Final Evaluation Report

Your Details	
Full Name	Robert Wellington Lamb
Project Title	Building resilience of Galapagos marine food webs to climate change
Application ID	28546-D
Date of this Report	July 24, 2022

1. Indicate the level of achievement of the project's original objectives and include any relevant comments on factors affecting this.

Objective	Not achieved	Partially achieved	Fully achieved	Comments
Carry out reef fish population censuses across 12 sites				We continued our monitoring program (continuously funded by Rufford since 2014) to census reef fish communities through August 2021.
Collect fish and primary producer specimens				We collected a total of 543 specimens from 34 species of algae, fish, and invertebrates.
Carry out stable isotope analysis for food web modelling				We processed 234 individual samples through gas chromatography and mass spectrometry.
Document in-situ species interactions				We documented 2644 interactions between fish species (cleaning, cooperation, antagonism) and 2764 interactions between fish and the reef (herbivory).

2. Describe the three most important outcomes of your project.

a). Using amino acid-specific analysis of carbon stable isotopes, we have documented the first known cases of dietary switching between algal and planktonic/detrital food web pathways in three different species of reef fish (*Prionurus laticlavius, Stegastes beebei,* and *Microspathodon dorsalis*) along a temperature/upwelling gradient (Figure 1). This suggests that some species may have the capacity to adapt to warmer ocean temperatures due to their ability to persist on a variety of food items, some of which are available in warmer conditions with less nutrients available (such as coral), others of which are available in greater abundance during cooler conditions with more nutrients available (such as plankton).

b). By combining population records, oceanographic variation in temperature and primary productivity rates, and dietary information from stable isotope analysis, we have shown that population variation in marine fishes is dependent on dietary specificity and the seasonal and spatial variation in availability of diet items. Specifically, obligate planktivores, those fish species that can only persist on a diet of planktonic animals such as copepods and tunicates, have notable boom and bust periods that produce large fluctuations in population over time (Figure 2). During El Niño periods, warm water suppresses the growth of plankton, causing species such as Xenocys jessiae and Paranthias colonus to decline. During cooler La Niña periods, these same species rebound in population as the abundant planktonic food fuels massive reproduction and recruitment of young fish to the reef. Other fish species that rely on more consistently available food types such as coral and benthic algae have much more stable populations.

