Habitat Suitability and Population Viability Analysis of the Black-browed Albatross in the Falkland Islands

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1. Introduction

The Falkland Islands are home to the world's largest breeding population of Black-browed Albatrosses, with an estimated 70% of the global population breeding on the Island (ACAP, 2010). The most recent archipelago-wide census was completed in 2010, estimating between 475,000 and 535,000 breeding pairs and a 4% increase per annum between 2005 and 2010 (Wolfaardt, 2012). The Falkland Islands albatross population is considered resident, foraging on the Patagonian Shelf year round (Ponchon et al., 2019). Accordingly, quantifying the vulnerability of this species to climate change is essential for global conservation and management.

Black-browed Albatrosses have been classified by the IUCN as Least Concern since 2018, shifting from an Endangered classification in 2012. Increases in Black-browed Albatross population trends, while mainly unclear, have been attributed to reduction of seabird bycatch in regional fisheries (Moreno et al., 2008; Wolfaardt, 2012). Although, as environmental conditions become less favorable, even a small level of bycatch could contribute to population decline (Catry et al., 2011). Changes in sea surface temperature during late winter was shown to have the biggest impact on population growth rate, resulting in lowered survival rates of Black-browed Albatross juveniles (Jenouvrier et al., 2018). A recent study also found that higher "divorce rates" among Black-browed Albatrosses are directly related to environmental variables, increasing in years with warm sea surface temperature anomalies. The study hypothesized that warmer waters forced the albatrosses to hunt longer and fly further, causing them to fail to return for the breeding season, and generally increased stress hormone levels in the birds (Ventura et al., 2021a). While the Falkland Islands are home to the only remaining stable increasing populations of Black-browed Albatrosses, this disruption in pairing will nonetheless cause disturbance in breeding processes. Additionally, another study found that Black-browed Albatrosses on Macquarie Island off New Zealand are vulnerable to predicted climate-driven changes in wind patterns in the Southern Ocean (Cleeland et al., 2019).

In general, seabirds are sensitive to global climate change due to their dependence on oceanographic conditions (Diamond & Devlin, 2003) and understanding the level of vulnerability is crucial for determining thresholds of concern. Colonial seabirds can be more easily monitored than many other marine species and have proven to be good indicators of ecological change (Hazen et al., 2019). Therefore, if we can study what's happening at local levels, these seabirds can act as sentinels for the rest of the ecosystem. Globally, albatrosses are one of the most threatened groups of seabirds, with the only exception being the Falkland Islands population (Birdlife International, 2018). As ocean ecosystems dramatically shift due to climate change, decreasing populations of apex predators like the Black-browed Albatross threaten to further upend the equilibrium of these ecosystems. It is therefore essential to understand how this population may shift due to global climate change at this critical turning point.

1.1. Research Objectives

1. Estimate a Black-browed Albatross habitat suitability model based on historical climate conditions
2. Estimate a Black-browed Albatross habitat suitability model based on predicted climate conditions for RCPs 4.5 and 8.5
    a. Determine difference in habitat suitability between historical and predicted
3. Conduct Population Viability Analysis (PVA) to determine Black-browed Albatross population-level consequences of predicted changes in marine ecosystems, particularly sea surface temperature and the large-scale climate index Southern Annular Mode (SAM)

2. Methods

2.1. Study Site and Data Sources

This study was focused on the Falkland Islands, an archipelago in the South Atlantic Ocean on the Patagonian Shelf. Black-browed Albatrosses breed at 12 distinct sites in the Falkland Islands (Figure 1) during austral summer, with the largest colony on Steeple Jason (Appendix A). Climate variables were downloaded from the National Center for Atmospheric Research Climate Change Portal (https://gisclimatechange.ucar.edu/gis-climatedata). A bounding box was drawn around the entirety of the Falkland Islands for data download. Historic climate data from 1985-2005 was downloaded for mean austral summer temperature (Celcius), mean annual precipitation (mm), and sea surface temperature (Celcius). Climate predictions for the three variables listed above were then downloaded for the 2040-2060 period (referred to as the 2050s), using the Representative Concentration Pathways of 4.5 and 8.5 and Ensemble Average as the climate prediction model. Representative Concentration Pathways (RCPs) indicate the concentrations of atmospheric greenhouse gas and the trajectory that is taken to reach those concentrations. RCP 4.5 is described by the IPCC as the middle of the road scenario, with emissions peaking by the 2050s and then declining. RCP 8.5 is described as emissions continuing to rise throughout the century, often known as the worst-case scenario (IPCC, 2013). All climate data (historical and predicted) was downloaded as point feature classes. The digital elevation model, land cover classification, and Falkland Islands boundary shapefile were downloaded from the Falkland Islands Data Portal (http://dataportal.saeri.org/organization/fig). The foraging range of Black-browed Albatrosses was estimated using Seafloor Bathymetry (from the ArcGIS Living Atlas) and data from Huin (2002).

Figure 1. Location of the Falkland Islands and the 12 distinct Black-browed Albatross breeding colonies.

2.2. Climate Data

Within ArcGIS, the climate data was interpolated into rasters using the Spline tool then clipped to the Falkland Islands boundary using Extract by Mask. The predicted austral summer temperature and annual precipitation rasters were subtracted from the historical temperature and precipitation rasters to estimate climate anomalies for reference (Appendix B).

