EXPLORING THE EFFECTS OF HISTORICAL ENVIRONMENTAL CHANGE AND FISHING ON THE FALKLANDS MARINE ECOSYSTEM: A PRELIMINARY REPORT

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12/3/2024 VERSION 2

VERSION CONTROL

VERSION	AUTHOR	DATE
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2	Jesse van der Grient	12/3/2024

Acknowledgements:

This work is funded by the DEFRA Darwin Plus Scheme as the DPLUS148 project. It is co-funded by the Falkland Islands Government Environmental Studies Budget. We thank Oregon State University for hosting a workshop that aided the development of the Falklands ecosystem model, and the workshop participants who kindly gave their time and shared their expertise.

Citation:

van der Grient, JMA. 2024. Exploring the effects of historical environmental change and fishing on the Falklands marine ecosystem: A preliminary report. Report for the South Atlantic Environmental Research Institute under the DPLUS148 project – Climate Resilience in the Falkland Islands fisheries and marine ecosystem.

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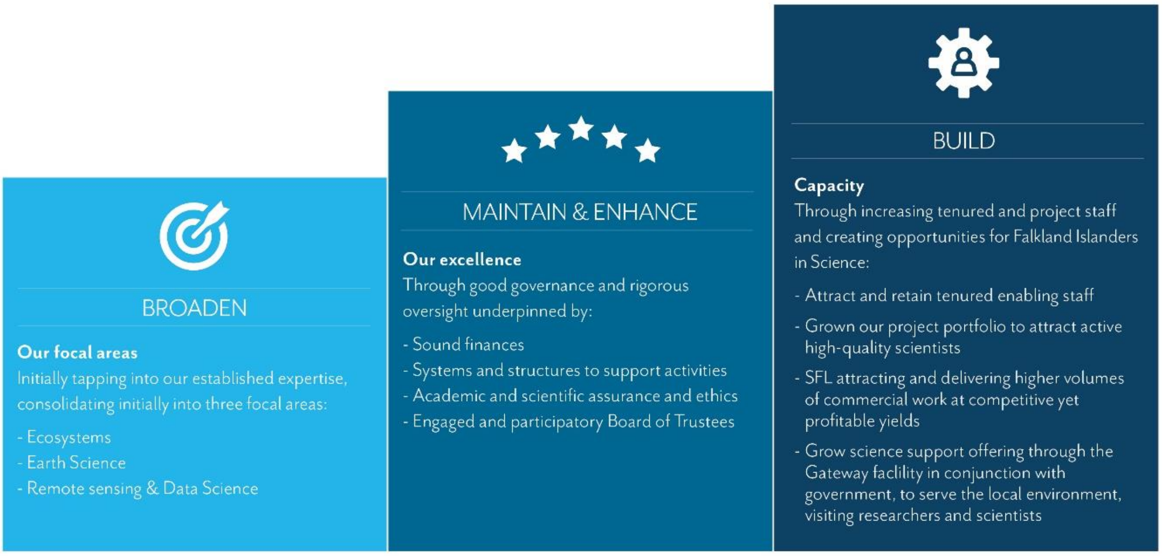

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1. SUMMARY

This preliminary report presents the initial result of a static ecosystem model that captures the ecosystem structure and function of the Falklands marine food web. The Falklands marine food web may change in response to climate change, which involves a multitude of environmental variables. Predicting future change can, however, be difficult. To build confidence in the ecosystem model, we first aimed to create a model that can replicate reasonably historical patterns. Such efforts can provide an indication what environmental factors are influential in the marine food web. Such a model can then be projected into the future to understand how climate change may impact the food web and Falklands fisheries. The static model, a snapshot of energy flow, was calibrated using data averaged for 2001-2005 using the software Ecopath with Ecosim (EwE). Currently, the model is fitted against historical timeseries data, to then be used to predict future trends. The objectives for the whole study are to increase the food-web and fisheries resolution compared to previous Falklands ecosystem models, understand energy flow in the system, and fit time-dynamic solutions to census biomass or fisheries-reconstructed biomass time series to understand historical change. Last, the future effect of marine heatwaves and long-term ocean warming on Patagonian squid will be investigated via impacts on squid development and recruitment.

