td>
<td>Stable / uncertain</td>
<td>7, 9, 10</td>
<td>-</td>
</tr>
<tr>
<td>Leucophaeus fuliginosus</td>
<td>SQ</td>
<td>Loss of habitat Disturbance</td>
<td>Fisheries continue; unknown impact</td>
<td>Minimum control of dogs, cats, rats</td>
<td>Continue unknown</td>
<td>Continue unknown</td>
<td>-</td>
<td>-</td>
<td>Stable / uncertain</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2. Assessment of threats, current action and mitigation and management strategies under status quo (SQ) and the vision (V) for the conservation of Galápagos avian diversity: terrestrial birds, including indigenous species (i.e. native and endemic).

<table>
<thead>
<tr>
<th>Species</th>
<th>Scenarios</th>
<th>Climate Change and Severe Weather</th>
<th>Human Intrusions and Disturbance</th>
<th>Biological Resource Use</th>
<th>Invasive Species</th>
<th>Diseases</th>
<th>Pollution</th>
<th>Geological Events</th>
<th>Loss Genetic Diversity</th>
<th>Population Trends</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galápagos Rail Laterallus spilonota</td>
<td>2018</td>
<td>Change the habitat</td>
<td>Loss of habitat</td>
<td>Some vehicular collisions</td>
<td>Dogs, cats, rats affected individuals</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Unknown</td>
<td>-</td>
<td>35, 41</td>
</tr>
<tr>
<td></td>
<td>SQ</td>
<td>Continue changes in the habitat</td>
<td>-</td>
<td>Increased vehicular collisions</td>
<td>Minimum control of dogs, cats, rats</td>
<td>Continue; unknown</td>
<td>Continue; unknown</td>
<td>-</td>
<td>Continue; unknown</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>-</td>
<td>Educational program and environmental outreach to reduce disturbance in habitat areas</td>
<td>Zero impact</td>
<td>Aggressive control on feral species</td>
<td>Data collected and known</td>
<td>Data collected and known</td>
<td>-</td>
<td>Data collected and known</td>
<td>Stable / uncertain</td>
<td>-</td>
</tr>
</tbody>
</table>


Galápagos Hawk Buteo galapagoensis

<table>
<thead>
<tr>
<th>Species</th>
<th>Scenarios</th>
<th>Climate Change and Severe Weather</th>
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<th>Diseases</th>
<th>Pollution</th>
<th>Geological Events</th>
<th>Loss Genetic Diversity</th>
<th>Population Trends</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2018</td>
<td>Same as above</td>
<td>-</td>
<td>Educational program and environmental outreach program to reduce disturbances in habitat areas</td>
<td>Zero impact</td>
<td>-</td>
<td>No emerging diseases. Data collected</td>
<td>-</td>
<td>Small populations on some Islands</td>
<td>Stable / uncertain</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SQ</td>
<td>Same as above</td>
<td>-</td>
<td>Increase vehicular collisions</td>
<td>Cats, rats? affected individuals</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Unknown</td>
<td>-</td>
<td>1, 7, 9</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Same as above</td>
<td>-</td>
<td>Reforesting breeding areas in GNP, and in agricultural areas (gulch) with the collaboration of farmers</td>
<td>Zero impact</td>
<td>Aggressive control on feral species</td>
<td>Data collected and known</td>
<td>Data collected and known</td>
<td>-</td>
<td>Declining</td>
<td>17, 35, 41</td>
</tr>
<tr>
<td>Little Vermilion Flycatcher Pyrocephalus nanus</td>
<td>2018</td>
<td>Change the habitat</td>
<td>Loss of habitat</td>
<td>Some vehicular collisions</td>
<td>Cats, rats? affected individuals</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Declining</td>
<td>17, 35, 41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SQ</td>
<td>Same as above</td>
<td>-</td>
<td>Increase vehicular collisions</td>
<td>Cats, rats? affected individuals</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Declining</td>
<td>17, 35, 41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Same as above</td>
<td>-</td>
<td>Reforesting breeding areas in GNP, and in agricultural areas (gulch) with the collaboration of farmers</td>
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<td>Aggressive control on feral species</td>
<td>Data collected and known</td>
<td>Data collected and known</td>
<td>-</td>
<td>Stable / uncertain</td>
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<td>Species</td>
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<td>Climate Change and Severe Weather</td>
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<td>Source</td>
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</tr>
<tr>
<td>Galápagos Martin Progne modesta</td>
<td>2018</td>
<td>Change the habitat</td>
<td>-</td>
<td>-</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Small populations?</td>
<td>Uncertain</td>
<td>-</td>
</tr>
<tr>
<td>SQ</td>
<td>More habitat affected; Unknown</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Continue; unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Continue; unknown</td>
<td>Uncertain</td>
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<tr>
<td>V</td>
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<td>-</td>
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<td>Data collected and known</td>
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<td>Data collected and known</td>
<td>Stable / uncertain</td>
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</table>

