The Rufford Foundation
Final Report

Congratulations on the completion of your project that was supported by The Rufford Foundation.

We ask all grant recipients to complete a Final Report Form that helps us to gauge the success of our grant giving. The Final Report must be sent in **word format** and not PDF format or any other format. We understand that projects often do not follow the predicted course but knowledge of your experiences is valuable to us and others who may be undertaking similar work. Please be as honest as you can in answering the questions – remember that negative experiences are just as valuable as positive ones if they help others to learn from them.

Please complete the form in English and be as clear and concise as you can. Please note that the information may be edited for clarity. We will ask for further information if required. If you have any other materials produced by the project, particularly a few relevant photographs, please send these to us separately.

Please submit your final report to jane@rufford.org.

Thank you for your help.

Josh Cole, Grants Director

Grant Recipient Details	
Your name	Robert Lamb
Project title	Assessment and mitigation of the effects of the 2015-16 El Niño event on reef fishes of the Galapagos Islands
RSG reference	19984-B
Reporting period	November 2016 – November 2017
Amount of grant	£10,000
Your email address	Robert_lamb@brown.edu
Date of this report	December 18, 2017

1. Please 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
Assessment of Galapagos fish population trajectories over ENSO cycle			■	Not only did we document the declines in populations of several species of marine fish during El Niño, we also saw a surprising rebound of several populations during La Niña.
Predictive trait-based model of species-specific susceptibility to El Niño			■	We found that planktivorous fish species are most susceptible to El Niño, but also have greatest capacity for resilience during La Niña.
Epidemiological analysis of fish disease outbreak			■	We described the full outbreak, distribution, prevalence, affected species, pathology, and symptoms of the novel outbreak of disintegrating skin disease.
Identification of disease triggers and pathogen		■		We obtained a tentative pathogen ID of a bacterium in the genus *Pantoea.*
Analysis of ecological effects of disease outbreak		■		We have documented declines in important territorial gardening species (damselfishes) and altered behaviour at fish cleaning stations.
Reporting and planning with Galapagos National Park for ENSO mitigation			■	We have held meetings and workshops with the Park authorities, and presented our findings at several local and international conferences.

2. Please explain any unforeseen difficulties that arose during the project and how these were tackled (if relevant).

Research diving in the Galapagos Islands is always physically challenging. Some challenges during this project included a boat engine failure while surveying fish communities at a remote island (4 Hermanos), severe storms that kicked up 4 m high waves which made it very difficult to perform surveys, and very cold water temperatures during November-December 2016. Some of the more unforeseen challenges are outlined below.

In order to make a definitive attribution of a disease outbreak to a particular pathogen, a good supply of sick individuals is necessary in order to obtain samples of infected tissue to use in cultures and histological analyses. We embarked on

sampling trips throughout the year, but almost as soon as El Niño conditions subsided, the disease disappeared completely from the Galapagos (March 2016). This severely limited our ability to make strong inferences of causality from the pathogen that we identified from initial samples (a bacterium in the genus *Pantoea*). However, we now have a live culture of the bacterium that we were able to extract from two diseased fish in our laboratory in the USA, which hopefully can be used in the near future to test Koch's postulates for disease attribution.

At one point we were attempting to catch a few sick fish individuals using a hand spear, which was necessary in order to isolate the pathogen causing the disintegrating skin disease. The disease had become scarce at this point, since El Niño conditions had since subsided, and so any sick individuals that we found were critical and necessary for our pathological analyses. I found one *Myripristis leiognathus* with extensive lesions hiding under a rock ledge, maneuvered into position, and fired my Hawaiian sling to spear it. As I was pulling a plastic bag out of my pocket a moray eel emerged from a crevice and stole the fish right off the tip of my spear, and in less than a second had swallowed it whole and swam away.

It was also difficult to manage the permits and paperwork associated with fish collection and export to the USA for analysis. The Ecuadorian government recently instated a new system of laws governing the export of biological samples, in particular those which are destined for genetic analysis. In addition, the USA manages sample imports through the US Fish and Wildlife Service, which has strict regulations regarding the type of sample, the species of origin, and the potential for biological contamination of pathogens. We were able to navigate both systems by submitting multiple inquiries early in the process and establishing a good rapport with the Galapagos National Park authorities. This positive, mutually beneficial relationship has become an invaluable asset for our work on this project.