2.3. Habitat Suitability Data

Using the workflow outlined in Figure 2, various habitat suitability variables were derived and transformed. Slope data was derived from the DEM and the foraging range was derived from the Patagonia Shelf boundary using Euclidean distance. Land cover and slope were reclassified on a 1-10 scale, with 10 being the preferred variable. For land cover, the values were reclassified according to the table in Appendix B, with tussac grass and bare ground being the most prefered. For slope, a value of 10 indicated the preferred slope of 0-10%. While Black-browed Albatrosses prefer to nest around steep slopes, the nesting sites themselves are on flat ground. The Euclidean distance to the Patagonian Shelf was rescaled according to the MS Small transformation function, with the closest distance classified as a value of 10. For reference, land cover and foraging data is included in Appendix B. Sea surface temperature, mean austral summer temperature, and mean annual precipitation were all rescaled using the Gaussian transformation for the historical data. Using the historical data as a reference for ideal conditions, the predicted climate data was rescaled according to the deviation from historical.

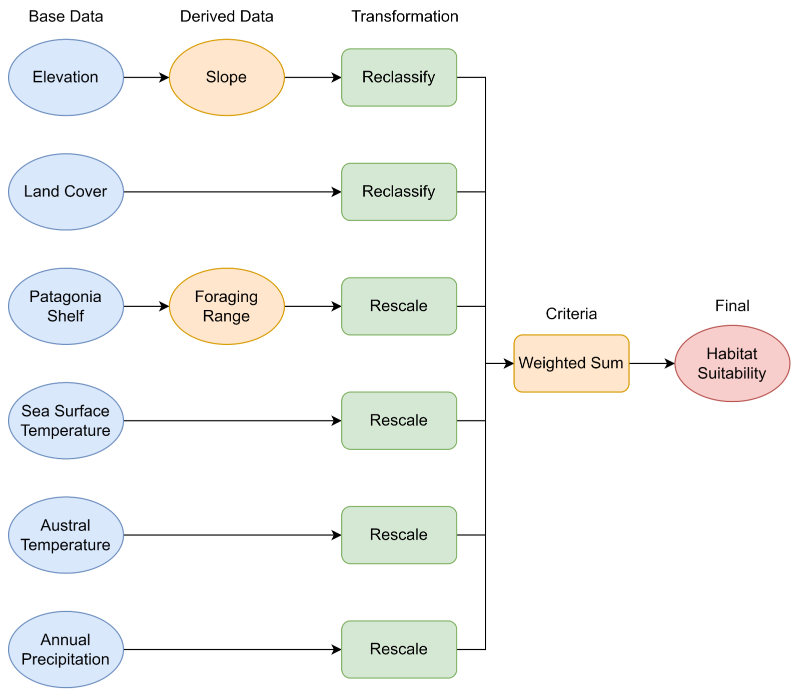

Figure 2. General workflow for the Black-browed Albatross habitat suitability analysis.

For both the historical and predicted habitat suitability analysis, all variables were combined using Weighted Sum, with precipitation and distance to the Patagonian Shelf weighted lower than the other variables. It has not been documented that precipitation impacts Black-browed Albatross breeding, and this species is known for their ability to forage up to 1,000km away from their breeding sites, so these two variables are not as significant as the others. The results of Weighted Sum are seen in Appendix C with a value of 5 indicating most preferred habitat and a value of 1 indicating least preferred. The two habitat suitability rasters were then subtracted to indicate areas of change.

2.4. Population Viability Analysis

Natural England developed a web-based tool for conducting Population Viability Analysis (PVA), using a stochastic Leslie matrix model, on seabird population changes due to offshore renewable developments (https://github.com/naturalengland/Seabird_PVA_Tool). PVA uses demographic rates to estimate future populations under both baseline conditions and scenarios of impact set by the user. Using modelled demographic responses to environmental change of Black-browed Albatross in the Falkland Islands from Ventura et al. (2021b) and demographic parameters estimated by Catry et al. (2011) and Pardo et al. (2017), the PVA tool was run to assess impact of climate change on Black-browed Albatross populations in the Falkland Islands. The inputs for analysis and associated data sources are outlined in Table 1. A negative value indicates a positive change in the associated variable. The two types of impact scenarios, Sea Surface Temperature Anomaly (SSTA) and Southern Annular Mode (SAM), are environmental proxies for food availability and accessibility that directly impact breeding productivity and survival. SSTA is treated as a fine-scale and short-lived proxy and SAM is treated as a large-scale climate index. Adult survival is the demographic parameter with the highest sensitivity and is primarily influenced by deeper ecosystem changes (SAM), while local oceanographic variables (SSTA) are shown to primarily affect productivity rate as individuals invest less in reproduction and more in survival in harsh conditions (Ventura et al., 2021b). The SAM index is the main mode of inter-annual climate variability in the Southern Ocean and is defined as the "atmospheric pressure difference between the latitudes 40ºS and 65ºS" (Marshall, 2003). SAM is the main factor influencing atmospheric and ocean circulation on the Patagonian Shelf and in the Southern Ocean. Positive values of the SAM index, associated with contraction of the westerlies, indicate warmer SSTA and increased downwelling events (Lovenduski & Gruber, 2005). Positive SSTA values (warmer sea surface temperatures) directly and negatively affect primary productivity in the trophic web.

The tool was run with the initial population set at 535,000 for the year 2010 (Wolfaardt, 2012). Environmental and demographic stochasticity were included and 1000 simulations were run. Juvenile survival rate refers to birds that are 1-4 years old. Once birds enter the immature age class (5 years old), they have the same survival probability as adults (Pardo et al., 2017). Impacts were assessed for the years 2015-2050, with full analysis run on the years 2010-2050.