| Floreana Mockingbird Mimus trifasciatus | 2018 | Change the habitat | Loss of habitat | - | Dogs, cats, rats affected individuals on Floreana | Few diseases recorded | Unknown | Fire | Small populations | Stable on islets | 9 |
| SQ                                    | La Niña affected more frequently the islands | - | - | Introduced species arrived to islets | Few diseases recorded | Unknown | Fire | Small populations | Stable on islets | 50, 51, 75, 77, 82 |
| V                                     | - | Restoration habitat on GNP | - | Aggressive control of feral species on Floreana | Data collected and known | Data collected and known | - | New colonies on Floreana. Implement 50/500 rule for minimum viable population; develop a breeding center | Increased on Floreana / stable | - |

| Española Mockingbird Mimus macdonaldi | 2018 | Change the habitat | Some area with human interaction | - | Unknown | Unknown | - | Small populations | Stable / uncertain | 50, 51, 77 |
| SQ                                    | La Niña affected more frequently the islands | - | - | More human interaction | Continue unknown | Continue unknown | Fire | - | Stable / uncertain | - |
| V                                     | - | Restrict daily tourism tours. Better biosecurity to visit the island | - | Better biosecurity to visit the island | Data collected and known | Data collected and known | - | 50/500 rule rule for minimum viable population; develop a breeding center | Stable | - |