The model domain covers the Falkland Islands exclusive economic zone, and the food web is captured into 37 single- and multispecies groups, representing groups ranging across the food web, from detrital and primary producer groups to benthic invertebrates, zooplankton, benthic and pelagic fishes, squid, birds, and marine mammals. Initial results confirm expected patterns (e.g., the role of Patagonian squid in the food web), but also shows some surprises (e.g., high biomass values for deep pelagic fishes). This work is still in progress and will be submitted in the near future for peer-reviewed scientific publication.

2. INTRODUCTION

The cold temperate Falkland Islands archipelago on the Patagonian Shelf contains a diverse marine biological community, including globally significant breeding populations of seabirds and marine mammals (summarised in van der Grient et al., (2023)), and commercially important fisheries for the Falkland Islands. The Falkland Current strongly influences the regional oceanographic dynamics and stimulates high primary productivity in the area. The Falkland Current is a northward-flowing current that originates from the Antarctic Circumpolar Current. The upwelling fronts along the shelf break that are generated by the Current also influences species recruitment and migration patterns (van der Grient et al., 2023). The offshore community is linked to inshore environments via ontogenetic migrations of various species, including by the wasp-waist species Patagonian squid (*Doryteuthis gahi*) which uses the kelp forest as spawning grounds (Bayley et al., 2021; Laptikhovsky et al., 2013; Riccialdelli et al., 2020; van der Grient et al., 2023). Wasp-waist species, being mobile zooplanktivorous species, are known to be sensitive to environmental change (Bakun, 2006), and squid in general are known to be sensitive to these effects too (Forsythe, 2004; Pecl and Jackson, 2008). Meaning, environmental impacts on the Patagonian squid can be transferred to the wider food web as this species exerts a dominant influence on the food web. In addition, the

Patagonian squid is an important species for the Falklands fisheries in terms of catch and revenue. Like many other small island nations, the Falkland Islands are dependent on their marine environment for resources and their economy. In the past, the Falklands marine ecosystem has changed, with stock collapses of southern blue whiting and rock cod, both wasp-waist species, too (Laptikhovsky et al., 2013).

Table 1. Environmental factors that could affect the marine food web in the Falklands waters.

Environmental factor	Trend	Reference
Air temperature	Increasing	Hoegh-Guldberg et al., (2018)
pH	Off the coast of Brazil, pH has dropped between -0.1 ± 0.06 and -0.2 ± 0.1, depending on water mass measured, since the Industrial Revolution. Whether this is true for the Falkland Islands is not known	Bianchi et al., (2009)
Marine heatwaves	Frequency and intensity, but not necessarily duration, are increasing	Oliver et al., (2018); Sen Gupta et al., (2020); Xu et al., (2022)
Falkland Current temperatures	Stable or slightly declining, depending on the models used	Franco et al., (2020, 2022)
Confluence location	Shifting southwards with -0.11° ± 0.076° decade^{-1}	Franco et al., (2022)
Combined effect of wind speed, upwelling and primary production	An increase in more southerly winds and an increase in the temperature gradient between the Falkland Current and adjacent shelf waters could result in increased turbulent mixing, which in turn can result in increased primary production when nutrients are brought to the surface. Chlorophyll production has increased by 1 mg m^{-3} decade^{-1} on the shelf and slope	Carranza et al., (2018); D'Asaro et al., (2011); Franco et al., (2018, 2022); Marrari et al., (2017); Risaro et al., (2022)
Falkland current strength and direction	Unknown	
Inshore temperatures	Unknown	

Potential future environmental changes may change the food web further, but these effects are poorly understood. This, however, can be explored by taking a holistic approach to food-web effects, and understanding if and how historical effects have affected the food web. From here, it is possible to project future conditions to understand if and how the food web may change in response to climate change scenarios. There are various climatic factors that could affect the Falklands food web. For example, the southwest Atlantic Ocean is a carbon sink thus indicating this area may see strong acidification in the future (Bianchi et al., 2009). It is also a warming hotspot (Hobday and Pecl, 2014). However, regional trends for the southwest Atlantic Ocean may not be necessarily similar for the Falkland Islands because of the influence of the Falkland Current. For example, while the Patagonian Shelf region has been warming, the Falkland Current has remained stable and cold in temperature (Franco et al., 2022, 2020). Coastal warming via marine heatwaves, however, remains possible, and via ontogenetic migration could impact offshore species, including species of commercial interest (Arkhipkin et al., 2013; Hoegh-Guldberg et al., 2018; Oliver et al., 2018; Xu et al., 2022). While the Falkland Current is not changing in temperature, there are other potential changes related to the Current that may affect the wider food-web system (table 1). For example, the Falkland Current strength and direction influences Patagonian squid feeding success and Patagonian toothfish recruitment success, and these factors may change in the future because of climate change (Arkhipkin et al., 2004; Lee et al., 2021).