Demographic Parameter	**Value**	**Source**
Age at first breeding	6 years	Pardo et al. (2017)
Adult Survival	0.94 (SD: 0.023)	Catry et al. (2011)
Juvenile Survival	0.75 (SD: 0.03)	Catry et al. (2011)
Productivity rate per pair	0.525 (SD: 0.144)	Catry et al. (2011)
Impact Scenario 1: SSTA decrease by 1	Productivity: mean = -0.0048	Ventura et al. (2021b)
Impact Scenario 2: SSTA decrease by 2	Productivity: mean = -0.0096	Ventura et al. (2021b)
Impact Scenario 3: SSTA increase by 1	Productivity: mean = 0.0048	Pardo et al. (2017); Ventura et al. (2021b)
Impact Scenario 4: SSTA increase by 2	Productivity: mean = 0.0096	Ventura et al. (2021b)
Impact Scenario 5: SAM decrease by 1	Survival: mean = -0.0032	Ventura et al. (2021b)
Impact Scenario 6: SAM increase by 1	Survival: mean = 0.0032	Ventura et al. (2021b)
Impact Scenario 7: SAM increase by 2	Survival: mean = 0.0064	Ventura et al. (2021b)

Table 1. Parameters for the Population Viability Analysis. SSTA and SAM are standardized values and impacts are treated as the baseline rate minus the scenario rate. For example, in Impact Scenario 3, there is a 0.48% reduction in mean productivity rate (52.50%-52.02%), so the input is 0.0048.

3. Results and Discussion

3.1. Habitat Suitability

The results of the habitat suitability analysis are found in Figure 4 for RCP 4.5 and Figure 5 for RCP 8.5, where a value of “increase” indicates positive suitability change, a value of “no change” indicates no change in suitability, and a value of “decrease” indicates negative suitability change. One of the main breeding sites, the Jason Islands, showed no change in habitat suitability for the RCP 4.5 scenario, while a significant portion showed a decrease in suitability for RCP 8.5. Steeple Jason and Grand Jason are home to the island’s largest breeding population and third largest, respectively. West Point Island, Grave Cove, Saunders Island, and Keppel Island all indicated a decrease in habitat suitability for both RCP scenarios. West Point Island has the fifth largest population, Saunders Island has the sixth, Keppel Island has the tenth, and Grave Cove has the smallest population. The 12 breeding sites with their respective populations from the latest census are listed in Appendix A. The second largest colony, Beauchene Island, did not have enough data to produce a habitat suitability analysis. This is most likely due to the remote location of the island, the small size, and the coarseness of climate prediction data.

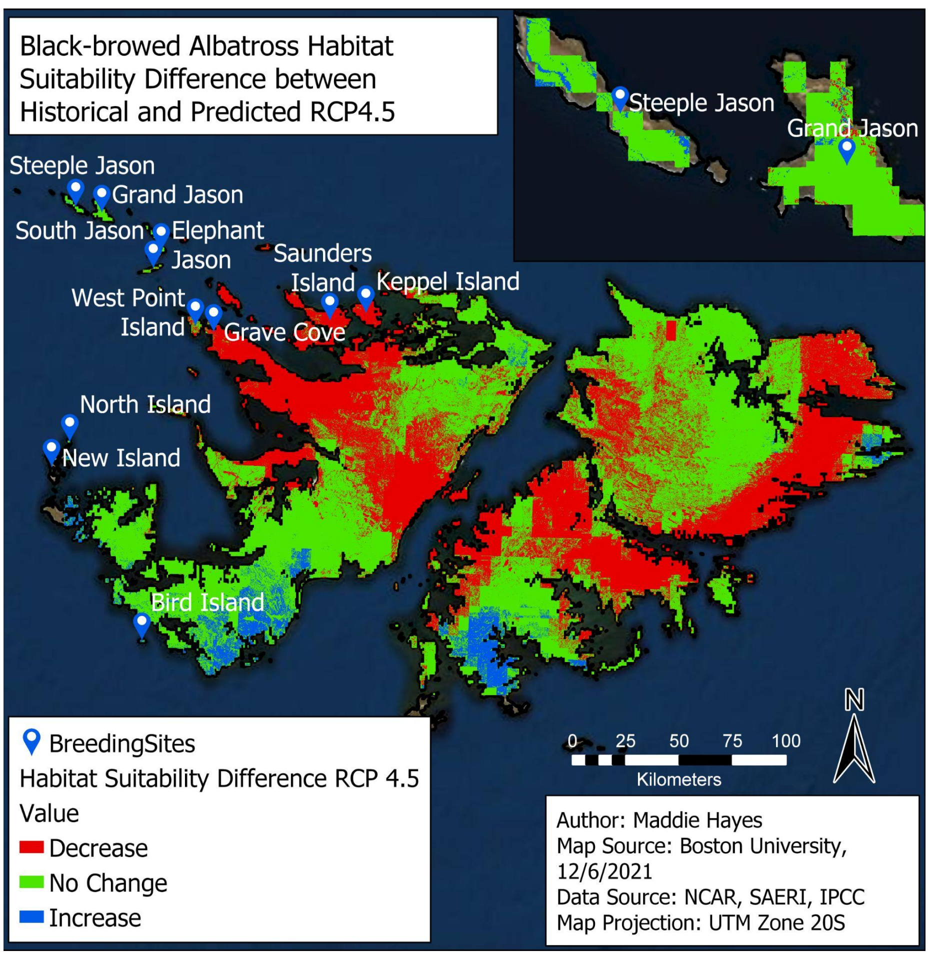

Figure 3. Habitat suitability analysis for RCP 4.5.