<p>| San Cristóbal Mockingbird Mimus melanotis | 2018 | Change the habitat | Loss of habitat | Some vehicular collisions | Dogs, cats, rats affected individuals | Unknown | Unknown | - | Small populations | Stable / uncertain | 50, 51, 77 |
| SQ                                    | Same as above | Loss of habitat | Some vehicular collisions | No control of dogs, cats, rats | Continue unknown | Continue unknown | Fire | Small populations | Stable / uncertain | - |</p>
<table>
<thead>
<tr>
<th>Species</th>
<th>Scenarios</th>
<th>Climate Change and Severe Weather</th>
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<th>Geological Events</th>
<th>Loss Genetic Diversity</th>
<th>Population Trends</th>
<th>Source</th>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>Unknown</td>
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<td>50/500 rule for minimum viable population; develop a breeding center</td>
<td>Stable</td>
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</tr>
<tr>
<td>SQ</td>
<td>Same as above</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Continue; unknown</td>
<td>Continue; unknown</td>
<td>Fire</td>
<td>Unknown poblational</td>
<td>Stable / uncertain</td>
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<td>Vampire Ground-finch Geospiza septentrionalis</td>
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<td>Change the habitat</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Unknown</td>
<td>Unknown</td>
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<td>Small populations</td>
<td>Stable / uncertain</td>
<td>23, 32, 80</td>
</tr>
<tr>
<td>SQ</td>
<td>Same as above</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Continue; unknown</td>
<td>Continue; unknown</td>
<td>Fire</td>
<td>Unknown population</td>
<td>Stable / uncertain</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>Unknown</td>
<td>Unknown</td>
<td>-</td>
<td>Small populations</td>
<td>Stable / uncertain</td>
<td>23, 32, 80</td>
</tr>
<tr>
<td>SQ</td>
<td>Same as above</td>
<td>-</td>
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<td>Continue; unknown</td>
<td>Continue; unknown</td>
<td>Fire</td>
<td>Unknown population</td>
<td>Stable / uncertain</td>
<td>-</td>
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<tr>
<td>Medium Tree-finch Camarhynchus pauper</td>
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<td>Loss of habitat</td>
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<td>-</td>
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<td>23, 32, 53, 80</td>
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<tr>
<td>SQ</td>
<td>Same as above</td>
<td>Loss of habitat</td>
<td>Unknown vehicular collisions</td>
<td>Dogs, cats, rats affected individuals</td>
<td>New and emergent diseases</td>
<td>Continue; unknown</td>
<td>Fire</td>
<td>Unknown population</td>
<td>Stable / uncertain</td>
<td>-</td>
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<tr>
<td>Large Tree-finch Camarhynchus psitacula</td>
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<td>Loss of habitat</td>
<td>Some vehicular collisions</td>
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<td>-</td>
<td>-</td>
<td>Stable / uncertain</td>
<td>23, 41, 45, 80</td>
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<tr>
<td>SQ</td>
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<td>Loss of habitat</td>
<td>Increase vehicular collisions</td>
<td>Dogs, cats, rats affected individuals</td>
<td>New and emerging diseases</td>
<td>Continue unknown</td>
<td>Fire</td>
<td>Unknown poblational</td>
<td>Stable / uncertain</td>
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Threats and vision for Galápagos birds

The Open Ornithology Journal, 2019, Volume 12

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<tr>
<td>-</td>
<td>V</td>
<td>-</td>
<td>Reforesting breeding areas in GNP, and in agricultural areas (gulch) with the collaboration of farmers</td>
<td>Zero impact</td>
<td>Aggressive control on feral species</td>
<td>No emerging diseases. Data collected and known</td>
<td>-</td>
<td>Data collected and known</td>
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<td>Some vehicular collisions</td>
<td>Dogs, cats, rats affected individuals</td>
<td>Few diseases recorded</td>
<td>Unknown</td>
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<td>SQ</td>
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<td>Loss of habitat</td>
<td>Increased vehicular collisions</td>
<td>Dogs, cats, rats affected individuals</td>
<td>New and emerging diseases</td>
<td>Continue; unknown</td>
<td>Fire</td>
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<td>V</td>
<td>-</td>
<td>Reforesting breeding areas in GNP, and in agricultural areas (gulch) with the collaboration of farmers</td>
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<td>-</td>
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<td>-</td>
<td>Cats, rats affected individuals</td>
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<td>-</td>
<td>Small populations</td>
<td>Declining</td>
</tr>
<tr>
<td>SQ</td>
<td>Same as above</td>
<td>Loss of habitat</td>
<td>-</td>
<td>Cats, rats affected individuals</td>
<td>New and emerging diseases</td>
<td>Continue; unknown</td>
<td>Fire, tsunamis, volcanic eruptions, higher tide levels affected nests near the coast</td>
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<td>Declining</td>
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<tr>
<td>V</td>
<td>-</td>
<td>Searching and exploring new breeding areas</td>
<td>Aggressive control on feral species</td>
<td>No emerging diseases. Data collected and known</td>
<td>Recovery of dunes and mangrove habitat affected by tsunamis and higher tide levels in breeding areas</td>
<td>Data collected and known</td>
<td>Data collected and known</td>
<td>50/500 rule for minimum viable population</td>
<td>Stable / uncertain</td>
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*2018 = 2018 status, SQ = Status quo, V = 2028 Avian Diversity Vision GNP = Galapagos National Park

birds and coastal waterbirds [8, 9] Furthermore, ENSO events may also affect the habitat of land birds and possibly the prevalence of infectious diseases carried by biological vectors, such as mosquitoes and flies, which may be affected by availability of water [1].