Understanding holistically what historical and future effects may act upon a food web requires the use of ecosystem modelling. Ecosystem modelling can aid in understanding the state of living marine resources (historical, current, and future states), investigate trade-offs between policy options and management interventions, and use these outcomes to develop strategic and tactical advice (Craig and Link, 2023). There are a range of ecosystem models, of which Ecopath with Ecosim (EwE) is the most widely used approach (Colléter et al., 2015). This preliminary report presents the initial result of an EwE static ecosystem model that captures the ecosystem structure and function of the Falklands marine food web averaged for 2001-2005. This static model is being used to create a dynamic model to understand the effects of historical fishing and environmental impacts on the marine food web. The dynamic model can be used to predict how climate change may impact the food web and fisheries, using a range of environmental factors. The objectives for the whole study are to increase the food-web and fisheries resolution compared to previous models, understand energy flow in the system, and fit time-dynamic solutions to census biomass or fisheries-reconstructed biomass time series to understand historical change. Last, the future effect of marine heatwaves and long-term ocean warming on Patagonian squid will be investigated via impacts on squid development and recruitment.

3. METHODS

Ecopath

Ecopath is a widely used framework that represents the food web as functional groups based on dietary and behavioural similarities (Christensen and Walters, 2004; Pauly et al., 2000). The functional groups are described in terms of biomass, consumption, and production, and they are linked via prey-predator interactions. Two master equations describe the mass-balanced food web. The first equation describes the production term P_i within each functional group i:

$$P_i = Y_i + M2_i \times B_i + E_i + BA_i + M0_i \times B_i \qquad [1]$$

where Y_i is the total fishery catch of group i, $M2_i$ is the instantaneous predation rate for group i, B_i is the biomass of group i, E_i is the net migration rate (emigration – immigration), BA_i is the biomass accumulation of group i, and $M0_i$ is 'other' mortality which is a catch-all rate that includes all mortality that is not accounted for elsewhere.

The energy balance within each group is required in Ecopath but is constrained so that consumption of any group is equal or less than its production. The second equation describes the energy balance for each functional group i:

$$Consumption = production + respiration + unassimilated\ food \qquad [2]$$

Advice from Link (2010) and Heymans et al. (2016) were followed in the building and balancing of the EwE model. Ecopath version 6.6.7 was used to create a balanced model.

Model design

Currently, two Ecopath models exist for the Falklands, covering either part of the Falklands EEZ (FICS) and based on recent data (Büring et al., 2024), or the whole EEZ (FICS and FOCS) but with some crucial components informed by data from the northern hemisphere rather than southern hemisphere (Cheung and Pitcher, 2005). Here, we expand on the previous work, and although only preliminary results are presented here, the final results will be submitted to a peer-reviewed scientific journal.

Domain, Functional groups, and Fisheries

The model domain is defined by the Falkland Islands EEZ, covering an area of approximately 455,500 km^2. The food web was captured into 37 single- and multispecies groups, representing groups ranging across the food web (Appendix 1), from detrital and primary producer groups to benthic invertebrates, zooplankton, benthic and pelagic fishes, squid, birds, and marine mammals. Initial biomass estimates for various groups were based on the average population biomass between 2001-2005, although for some groups only a single year estimate was available. Stomach analyses were used to inform the dietary matrix and to estimate the dietary contribution of prey to predator groups. A general summary of food-web interactions in the Falklands marine environment and other characteristics is presented in van der Grient et al. (2023). Some groups are residents, while others are seasonal migrants, which was reflected in the food web matrix. The production/biomass ratio (P/B), consumption/biomass ratio (Q/B) and production/consumption ratio (P/Q) values for the different trophic groups were either obtained from literature, calculated from stock assessments, or taken from previous Ecopath models based on the Falklands or (sub)Antarctic areas (Falkland marine ecosystem: Büring et al. (2024); western Antarctica: Dahood et al. (2019); Ross Sea: Pinkerton et al. (2010); South Georgia Shelf: Hill et al. (2012); and Kerguelen Plateau: Subramaniam et al. (2020)).