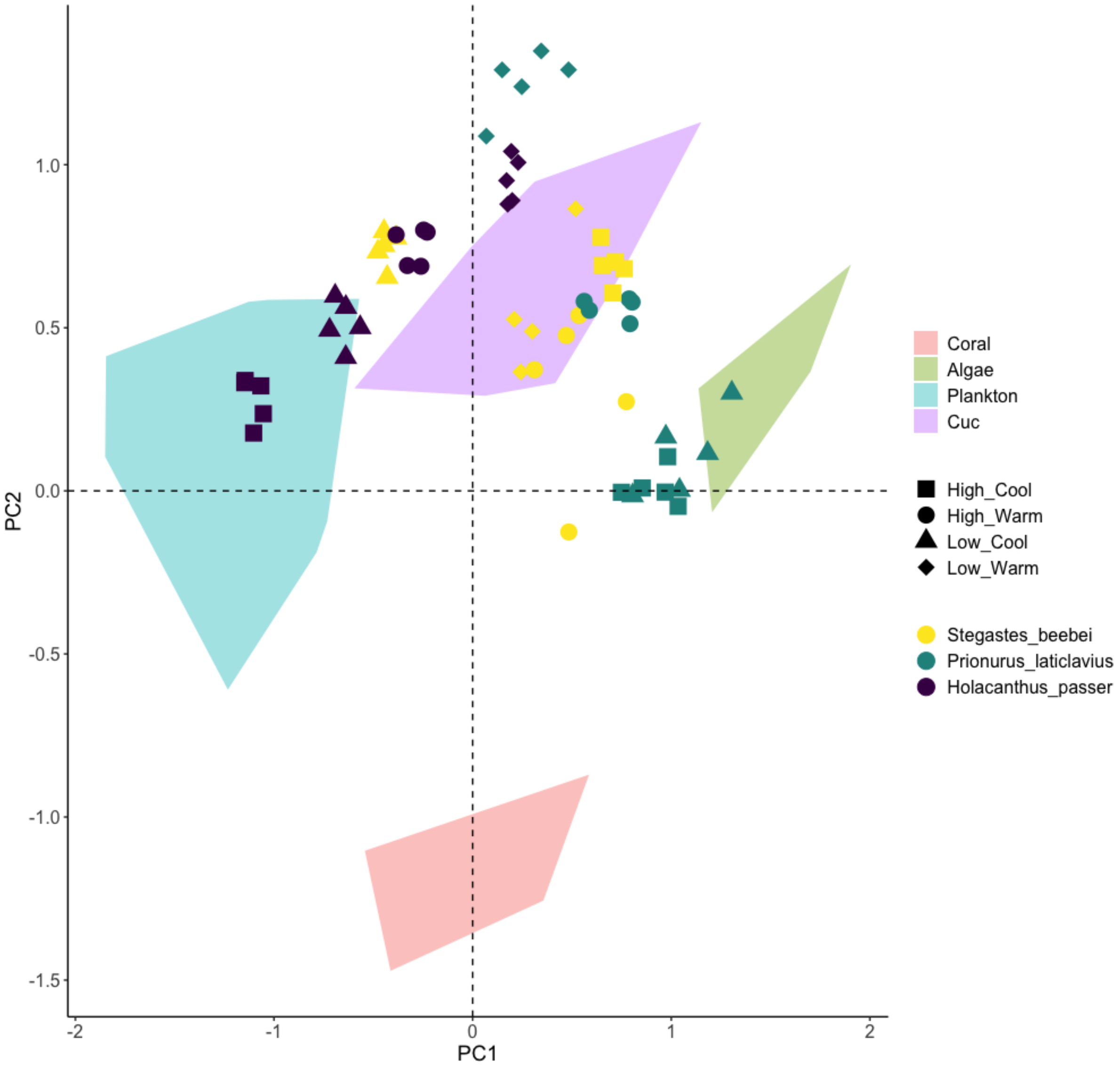

Figure 1 | Three species of reef fish from the Galapagos show the ability to shift their diets based on the surrounding oceanographic conditions. This is a visualization of a principal coordinate's ordination depicting the first two (most important) axes of multivariate diet sources using 5 essential amino acids as the original data. We first map different primary producers to this ordination to obtain an isotopic "fingerprint" of the different sources of carbon entering into the ecosystem (coral - red polygon, algae - green polygon, plankton - blue polygon, and detrital microbes - purple polygon [using sea cucumber tissues as a proxy]). We then plot the signature of each individual fish we caught, represented by points in different colours. These samples were taken from the high-upwelling western Galapagos ("high") or the low-upwelling north-eastern Galapagos ("low"), and during the high-upwelling cool season ("cool") and during the low-upwelling warm season ("warm"). The king angelfish (Holacanthus passer) exhibits a shift from planktonic food sources in the high upwelling region during the cool season to a detrital-based food web in the low upwelling region during the *warm season, with the low upwelling region during the cool season and the high upwelling region during the warm season located in the intermediate multivariate space. Similarly, the razor surgeonfish Prionurus laticlavius shifts from an algal-dominated diet in the high upwelling region during the cool season to a detrital-based food web in the low upwelling region during the warm season, with intermediate diets. The ring-tail damselfish, Stegastes beebei, utilizes a broader mix of resources, but also shows more reliance on planktonic food during the cool season in the high-upwelling region.*