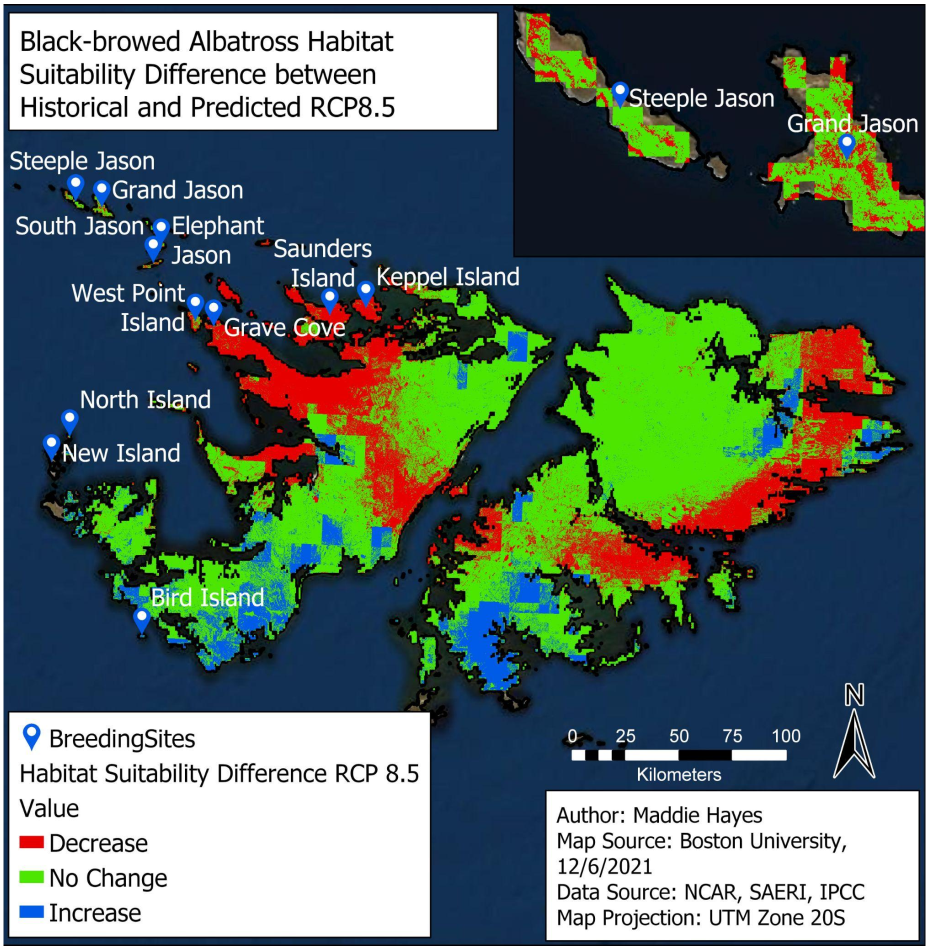

Figure 4. Habitat suitability analysis for RCP 8.5.

Overall, it appears that the majority of colonies will not experience a significant decrease in habitat suitability by the 2050s for the RCP 4.5 scenario. The RCP 8.5 scenario indicates half the colonies will experience a decrease in suitability. At its most basic level, this is the expected outcome, as higher greenhouse gas concentrations will negatively shift the ideal habitat requirements. The RCP 8.5 scenario was known as the worst case scenario when it was first published in 2013. Since then, the Paris Agreement was signed by almost 200 countries and new climate policies were adopted across the globe. Renewable energy is becoming more accessible as well. Yet, while the RCP 8.5 scenario seems less likely now, the world is still nowhere near on target with Paris Agreement mitigations. Additionally, the RCPs are now considered alongside Shared Socioeconomic Pathways, which outline qualitative scenarios and are outside the scope of this study. Climate modelling in general involves many uncertainties, so the RCPs tested in this study should be treated as possibilities instead of definite.

3.1.1 Habitat Suitability Considerations

The only values that were changed for the predicted habitat suitability analysis were temperature, precipitation, and sea surface temperature. It can be assumed that land cover will change in the upcoming century, and slope could possibly change as a result of erosion or weathering. It is worth noting that the climate predictions have a very low spatial resolution at 105 km and the total area of the Falkland Islands is 12,000 km^2, with the colonies themselves being much smaller. Due to the coarseness of global climate predictions, they must often be downscaled for localized studies. However, the majority of downscaling methods are only available for the continental US, Europe, and Japan, where long-term data is available for calibration and verification (Hoar & Nychka, 2008). Therefore, the habitat suitability analysis presented in this study should only serve as a guide for future analysis and/or as supporting information for decision-making. Assuming a similar level of data uncertainty and error between the two maps, they can be reliably compared to one another.

3.2. Population Viability Analysis

For long-lived species like the Black-browed Albatross, population dynamics are mainly driven by adult survival. This is seen in the output of the PVA (Figure 5) as the impact scenario that was projected to decrease population size the most was an increase in the Southern Annular Mode index (SAM). SAM represents a deeper ecosystem change that Black-browed Albatross adult survival rate is highly sensitive to. This is confirmed by the PVA results, showing that increases in SAM have a much higher impact on population size than sea surface temperature. While increases in SSTA also negatively impacted population size, the effect was smaller and remained at the same level as the baseline in some simulations. It has been documented that this limited response to local environmental variability may be due to the fact that historical SST has been lower than optimal SST, creating a buffered effect on population dynamics (Pardo et al., 2017). Comparing the projected population growth rate (Figure 6) and population size (Figure 7) under scenario to the baseline further confirms that increases in SAM and warmer SSTA negatively affect population dynamics while cooler SSTA and decreases in SAM had a positive effect. The counterfactual population growth rate (Figure 6) indicates that, regardless of the impact year, growth rate will decrease significantly. This result agrees with previous findings that, while adult birds are able to adjust to a certain level of environmental variability, this results in lowered breeding productivity. Additionally, local environmental variability impacts juvenile survival rate. The counterfactual of population size result (Figure 7) follows the expected trend, with population size decreasing more in the later impact years.