Several species are fished in the Falklands, including Patagonian toothfish, southern blue whiting, hakes, hoki, rock cod, red cod, kingclip, skates (Rajidae), Patagonian squid, and Argentine squid. For simplicity, fisheries are represented in this model as: *Illex* fisheries, *Loligo* fisheries, *finfish* fisheries, *skates* fisheries, and *toothfish* longline fisheries. Landing data for the species were based on averaged reported catches for the years 2001-2005 (FIFD, 2005; FIG, 2006). Note that rock cod were not commercially targeted until 2007. However, Spain already recorded landings for rock cod in 2002 according to the Sea Around Us database

(Dunstan et al., 2020; Palomares and Pauly, 2015). Thus, this dataset was used to supplement the Falkland Islands reported catch and bycatch data. Landing and discard data are listed in Appendix 1.

4. RESULTS AND DISCUSSION

Balancing the Ecopath model

The initial model was unbalance, with estimated ecotrophic efficiency values for several groups greater than 1. This was first addressed by adjusting the dietary matrix, as the model estimates indicated that several groups fed at higher trophic levels than would be reasonable based on their own trophic position estimate. Changes to the diet of *T. gaudichaudii*, Argentine squid, large other cephalopods, small demersal fishes, and rock cod were made to better reflect their trophic position. The P/B and Q/B rates for the various fishes groups were recalculated based on FishBase estimates rather than using estimates from other models. P/B and Q/B rates for the whales, seabirds, sharks, and skates were lowered. Both toothfish and skates biomass estimates used initially were known underestimates as the estimates were based on part of the Falklands marine environment, while the populations are likely large. Their biomass estimates were increased to facilitate model balancing. We are still finalizing the dietary matrix and resulting balanced vital biological parameters, but we anticipate the final results will be published in a peer-reviewed scientific publication later this year. The food web is depicted in figure 1.

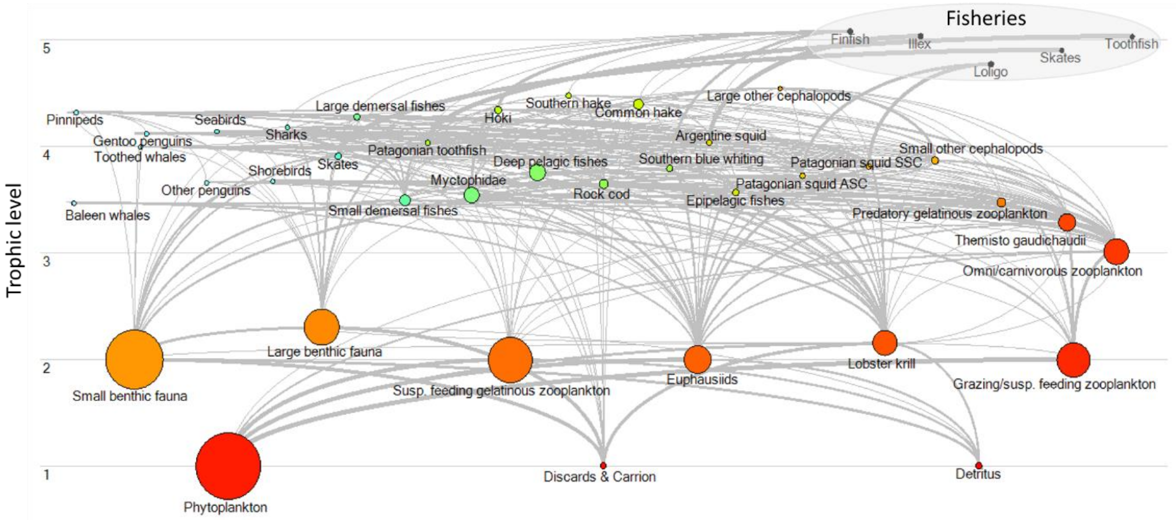

Figure 1. The balanced food web from the Falkland Islands along their tropic level positioning. The filled coloured circles gives an idea of biomass differences, with larger circles indicating more biomass. The fisheries are presented in the transparent grey circle.