Conversely, ENSO events could be beneficial for terrestrial birds in Galápagos because greater rainfall increases the food availability for land birds, although this positive impact could be a double-edged sword promoting the establishment and spread of invasive insects and plants [32, 33] (Table 2). Other effects derived from climate change may include changes of ocean circulation pattern, that in turn may affect food abundance and shifts in foraging ground for seabirds.

3.2. Human Intrusions and Disturbances

With the establishment of Galápagos National Park in the 1960s, 96.7% of the land area in the Galápagos was designated as protected (including tourism areas). The remaining percentage is used for urban and agricultural areas, roads and docks [34]. However, since the time that humans arrived to the islands, they began impacting the islands because of the necessity for roads, houses and demand for food. The establishment of agricultural and military areas was inevitable. The islands occupied by humans were Floreana, San Cristóbal,
Isabela, Santa Cruz, Baltra, and Santiago, with towns primarily located near the coast and agriculture found in the transition and humid zones, as these areas provided more natural resources to humans [3].

In the last fifty years, several islands and islets in the Galápagos archipelago have been restored, including Santiago, Baltra, and Plazas. However, on inhabited islands (Santa Cruz, Santa Crístopal, Floreana, and Isabela), approximately 3.96% of land area was converted to agricultural use, and the proportion of humid zones in natural condition has diminished. The arid and transition vegetation zones have also been affected [35]. This has reduced the natural habitat available for several species such as Galápagos Petrel (Pterodroma phaeopygia), Lava Gull (Leucophaeus fuliginosus), Galápagos Short-eared Owl (Asio flammeus galapagoensis), San Crístopal Mockingbird (Mimus melanotis), Galápagos Rail (Laterallus spilonota), Medium Tree-finch (Camarynchus pauper), and Vegetarian Finch (Platyspiza crassirostris). It has also caused the extirpation of some island populations such as Floreana Mockingbird (Mimus trifasciatus), Galápagos Rail, Little Vermilion Flycatcher (Pyrocephalus nanus), Vegetarian Finch, Gray Warbler-Finch on Floreana Island and the extinction of Least Vermilion Flycatcher (Pyrocephalus dubius) (Tables 1 and 2).

Human activities also interact with species like the Galápagos Penguins (Spheniscus mendiculus), which are affected by collisions with motorboats in breeding areas. The Flightless Cormorant (Phalacrocorax harrisi) and Waved Albatross (Phoebastria irrorata) are also disturbed by human interactions on their breeding areas (Table 1). Other examples occur on terrestrial habitats, where land birds are killed in collisions on the road with automobiles especially on Santa Cruz Island (Table 1 and 2).

### 3.3. Biological Resource Use

While fisheries, mainly longline fisheries, are the principal threat affecting the survival of the Waved Albatross (Phoebastria irrorata) outside of Galápagos Marine Reserve (GMR) [10, 39, 40], Galápagos Penguins are exposed to interactions with artisanal fisheries in the GMR [14] (Table 1). On land, the human persecution has caused the extirpation of some birds populations on inhabited islands such as the Galápagos Hawk (Buteo galapagoensis) on Santa Cruz and San Crístopal Islands, and Galápagos Barn Owl (Tyto alba punctatissima) on Floreana Island [41] (Table 2).

### 3.4. Invasive & Other Problematic Species, Genes & Disease

#### 3.4.1. Invasive Species

Invasive species emerged as a threat as soon as humans arrived on the islands. Introduced plants and animals affected all species directly or indirectly, causing serious or irreparable damages. In addition to predation on eggs, chicks, and adults, introduced species compete for habitats and food, carry or become reservoirs of infectious pathogens and can also be biological vectors of diseases and parasites [1, 9, 42] (Tables 1 and 2).