3. Briefly describe the three most important outcomes of your project.

3.1) Fish disease outbreak. In January 2016, we discovered a novel disease outbreak affecting shallow reef fishes in the central Galapagos Islands, currently referred to as "disintegrating skin disease". A total of 18 species of teleosts were observed with similar symptoms. Species varied in terms of prevalence and phylogenetic and ecological characteristics. The highest prevalence rates were observed in the ring-tailed damselfish *Stegastes beebei* (51%) and panamic soldierfish *Myripristis leiognathus* (29%), which experienced 10-50% mortality over a 12-month period. The outbreak was widespread throughout the central archipelago but had a center of high prevalence in the 4 Hermanos group of four small islands. Symptoms mainly involved ulcerated patches of skin where scales had sloughed off and the underlying dermis was exposed and bloodied. Altered behaviour included increased visitation to cleaning stations and "dashing" against rocks, presumably to relieve discomfort. Histology showed signs of cellular necrosis and acute inflammation, but was inconclusive in terms of the causal pathogen. We did observe large aggregations of bacteria of the genus *Pantoea* on the lesions of several individuals, but it is unclear whether this was the cause of the lesions or simply colonisation of pre-existing wounds. We attribute this outbreak to the extreme El Nino

event of 2015-16 due to the absence of such epidemics in previous years and the disappearance of the disease as warm sea surface temperatures subsided during the transition to the La Niña period in March 2016.

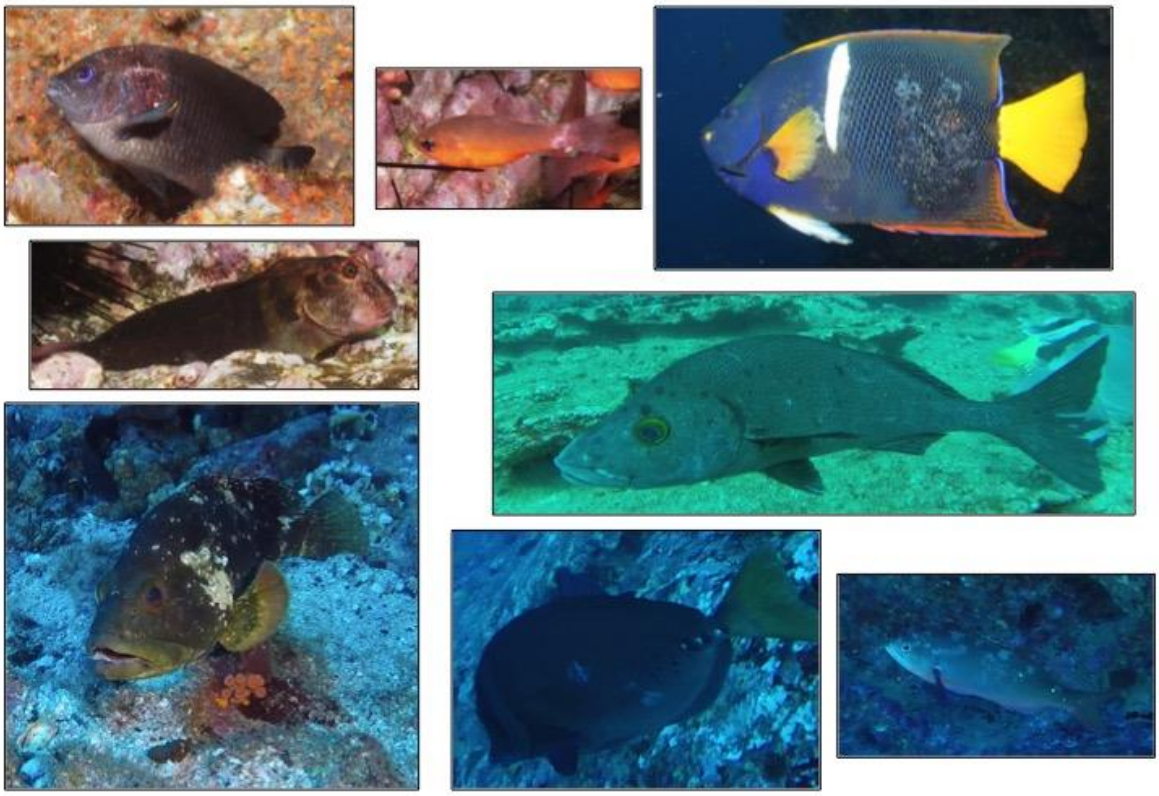

Figure 1. Composite photograph of several of the fish species observed with lesions consistent with disintegrating skin disease symptoms (a total of 18 species were observed) at the height of the 2016 El Niño. The characteristic lesions are seen first as circular white patches on the skin, which progress to areas of scale dehiscence and eroding skin that show sub-epidermal red tissue. Clockwise from top left: *Stegastes beebei, apogon atradorsatus, Holacanthus passer, Orthopristis forbesi, Paranthias colonus, Prionurus laticlavius, Epinephelus labriformis*, and *Ophioblennius steindachneri*. All photographs were taken by Jon Witman or Robert Lamb in January 2016.