Two model results are discussed below: ecotrophic efficiencies and biomass estimates. Ecotrophic efficiency is an estimate for how much of a particular group is used (in terms of its biomass) within the ecosystem (including fisheries). In other words, how much of the consumption of the net annual production is explained within the system. High values mean much if not all of a group's biomass is consumed within the food web while only little is left for detritus, or, the model is accounting for a consumption of biomass of that particular group.

Biomass estimates are important to understand if there are any large biomass pools that may be unexpected, which could mean an underappreciated role in the food web (and its stability and functioning, potentially). Values that deviate are an indication of gaps in our understanding.

Ecotrophic efficiencies

As expected, higher trophic-level groups, such as whales, pinniped and seabirds had low ecotrophic efficiency values, as these groups have no or only a few predators. Gentoo penguins had a higher efficiency value compared to other penguins, possibly reflecting the migratory effect of other penguins. The Ecopath model estimated high ecotrophic efficiencies for skates, rock cod, and Patagonian squid. This is expected for wasp-waist species such as the Patagonian squid and rock cod, but not for the skates, which likely reflects issues of using a species complex in model construction.

Biomass estimates

The biomass of several groups was estimated by the model. Low biomass was predicted for groups such as sharks and large other cephalopods. Zooplankton biomass was predicted to be high for various groups such as krill, lobster krill and *Themisto gaudichaudii*, which agrees with the notion that these are important zooplankton supporting much of the food web. Surprisingly, very high biomass was predicted for suspension feeding gelatinous zooplankton, deep pelagic fishes and myctophids. these groups have been previously identified as understudied in the Falkland marine ecosystem although their role could be quite important (van der Grient et al. 2023).

Future work

The Ecopath model is fitted against historical timeseries data based on catches and environmental data. This work will aid us in understanding how the ecosystem has changed over time and what drives this change. Based on those findings, projections into the future incorporating that information can provide insight into where vulnerabilities may lie. This work is still in progress and will be submitted in the near future for peer-reviewed scientific publication.

Once the work is completed, and the model is appropriately fitted and forecasted, the model will meet the objectives for this study, including having improved on the food-web and fisheries resolution, improving our understanding of the energy flow within the Falkland Islands exclusive economic zone, improving our understanding of what environmental factors and past fishing have influenced the system, and last but not least, if and how ocean warming in coastal waters may affect the offshore area via ontogenetic migration.

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APPENDIX 1 Fisheries landings and discard (t km^{-2}) values used in the Falklands model

Functional group	Landings					Discards
	Finfish	Illex	Loligo	Skates	Toothfish	Finfish
Baleen whales						
Toothed whales and dolphins						
Pinnipeds						
Other penguins						
Gentoo penguins						
Shorebirds						
Seabirds						
Skates				0.00988		0.000024
Sharks						0.000041
Small demersal fishes						
Large demersal fishes	0.00964					0.00001
Myctophidae						
Deep pelagic fishes						
Rock cods	1.00E-09					0.00666
Southern blue whiting	0.0444					0.000047
Patagonian toothfish	0.00329				0.000635	0.000001
Hoki	0.0496					0.000042
Southern hake	0.000075					
Common hake	0.00444					4.97E-07
Epipelagic fishes						
Argentine squid	0.00306	0.119				0.000208
Patagonian squid ASC			0.0432			
Patagonian squid SSC			0.0492			
Small other cephalopods						
Large other cephalopods						
Small benthic fauna						
Large benthic fauna						
Predatory gelatinous zooplankton						
Suspension-feeding gelatinous zooplankton						
Euphausiids						
Lobster krill						
Themisto gaudichaudii						
Omnivorous/carnivorous zooplankton						
Grazing/suspension feeding zooplankton						
Phytoplankton						
Discards & carrion						
Detritus						

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