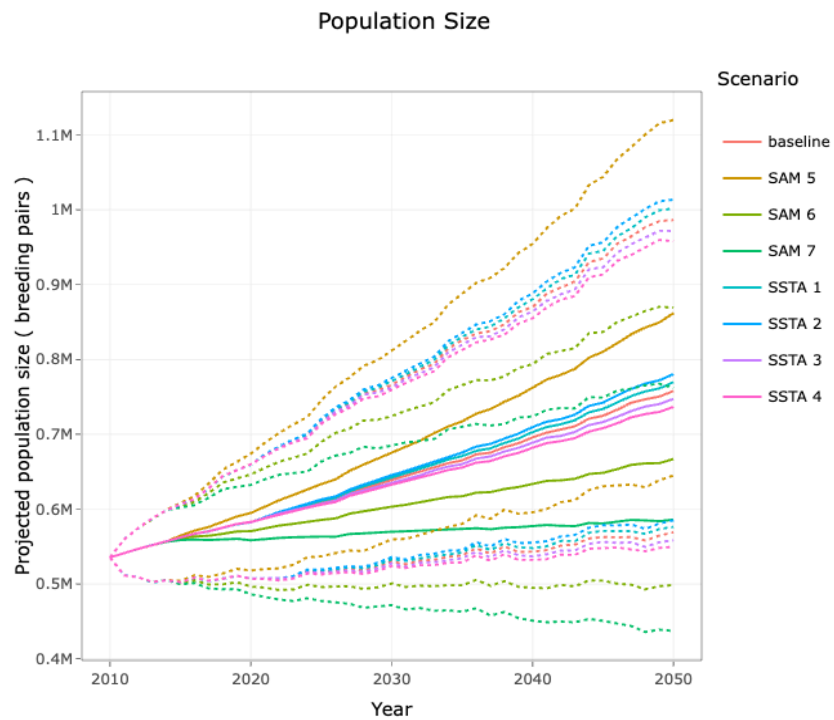

Figure 5. Projected Black-browed Albatross population size under the baseline and 7 impact scenarios for the years 2010-2050 (impacts start in the year 2015).

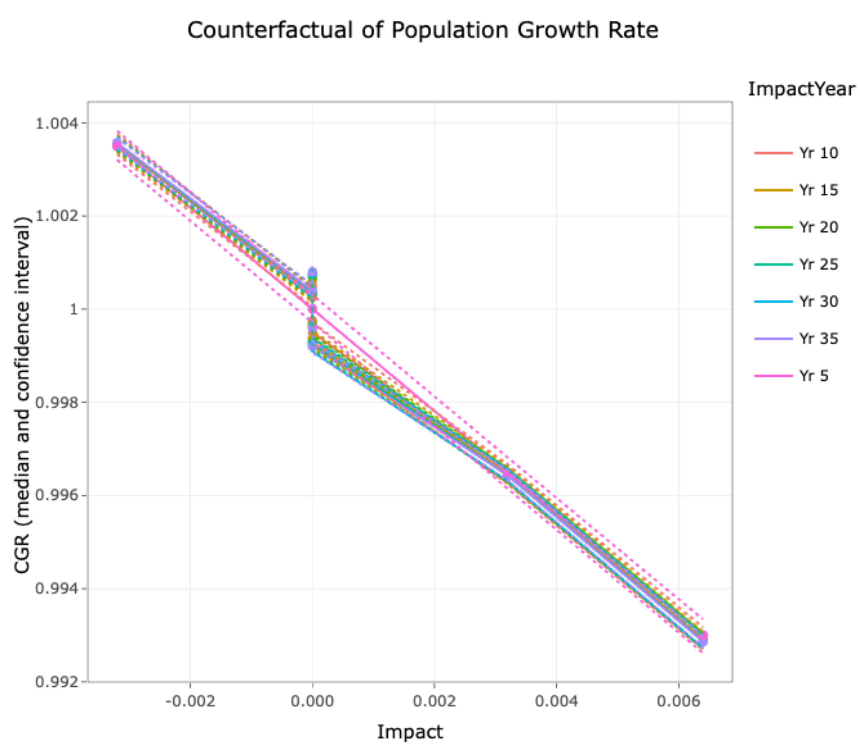

Figure 6. CGR is the ratio of annual growth rate under scenario to growth rate under the baseline for the same period.

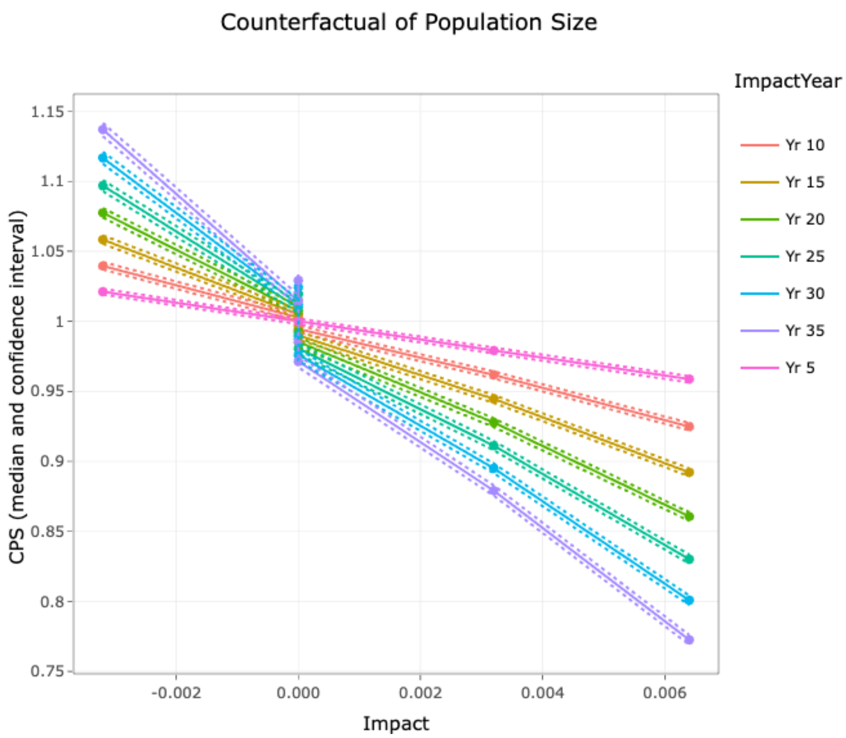

Figure 7. CPS is the ratio of final population size in scenario to final population size in baseline.