### 3.4.2. Diseases and Parasites

The indigenous bird species in Galápagos have endemic pathogens and parasites. Significant trauma to the native fauna can occur when introduced pathogens or parasites enter pristine areas, as occurred in Hawaii or New Zealand. On those islands, many species went extinct when non-native avian pox and avian malaria were introduced [43, 44]. In Galápagos, avian pox virus affects 15 species and has been present on the islands for more than 110 years [45 - 48]. Avian malaria (Plasmodium sp.) has been recorded in eight species including the Galápagos Penguin (Spheniscus mendiculus) [49]. The ectoparasite Philornis downsi affects more than 17 species and is present on more than 10 islands and islets in the Galápagos. It reduces the reproductive success of Passeriformes, affecting Critical Endangered species such as Mangrove Finch (Camarhynchus melanocephalus) [50 - 54]. Endoparasites have been recorded from Galápagos Penguin (Spheniscus mendiculus), Flightless Cormorant (Phalacrocorax harrisi), and Waved Albatross (Phoebastria irrorata), but they are common on marine birds [55, 56] (Table 1).

### 3.5. Pollution

Oils spills represent one of the major threats in terms of marine pollution for seabirds in the Galápagos [11]. On 16 January 2001, a large oil spill at Naufragio Bay, San Crístopal Island, caused by the wreck of the tanker MV Jessica threatened a significant area of the Galápagos Marine Reserve. The oil tanker released almost 100% of its total cargo consisting of 302,824 L of Fuel Oil 120 (bunker fuel) and 605,648 L of Diesel oil [57, 58]. Afterward, researchers conducting fieldwork on Española Island found five oiled Nazca Boobies (Sula granti) in January 2001, one oiled Waved Albatross (Phoebastria irrorata) in June 2001, and two oiled Nazca Boobies (Sula granti) in November 2001, indicating that these birds were polluted by spilled oil [59]. A second oil spill took place in the Galápagos in early July 2002, when a small tanker (BAE Taurus) sank and spilled diesel fuel in waters off the coast of Puerto Villamil, Isabela Island. Fortunately, most of the populations of endangered seabirds, such as Galápagos Penguin (Spheniscus mendiculus) and Flightless Cormorant (Phalacrocorax harrisi), were not affected by the direct impact of these spills [11]. However, the chemical exposure of seabirds to chronic residual levels of oil hydrocarbons in the long term is unknown. Elevated plasma corticosterone levels, reduction in growth, and high mortality were found in the endemic Galápagos marine iguanas (Amblyrhynchus cristatus) exposed to residual hydrocarbon traces during and/or after the MV Jessica oil spill [60 - 62]. This finding suggests that even low levels or traces of oil hydrocarbons have critical negative effects for marine iguanas and possibly with marine birds on Galápagos.

Although only a few studies have been carried out on persistent, bioaccumulative and toxic contaminants, including Persistent Organic Pollutants (POPs) and organic mercury (MeHg) as well as several other heavy metals and contaminants of emerging concerns (such as microplastics and pharmaceutical and personal care products (PPCPs)) in Galápagos [11, 63], recent ecotoxicological research has shown...
that the Galápagos are not immune to the global and regional pollution by organic contaminants in marine biota [11]. This has been demonstrated by the exposure to Persistent Organic Pollutants (POPs) in Galápagos sea lion (Zalophus wolffiaei) and marine fish [10, 11, 63 - 66].

Both exposures to and biomagnification of POPs (e.g. polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethanes (DDTs), and several others organochlorine pesticides) have been documented for the Galápagos sea lion (Phoebastria irrorata) and mullets, (Mugil sp.) [63, 65], which can also serve as potential prey for seabirds. This underscores the potential for biomagnification of these contaminants in the food chain of top predators, including biomagnification in the marine food web of seabirds and terrestrial food web of raptors (e.g., Galapagos hawk’s food web).