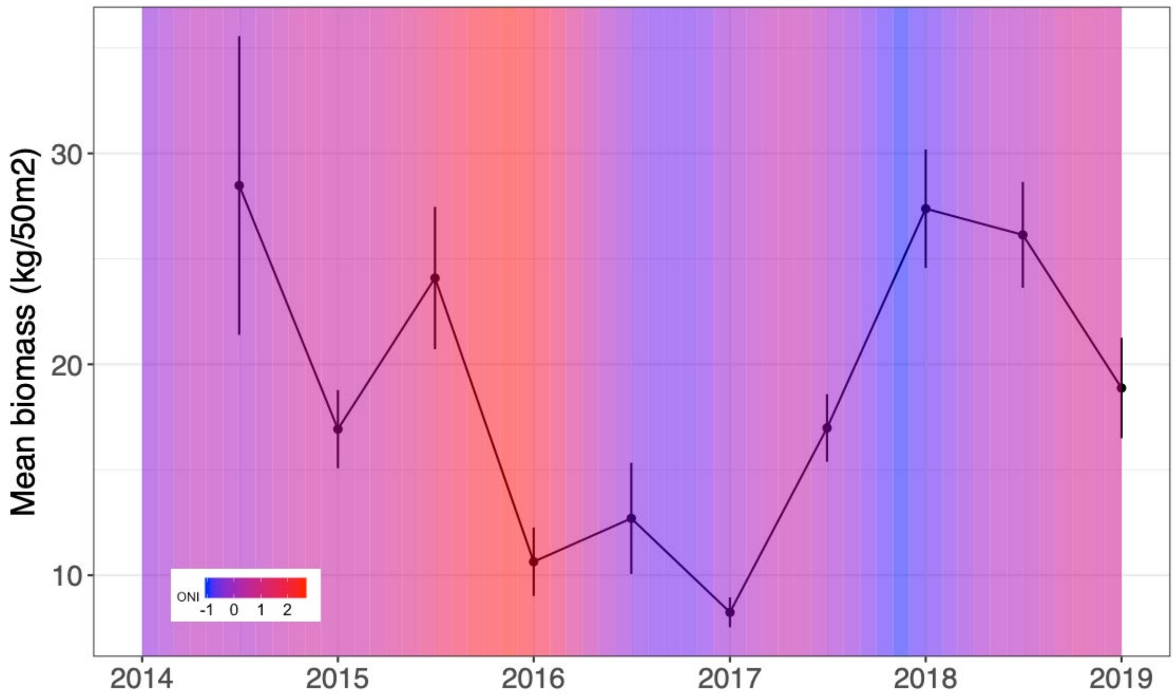

Figure 2 | The biomass of obligate planktivore species in the Galapagos dropped by 2/3rds from baseline levels to the El Niño event of 2015-16. Populations rebounded following the La Niña event of 2016-17. This resembles a boom-and-bust population dynamic that is repeated in both reef-dwelling and pelagic planktivores. No other trophic group exhibited both significant declines following El Niño and significant increases following La Niña, suggesting that planktivores are the most susceptible to decline related to warming oceans and decreased upwelling in the Galapagos Islands.
**shading reflects the oceanic niño index, a measure of sea surface temperature anomaly, with red indicating +2 degrees C anomaly for more than 6 months and blue indicating -2 degrees C anomaly.*
***data shown are mean +/- standard error*

We also revealed a striking relationship between the frequency of benthic herbivory and sea surface temperature (Figure 3). As water temperatures warm, there is a larger number of herbivorous fish species and individuals, as well as bites on the substrate. This adds further evidence to temperature-dependent feeding strategies in marine fishes and suggests that warmer oceans will favour species that feed on benthic algae while disfavouring planktivorous species.