3.2) ENSO cycles and marine fish populations. In addition to our work describing the outbreak of disintegrating skin disease, this project had the goal of quantifying the effects of El Niño (a period of warm, low-nutrient water) and La Niña (cold, nutrient-rich water) on the entire community of Galapagos reef fishes. Previous extreme El Niños (1982-83, 1997-98) had caused massive decreases in the abundance of several marine species, including the possible extinction of an endemic damselfish, *Azurina eupalama*. However, the lack of consistent monitoring before and after these previous events hampered our understanding of the specific consequences of these climate perturbations, as well as our ability to make predictions about future events. In order to produce a comprehensive picture of the effects of El Niño – Southern Oscillation (ENSO) cycles on Galapagos fish populations, we carried out

censuses at 12 sites in the central archipelago every six months between July 2014 and July 2017.

We observed a striking and consistent decrease in the abundance of several species of fish during El Niño (January 2016), with the common characteristic that these were all schooling reef-associated planktivores (Figure 2). On average, planktivores decreased in abundance by more than two orders of magnitude from baseline numbers. However, a moderate La Niña period directly followed El Niño, and this elicited a rapid recovery of all three species (January – July 2017).

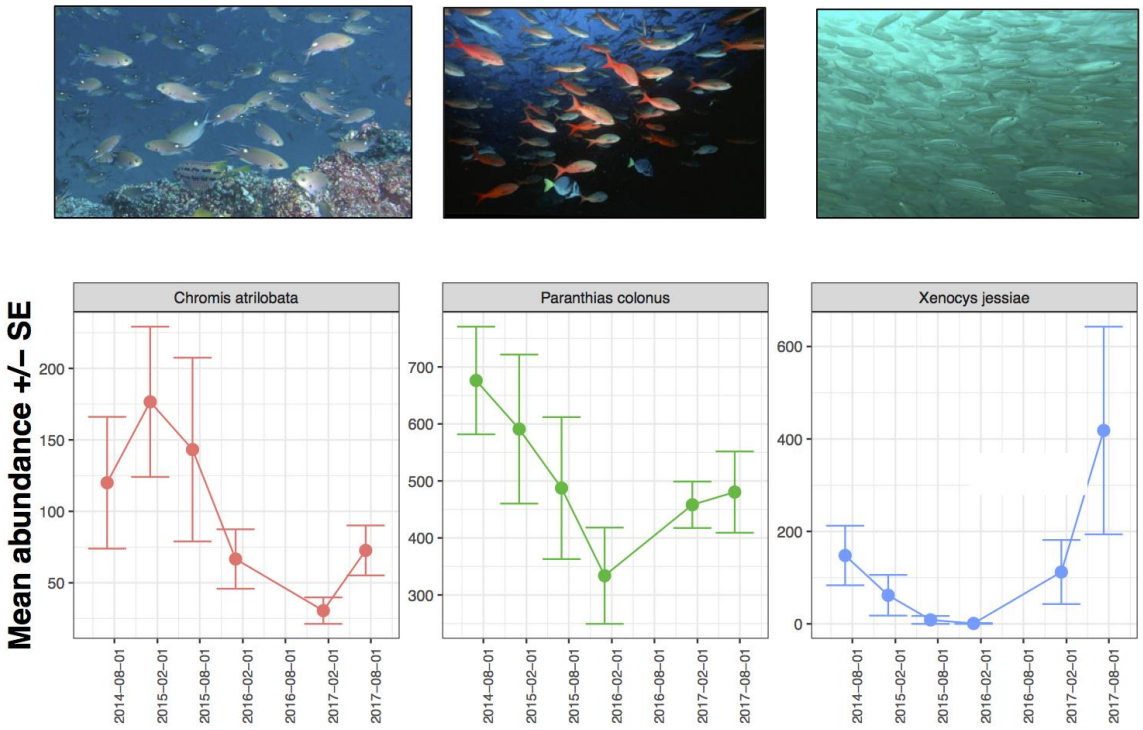

Figure 2. Trends in the abundance of planktivorous reef fishes *Paranthias colonus, Xenocys jessiae,* and *Chromis atrilobata* during the 2014-2017 ENSO. The data are average fish densities per 50m^2 at 12 monitoring sites in the central Galapagos Islands.