There is also strong evidence that current-use pesticides (CUPs) were used in the Galápagos [11]. While CUPs include organophosphate and carbamate classes, a wide variety of other groups of pesticides seem to have been applied in the Galápagos, including insecticides such as neonicotinoid (Acetamiprid) and synthetic Pyrethroids (PYR) (i.e. Deltamethrin to control the biovector of dengue, the mosquito Aedes aegypti) as well as herbicides such as glyphosate (Rodeo or Roundup) and paraquat (Gramoxone) to eliminate weeds and invasive vegetation [11, 63]. Though CUPs are generally less persistent and bioaccumulative than legacy POPs, some can be acutely toxic pesticides to fish [67, 68]. Almost all farmers in Galápagos use CUPs before sowing and during the growth period without taking into account the prescribed usage concentrations of these chemicals which result in mortality of Passeriformes (GJU, pers. obs.). The impact of insecticides and herbicides, along with the potential use of second-generation anticoagulant rodenticides to eliminate introduced rodents (e.g., black rats, Rattus rattus) and associated secondary poisoning are also issues of great concern for birds, particularly raptors such as the Galápagos hawk (B. galapagoensis), Galápagos Short-eared Owl (A. flammeus galapagoensis) and Barn owl (T. alba punctatissima) (JJA, pers. obs.) (Table 2). The second-generation anticoagulant rodenticides (SGARs) are extremely toxic, persistent, bioaccumulative and non-specific, affecting the blood clotting mechanism common to all vertebrates (for a review see Elliott et al. [69], and Rattner [70]). However, other species, for example, the Brown Pelican (Pelecanus occidentalis urinatus), take advantage of dead animals (namely fish) (GJU, pers. obs.) that may have been exposed to these pesticides.

Similarly, high concentrations of Methyl Mercury (MeHg) in yellow-fin tuna (Thunnus albacares) sampled around Galápagos waters have been detected [71]. While lead and cadmium levels have been detected in Galápagos Penguin (Spheniscus mendiculus), Flightless Cormorant (Phalacrocorax harrisi) and Waved Albatross (Phoebastria irrorata), a mercury analysis of Galápagos seabirds is currently underway [72]. Therefore, it is of paramount importance to measure the exposure to contaminants of the native and endemic birds of the Galápagos because these contaminants are likely to become a threat in the near future with implications at the individual level and population health [11, 66, 72] (Tables 1 and 2).

3.6. Geological Events

The Galápagos Islands are volcanic in origin, formed by the eruption of magma generated in the depths of the Earth [73]. This remains a current threat on Isabela and Fernandina Islands, where volcanic activity is frequent and this activity has the potential to affect numerous species, such as Galápagos Penguin (Spheniscus mendiculus), Flightless Cormorant (Phalacrocorax harrisi), Galápagos American Flamingo (Phoenicopterus ruber glyphorynchus) and Mangrove Finch (Camarhynchus heleniobates) [9, 74]. Included among potential disasters are wildfires, as happened on Floreana in the 19th century (human origin) which was possibly one of the causes of the Floreana Mockingbird extinction from the island [75]. Species that occur on single small islands or having restricted range would be at greatest risk from wildfires, such as Floreana Mockingbird (Mimus trifasciatus), San Cristóbal Mockingbird (Mimus melanothis), Española Mockingbird (Mimus macdonaldi), Mangrove Finch (Camarhynchus. heleniobates), Genovesa Ground-finch (Geospiza acutirostris), Genovesa Cactus-finch (Geospiza propinqua) and Medium Tree-finch (Camarhynchus pauper). Tsunamis in last decade have also affected the islands and species that breed on the coast are at risk, such as Galápagos Penguin (Spheniscus mendiculus) and Flightless Cormorant (Phalacrocorax harrisi) (GJU per. obs.). However, this threat is unlikely to affect entire populations, just a few local areas, although they could affect important breeding areas like the Marielas Islets (where there are usually between 50-100 breeding Galápagos Penguins) (Table 1).