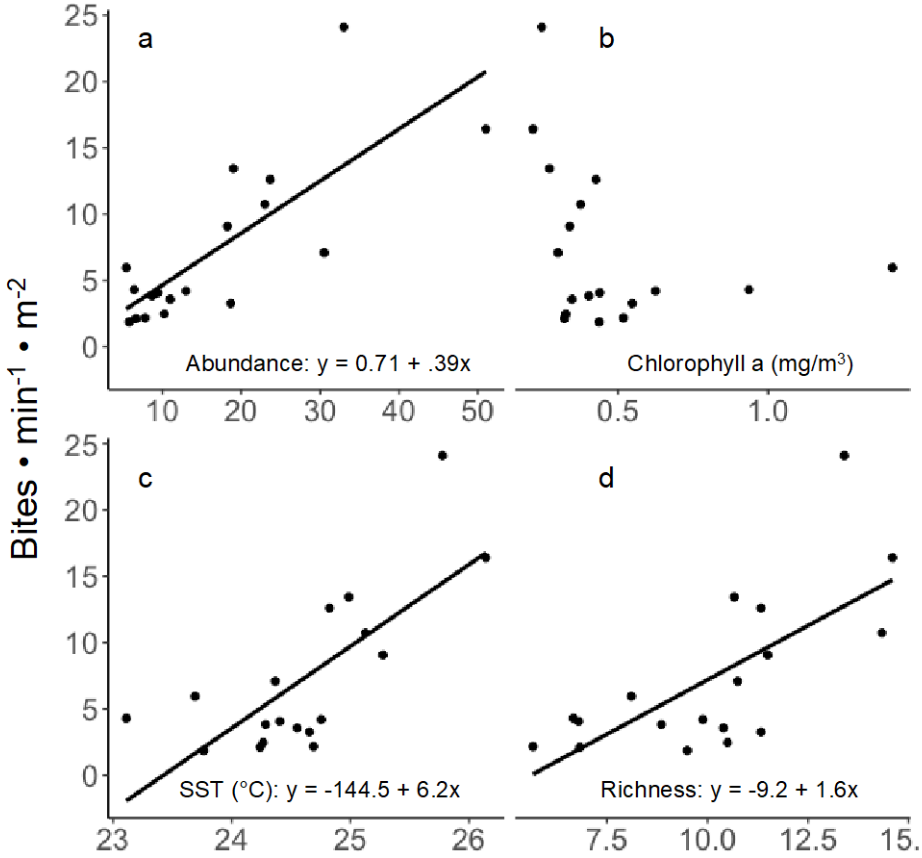

Figure 3 | The rate of herbivory (bites per minute per meter squared) on the benthos is predicted by the abundance (a) and diversity (d "richness") of herbivorous fishes, both of which increase with sea surface temperature (c). In contrast, surface chlorophyll, a measure of ocean productivity, does not predict herbivory rates (b).

c). We collaborated with the Galapagos National Park and the Charles Darwin Foundation to provide training in scuba diving and field research methods to three Ecuadorian students. Two of these are now pursuing their own PhDs in marine science with thesis research taking place in Galapagos, furthering the goals of developing local research capacities and understanding Galapagos marine ecosystems.

Figure 4 | Field research images depicting from top left: research team (R. Lamb, A. Perez Matus, and M. Greenhill) on the M/V Valeska, transiting to Fernandina Island in the cool western Galapagos; research team (R. Lamb, J. Manuel Alava, and Galapagos National Park Staff) on the M/V Queen Mabel taking oceanographic measurements at Marchena Island in the warm north-eastern Galapagos; P. Sangolgui collecting fish specimens; and an individual of Mycteroperca olfax undergoing dissection for preservation of muscle tissue for stable isotope analysis.

3. Explain any unforeseen difficulties that arose during the project and how these were tackled.

We encountered two major difficulties during this project: field logistics challenges and the development of the COVID-19 pandemic. The Galapagos National Park and the nation of Ecuador have very strict rules for the collection and export of wildlife. Since our project entailed collecting a small number of fish from several different species for stable isotope analysis, we were required to undergo a lengthy and complex permitting process. This was repeated when it came to exporting the samples to the United States for processing at Woods Hole Oceanographic Institution. Matters were complicated even more because the biochemical process for extracting and analysing stable isotopes from living tissues requires keeping the tissues frozen from the time of extraction until processing. This means samples could not be shipped via normal channels, and commercial flights prohibit the use of liquid nitrogen or dry ice. This was overcome by using specialised coolers. Another logistic challenge was reaching remote locations in the Galapagos archipelago during the peak sea cucumber fishery. This fishery is immensely profitable and draws away a significant portion of available boats and crew. We were able to share a research cruise with another research group and negotiate a rate with a boat that offset their losses from missing the fishery, while maintaining within our budget.