The recovery during La Niña could have been due to recolonization (i.e., fish populations left our study sites in search of food elsewhere, then returned when conditions improved), or due to the recruitment of new individuals (larvae) when increased oceanic productivity prompted greater reproductive output and larval survival. An analysis of changes in the size structure of the populations showed a notable shift from larger to smaller individuals over this period (Figure 3), indicating recruitment of new individuals during La Niña following a large mortality of adults during El Niño.

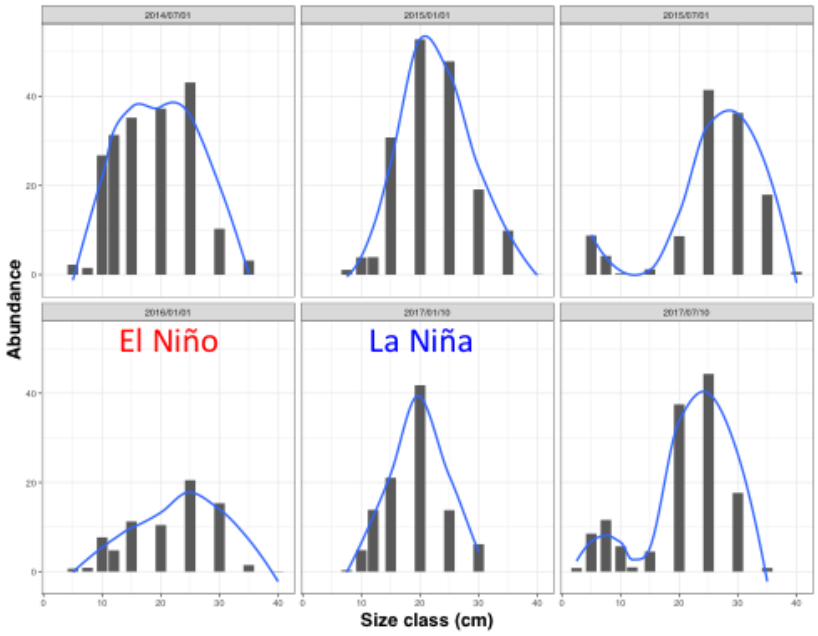

Figure 3. Changes in size structure during the 2014-17 ENSO cycle in the creole fish *Paranthias colonus*. This common planktivorous fish shows a normal distribution during the years leading up to El Niño. Substantial mortality occurred in January 2016 (red), followed by moderate recolonization during La Niña (blue). The bulk of the population recovery, however, was due to a large influx of new recruits (young larval fish, left side of the last panel)

3.3) Climate change and the conservation of the Galapagos Marine Reserve. This series of events has major implications for the conservation of Galapagos marine fish populations and the entire marine food web in general. The three planktivorous fish species noted above (Figure 2) together constitute on average more than 40% of all reef fishes found in the central archipelago. They provide a primary source of food for a variety of marine wildlife, including iconic species such as the Galapagos sea lion and the blue-footed booby, and important fishery species such as tuna and swordfish. The consistent and abrupt drop in abundance in January 2016 points to El Niño as the trigger of mortality, and the fact that the hardest hit species were all planktivores indicates that it was the lack of planktonic food (not a physiological effect of warm temperatures directly) that caused this mortality. The delayed but pervasive rebound in population densities 12-16 months later shows a surprising and massive potential for resiliency conferred by La Niña periods. We observed similar proliferations across all levels of the food web, from algae and plankton to barnacles to fish to higher carnivores such as sea lions and boobies. We are currently compiling this evidence together with collaborators who focus on these groups to present a comprehensive view of the marine ecosystem-wide effects of La Niña food pulses. These pulses have the potential to rescue marine populations following the devastating effects of extreme El Niño events. However, it is unclear whether the expected increase in the magnitude and frequency of these extreme events with climate change will challenge the ability of the marine community to respond in a

similar manner in the future. The added specter of renewed outbreaks of disintegrating skin disease makes it even more difficult to predict the outcome of future El Niño events. The combination of reduced planktonic food supply and disease outbreaks may have led to the extinction of the endemic Galapagos damselfish, *Aurina eupalama*, during the El Niño event of 1982-83. Future extreme El Niño events may result in local extinctions if our current climate trajectory is not averted.

4. Briefly describe the involvement of local communities and how they have benefitted from the project (if relevant).

4.1) Galapagos National Park and Ecuadorian Ministry of the Environment. Our work is fundamentally linked to the management goals of the Galapagos National Park, specifically to improve scientific understanding of Galapagos ecosystems and biodiversity for management and conservation. Our first action upon discovering the disease outbreak was to form a working team composed of representatives of Brown University, the Galapagos National Park, and the Charles Darwin Foundation. All of our efforts and resulting findings have been a result of this inter-disciplinary collaboration. In addition, the park has showed immense gratitude for our continued presence in the region over the past two decades, as our bi-annual monitoring programme was critical for detecting the ecosystem-wide effects of the extreme El Niño event. Throughout the past year and a half we have held regular meetings with the Ecosystems Director (Danny Rueda), the Marine Conservation Director (Eduardo Espinoza), and the National Park Director (Walter Bustos Navarrete) to present our findings. The park authorities have incorporated this knowledge into their working management plan for mitigating the effects of climate change on the Galapagos Marine Reserve.