The results of the PVA seem to agree with previous notions that Black-browed Albatross population dynamics are more driven by large-scale climate changes. Additionally, while the impact seems small in comparison, there is still a negative impact on breeding productivity due to warmer SSTA. SAM is a driving force in sea surface temperatures and primary and secondary productivity, limiting food availability and accessibility for seabirds. Positive SAM phases and warmer SSTA are predicted to increase in frequency as climate change worsens. As apex predators in the marine trophic web, changes in seabird foraging will directly impact the ecosystem they inhabit.

4. Conclusions

The results of this study emphasize an urgency for change. The Falkland Islands are home to one of the only remaining stable populations of albatrosses and the Patagonian Shelf is one of the most productive ocean ecosystems. The findings presented here indicate that this population of Black-browed Albatrosses is threatened by large-scale climate variability, with increases in the Southern Annular Mode index having the highest effect on adult survival. Increases in sea surface temperature and air temperature are also shown to negatively impact breeding productivity and habitat suitability. If this population starts to collapse, then the collapse of the Patagonian Shelf marine ecosystem could soon follow, creating a critical point of no return for biodiversity conservation.

Due to the complexities of climate change, different research methods should be used in conjunction, particularly for top-predators like the Black-browed Albatross. While they play a critical role in the equilibrium of marine ecosystems, seabirds can be elusive, with juveniles spending their first few years at sea. Therefore, different models and scenarios need to be explored to better understand the scope of the problem and make informed decisions. The IPCC is currently working on their sixth assessment report, with the Physical Science Basis already published in August, 2021. This new report will contain the most up to date information, and further iterations of this study should include the newest projections. Overall, this current study aims to highlight the importance of seabirds as indicators of environmental change. The term "canary in the coal mine" has long since emphasized the role of birds as sentinels, warning humans of detrimental effects. In this case, Black-browed Albatross are no different, and the results presented here are a warning that change is needed.

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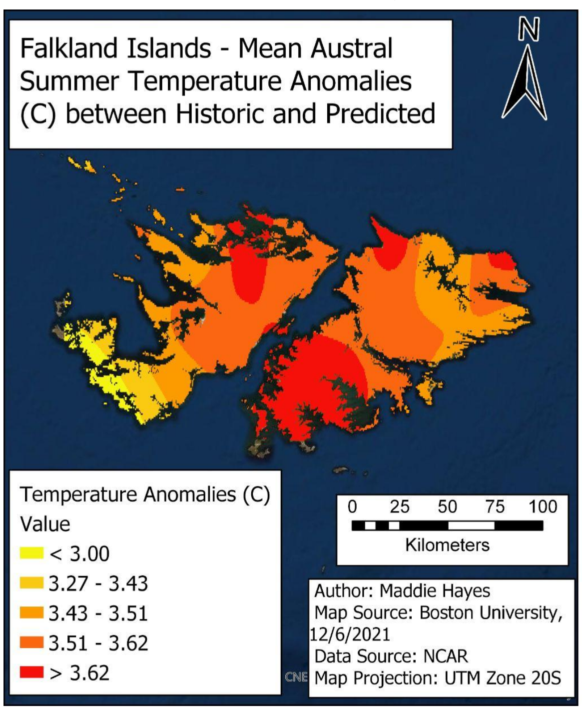
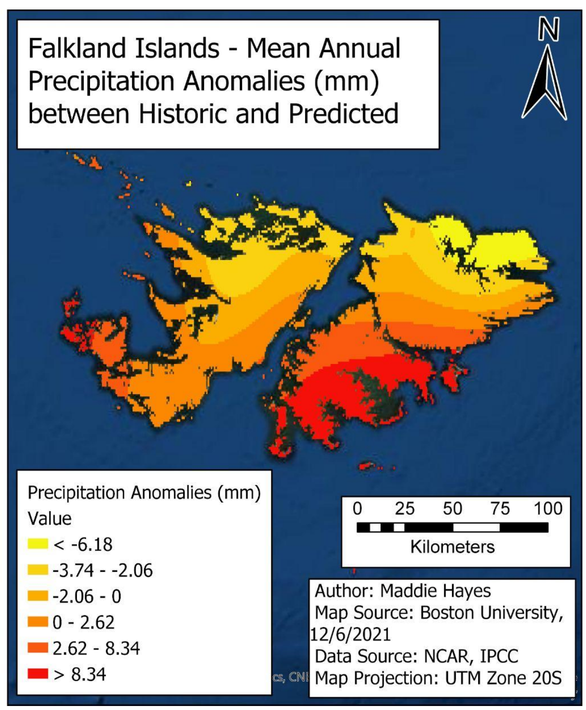
Appendix A. Black-browed Albatross population in 2010 by colony (Wolfaardt, 2012)