3.7. Loss of Genetic Diversity

Preserving the genetic diversity is recognized as a priority for the conservation of these avian species [76]. The species with smallest populations in Galápagos are the Mangrove Finch (Camarhynchus heleniobates) with less than 100 individuals or Floreana Mockingbird (Mimus trifasciatus) and Galápagos American Flamingo (Phoenicopterus ruber glyphorynchus) with less of 500 individuals. Species restricted to single islands, such as Genovesa Ground-finch (Geospiza acutirostris), Genovesa Cactus-finch (Geospiza propinqua) and Medium Tree-Finch (Camarhynchus pauper), have a high potential risk from loss of genetic diversity. For example, the population of Floreana Mockingbird (Mimus trifasciatus) on Champion Islet has been lost 39 percent of its heterozygosity, when comparing individuals from 1906 and 2008. The population on Champion Island also differs genetically from the only other population on Gardner by Floreana Island and both likely differ from that of the now-extirpated founder population on Floreana Island [77]. Another example is of the Galápagos Penguin (Spheniscus mendiculus), who showed low genetic diversity in relation with Magellanic Penguin (Spheniscus magellanicus) and Humboldt Penguin (Spheniscus humboldtii) [78] (Table 1).

4. DISCUSSION

Until very recently, Galápagos had no bird species present
on the list of extinctions [44]. However, the first recorded was the Least Vermilion Flycatcher (Pyrocephalus dubius) [17] although there have been extirpations of birds from some islands in the archipelago [79]. The conservation of long-term avian diversity on the islands begins with education, prevention, control, mitigation, monitoring and alliances to work together [6].

The pressure of multi- anthropogenic stressors with associated cumulative impacts by climate change, human intrusions and disturbance, biological resource use (incidental and direct fishing), invasive and other problematic species, and diseases, pollution (chemical and biological contamination, solid waste, urban sprawl), and loss of genetic diversity can in concert affect the populations of birds in the long term. This can be translated into impacts to the functioning and health of the Galápagos ecosystems and for local eco-tourism activities strongly relying on wildlife; for example, the presence of seabirds and terrestrial birds as icons for touristic attraction.

The cumulative pressure deriving from these threats can generate unnatural or anthropogenic selection forces re-shaping evolution in endemic bird species of the Galápagos. The unnatural selection has already been identified as a human environmental alteration that may be replacing natural selection as the major driving force of evolution in Darwin’s finches [80]. At present, the human interactions and associated impacts that affect both marine and land birds are of great concern, such as those occurring (i.e. fisheries interactions) with the Waved Albatross (P. irrorata) and the Galápagos Penguin (S. mendiculus) [14, 39, 40] because these threats are critical to the recovery of their populations (Table 1). Changes in fishing gear technology, incentives for fishing communities and better fisheries management practices at sea need to be further fostered and proactively implemented to mitigate these impacts.

On land, the terrestrial birds are basically divided in two groups depending on the magnitude and degree of urbanization and human disturbances, including those species found in inhabited islands where there are negative human-made activities (e.g., collisions by cars, predation by domestic animals, poisoning) and those inhabiting unoccupied islands where the disturbance is minimum (Table 2) [38]. Habitat loss and fragmentation can be reversed to recover suitable habitat by implementing ecological restoration programs for habitats of indigenous species. Reforestation initiatives utilizing native species within the agricultural areas and replacement of the urbanized-landscape with green-landscape are just two feasible recommendations to achieve this goal.

In islands harboring human centers and urbanization, the role of invasive species and emerging infectious diseases are of serious concern because according to the literature and historical data, in and out of Galápagos, the results show a dramatic decrease of bird populations, even extinctions [42 - 53, 55, 56]. The introduction of new diseases and parasites can be prevented by biosecurity control at the ports of entry from the continent, with continuity and reinforcement of fumigation and biosecurity control in all means of transport to the Galápagos. In doing so, the ongoing efforts and concerted improvements of management plans to prevent, control and eradicate introduced species and feral animals are of paramount importance to protect endemic and native species in the long term (Table 1).