The COVID-19 pandemic developed during our second research cruise for fish collections. Fortunately, we were able to quickly finish our field work and depart before the mandate to isolate the Galapagos Islands took effect. However, this also led to the closure of in-person work at Woods Hole Oceanographic Institution, where all the laboratory work was carried out. This produced an approximately 1-year delay since all projects were suspended, creating a backlog for samples to be run through the gas chromatograph and mass spectrometer to which we needed access. This produced delays in the completion of our project, delivery of the final report, and publication of research articles.

4. Describe the involvement of local communities and how they have benefitted from the project.

This project benefitted the Galapagos community in four ways. We trained three Ecuadorian students in scuba diving and underwater field research methods. We gave three public symposia, one at the Charles Darwin Station (Santa Cruz Island), one at the Galapagos Science Center (San Cristobal Island), and one at the Puerto Ayora public library. We provided financial support for two local Galapagos fishermen by chartering their boats for field work, which also diverted their efforts away from extractive fisheries. Finally, we have provided essential data for the Galapagos National Park to manage marine fisheries in an adaptive management strategy that incorporates the impacts of climate variations on wild fish populations.

5. Are there any plans to continue this work?

Pending future funding, we plan to carry out comparative genetic analyses on the same species of fish for which we now have detailed dietary information. This powerful approach would reveal the role that genetics play in determining the variation in diet among individuals of the same species. We also plan to continue our long-term monitoring programme, which currently stretches 8 years and includes data on 161 fish species and 12 different islands.

6. How do you plan to share the results of your work with others?

We have already presented our work at three different public symposia in the Galapagos Islands. In the future we plan to present at the Indo-Pacific Fish Conference, which will take place in New Zealand in 2023 and is the premiere gathering of fish biologists in the world. We also plan to publish three peer-reviewed publications on the subject, one describing dietary plasticity in response to oceanographic change, one connecting fish diet with long-term population trajectories, and another describing fish interactions and how they change with ocean temperature.

7. Looking ahead, what do you feel are the important next steps?

We badly need information on population genetic connectivity in Galapagos marine fishes. Recent developments in high-throughput sequencing such as RAD-seq inform both the genetic connectivity among discrete populations and the types of adaptations that arise in response to different environmental pressures. Application of these techniques to our study system would provide new insight into the level of genetic connectivity among populations of different reef fish species, which is essential information for proper fisheries management. We could also learn why some species are abundant across the temperature gradient in the Galapagos and why some are only found in cooler or warmer waters.

8. Did you use The Rufford Foundation logo in any materials produced in relation to this project? Did the Foundation receive any publicity during the course of your work?

We credited the Rufford Foundation as the primary funder of this project in the three public presentations mentioned above and will also provide publicity via the forthcoming peer-reviewed publications we are currently writing.

9. Provide a full list of all the members of your team and their role in the project.

Robert Lamb, PhD: Principal Investigator, primary field and laboratory researcher, logistics manager, grant and article writer.

Simon Thorrold, PhD: Co-Principal Investigator, Lab Director (Woods Hole Oceanographic Institution)

Jon Witman, PhD: Field researcher

Alejandro Perez-Matus, PhD: Field researcher

Jenifer Suarez: Field researcher, primary liaison with Galapagos National Park

Juan Manuel Alava: Field researcher

William Bensted-Smith: Field researcher

Paola Sangolqui: Field researcher

Maya Greenhill: Field researcher

Calvin Munson: Field researcher

10. Any other comments?