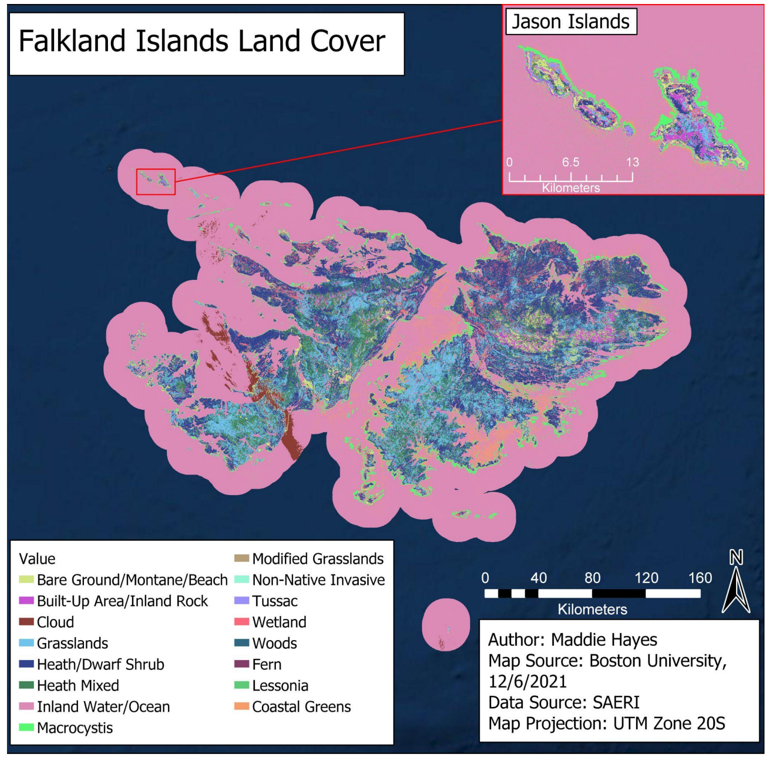
Colony Name	**Population**
1. Steeple Jason	214,203
2. Beauchene Island	139,336
3. Grand Jason	89,580
4. North Island	24,395
5. West Point Island	20,352
6. Saunders Island	13,053
7. New Island	15,350
8. Bird Island	14,048
9. South Jason	1,777
10. Keppel Island	1,735
11. Elephant Jason	1,573
12. Grave Cove	200