Chemical pollutants (heavy metals and POPs) can be managed if the sources are from human centers (semi-urbanized islands) and the islands, as in the case of oil spills [57], although these are difficult to control if originating from human sources outside of Galápagos [11, 63, 66, 72]. Concerted local and global management strategies are also strongly needed in the decision making processes to protect the Galápagos Marine Reserve and National Park from chemical pollution and biological assaults [11, 63].

The Galápagos Islands are a natural laboratory and have many species unique in the world, evolving over thousands of years and surviving natural events. However, concentrations of CO₂ are more in the present day (> 400 ppm) than a million years ago resulting in accelerated global warming and influencing natural events such as ENSO events, which in turn impact the bird populations in the archipelago with both negative (seabirds) and positive (land birds) impacts [8, 28, 76, 81]. While natural events such as El Niño have been affecting the Galápagos species for thousands of years, these species are resilient and have adapted to the changes imposed by these events [24]. However, ENSO events exacerbated by anthropogenic climate change (Table 1) threaten marine birds, which are being affected when their population numbers are declining [13, 25, 26, 28]. Meanwhile, some land bird species exhibit increased population numbers, but with uncertainty and consequences in the future as their natural habitat could be expected to change with the emergence of biological invasion by introduced species. In this case, any proposal to implement actions to mitigate the effects of climate change should involve a pathway to enhance the conservation of the resilience and adaptive capacity of species and protection of their habitats.

If anthropogenic stressors continue contributing to the perturbation of natural habitats and behavior of species, the natural evolutionary forces normally ruling speciation and radiation can be lost in the long term and, therefore, difficult to characterize, monitor, and preserve in its genuine state unless management and mitigation strategies are urgently implemented to minimize and reduce anthropogenic factors in the Galápagos [11, 82].

CONCLUSION

In this assessment, we identified threats that are driven by natural forces, such severe weather and geological events, and human-driven stressors, such as anthropogenic climate change, fisheries interactions, pollution and loss of habitat and genetic diversity. To address these threats, a set of management actions and recommendations to conserve species and protect their habitats have been projected with a new vision from present times to 2028.

Relying on an out of the box approach to contribute with effective conservation fronts (Tables 1 and 2) to understand what would be the case if threatened species (e.g., endemic) of Galápagos bird populations are dramatically reduced and
which should be the minimum number of a given population to intervene in the natural process, we propose as a recommendation to follow the 50/500 rule developed almost 40 years ago [83] as a guiding principle in conservation for assessing minimum viable effective population size in birds [84] in order to maintain the long-term genetic diversity in current and future conservation programs. In Galápagos, some putative examples of the application of this rule exist with endemic reptiles, but in birds, this seems only to be applied for the Mangrove Finch (C. heliobates).

The conservation challenge in Galápagos is the small population size for most threatened and/or endangered species. Conversely, for few bird species, the capacity to establish a breeding center for species such as the Galápagos Penguin (S. mendiculus), Floreana Mockingbird (M. trifasciatus), Española Mockingbird (M. macdonaldi), San Cristóbal Mockingbird (M. melanotis), and Medium Tree-finch (C. pauper) cannot be ruled out. As for the other species with less opportunity and difficult to breed through ex-situ conservation, the vision for the conservation of these Galápagos birds should focus on the preservation and enhancement of the resilience of habitats affected by natural disasters (e.g., tsunamis, fires, eruptions) to restore the impacted areas by following contingency plans.

Management in many cases needs to be more aggressive, principally with the threats we can mitigate or eliminate, to get more populations to status like stable or increasing based on minimum viable populations. A vision for Galápagos avian diversity needs a long term monitoring and adaptive management approach to evaluate the results from the research and conservation efforts invested over time, which will support the improvement of wildlife management to redirect conservation plans, if necessary

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Not applicable.

HUMAN AND ANIMAL RIGHTS
No animals/humans were used for studies that are the basis of this research.

CONSENT FOR PUBLICATION
Not applicable.

CONFLICT OF INTEREST
The author declares no conflict of interest, financial or otherwise.

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