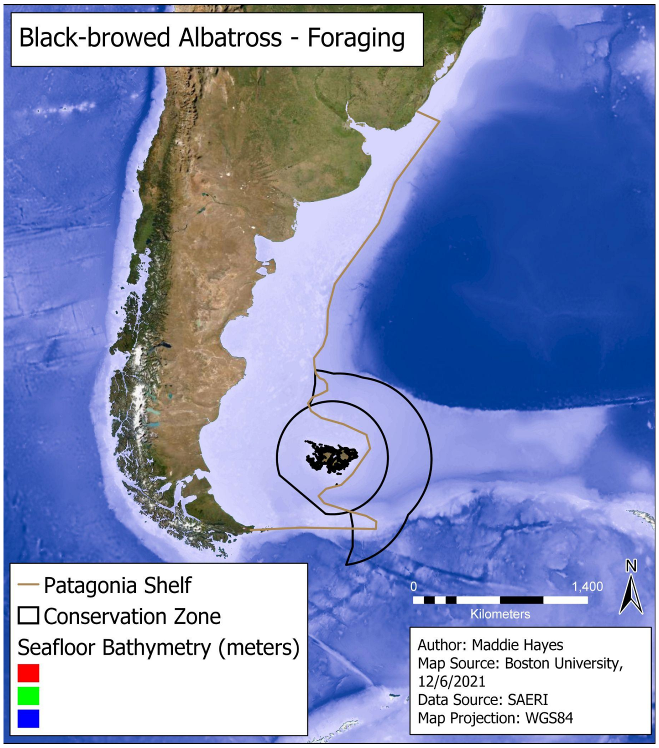
Appendix B. Habitat suitability data



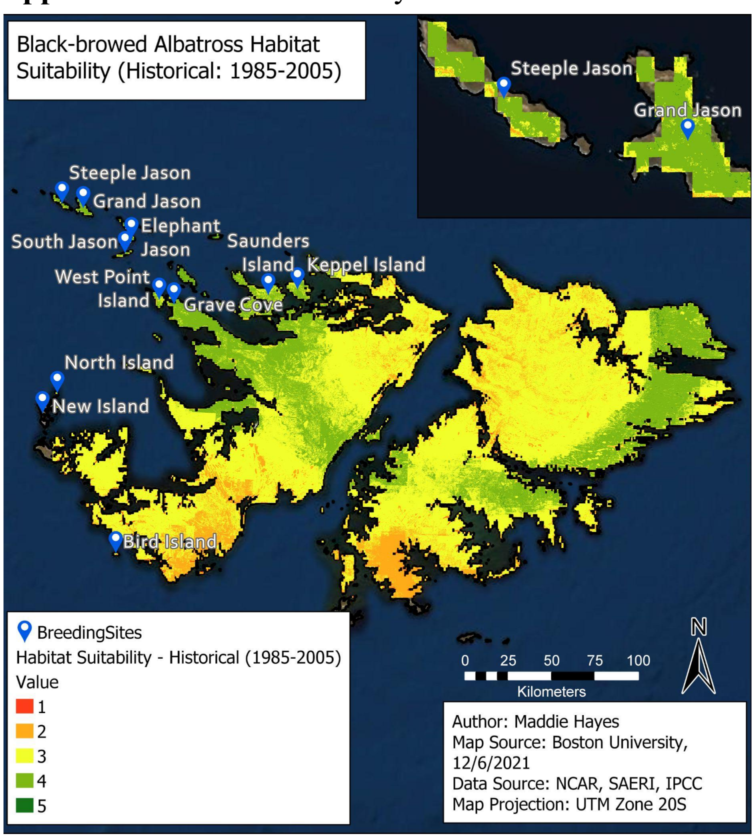


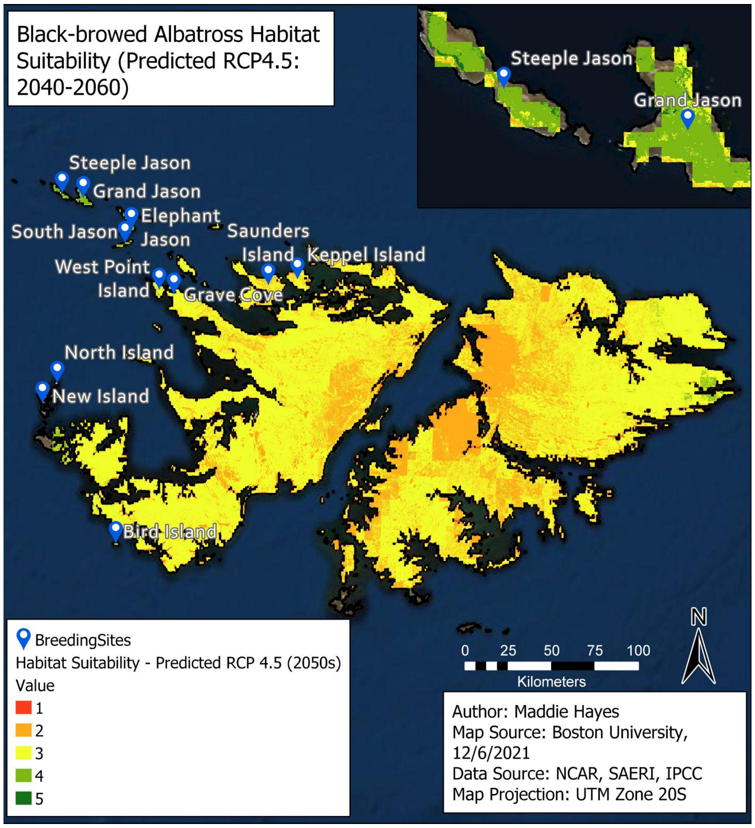
Land Cover	Value
Tussac	10
Bare Ground	9
Inland Rock	8
Dwarf Shrub	7
Grasslands	6
Heath Mixed	5
Macrocystis	4
Modified Grasslands	3
Non-native Invasive	1
Wetland	1
Woods	1
Fern	1
Lessonia	1
Coastal Greens	1
Clouds	0
Ocean	0

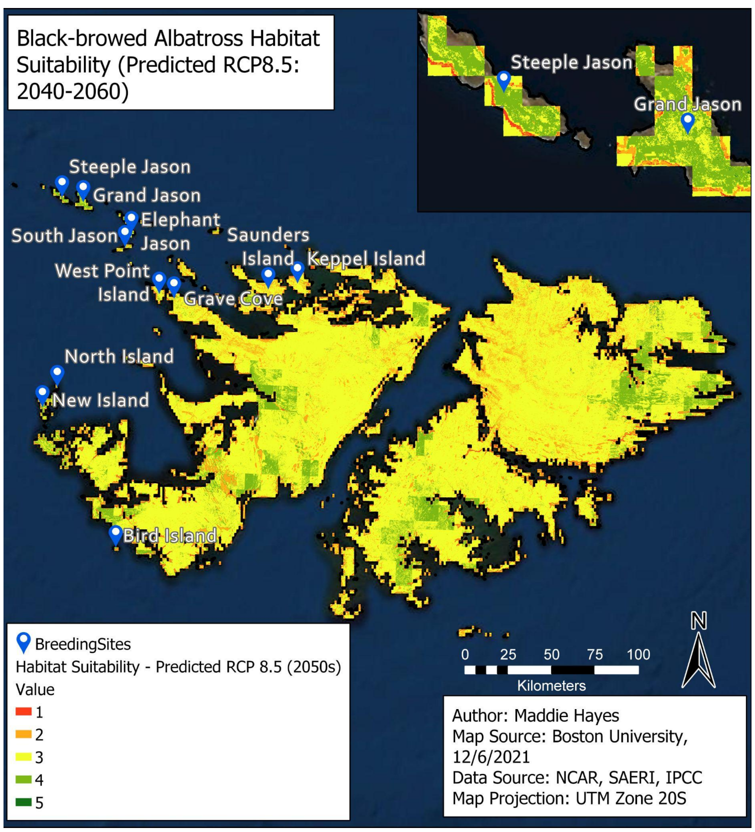




Appendix C. Habitat suitability results




Black-browed Albatross Habitat Suitability (Predicted RCP4.5: 2040-2060)
Steeple Jason
Grand Jason
Steeple Jason
Grand Jason
Elephant Jason
South Jason
Saunders Island
Keppel Island
West Point Island
Grave Cove
North Island
New Island
Bird Island
BreedingSites
Habitat Suitability - Predicted RCP 4.5 (2050s)
Value
1
2
3
4
5
0 25 50 75 100
Kilometers
N
Author: Maddie Hayes
Map Source: Boston University, 12/6/2021
Data Source: NCAR, SAERI, IPCC
Map Projection: UTM Zone 20S


Black-browed Albatross Habitat Suitability (Predicted RCP8.5: 2040-2060)
Steeple Jason
Grand Jason
Steeple Jason
Grand Jason
Elephant Jason
South Jason
Saunders Island
Keppel Island
West Point Island
Grave Cove
North Island
New Island
Bird Island
BreedingSites
Habitat Suitability - Predicted RCP 8.5 (2050s)
Value
1
2
3
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0 25 50 75 100
Kilometers
N
Author: Maddie Hayes
Map Source: Boston University, 12/6/2021
Data Source: NCAR, SAERI, IPCC
Map Projection: UTM Zone 20S