4.2) The Scientific Community. We have presented the results of this project to local stakeholders as part of one symposium and one workshop on climate change in the region. The first was a presentation given by Robert Lamb at the Simposio de Investigación y Conservación en Galápagos at the Galapagos Science Center, July 2017, and the second was a presentation by Jon Witman at the International Climate Change Workshop for the Galapagos Islands. Both events were attended by local experts in science and conservation, management authorities, and community members. We also submitted two year-end reports to the Galapagos National Park authorities in December 2016 and December 2017.

4.3) Local communities. We also presented our work in fun, engaging, and informative classes for young students (Figure 4). These classes discussed the El Niño phenomenon, climate change, and their effects on marine life. The students then performed their own experiments to learn about how fish orient themselves in water. We led these classes for the after-school marine conservation group in Puerto Ayora, Galapagos, and for the 5th grade class at the Agnes B Hennessey Elementary School in Providence, Rhode Island USA. In addition, together with colleagues from the Charles Darwin Station, Robert Lamb helped create and voiced an animated short film (https://www.facebook.com/darwinfoundation/videos/1405402532846235/) about shark biology and threats to shark conservation.

Figure 4. Robert Lamb presents on El Niño effects on Galapagos Reef fishes and leads engaging and fun experiments about fish movement in water with the after-school marine conservation group in Puerto Ayora, Galapagos (top). Below: Jon Witman (back row, second from left) joined other world-renowned experts on marine ecology and conservation in November 2017 to discuss the implications of climate change for the Galapagos Marine Reserve.

5. Are there any plans to continue this work?

This project has provided funding for the continuation of a long-term monitoring programme of marine ecosystem health in response to anthropogenic stressors such as climate change and fishing since 1999. We will continue this work, assessing the diversity and abundance of fish and benthic communities, every 6 months, through at least 2019. However, the cost of operations in the Galapagos Islands continues to increase, and funding has become even scarcer. We hope to apply to a 2nd Booster Grant in the coming year in order to ensure that our vigilance for similar outbreaks of disease and other manifestations of climate change in the Galapagos marine ecosystem will continue unbroken.

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

We are currently preparing a manuscript for publication in the peer-reviewed journal *Nature Ecology and Evolution* to present the principal findings of the fish disease outbreak at the height of the 2015-16 extreme El Niño event. In the coming year we also plan to publish an article on the effects of La Niña and El Niño on the entire Galapagos reef fish community, in particular focusing on the striking oscillations in the populations of planktivorous species in response to variation in pelagic productivity. We have also presented at the following international conferences:

• "Galapagos as a natural lab for understanding ENSO and Climate Change." International Climate Change Workshop for the Galapagos Islands. 10/2017.
• "El Niño causes habitat filtering and widespread disease in the Galapagos reef fish assemblage." Indopacific Fish Conference. 09/2017.
• "Mobility predicts top-down control in a periodically stressful environment." Ecological Society of America, Portland, Oregon. 08/2017.

• "Efectos de El Niño 2015-16 sobre peces de arrecife de Galápagos." Galapagos Research Symposium, Galapagos Science Center, San Cristobal Island, Ecuador. 07/2017.

• "El Niño causes habitat filtering and widespread disease in a tropical reef fish assemblage." Association for the Study of Limnology and Oceanography, Honolulu, Hawaii. 03/2017.

Our work has also been covered on a variety of news media outlets, including feature articles in National Geographic Magazine, Brown University, and our own blog at www.witmanlab.com/blog. Robert Lamb is also organising a Rufford Grants Conference to be held in the Galapagos Islands in January, 2019.

7. Timescale: Over what period was The Rufford Foundation grant used? How does this compare to the anticipated or actual length of the project?

We utilised the Rufford Booster Grant funds in a similar period to that projected in our original application (June 2016 – August 2017). During this period, our efforts were shared roughly equally between field data collection and meetings with the Galapagos National Park authorities, presenting at conferences and providing classes to students in the Galapagos Islands, and data analysis, laboratory studies, and writing at Brown University, USA.

8. Budget: Please provide a breakdown of budgeted versus actual expenditure and the reasons for any differences. All figures should be in £ sterling, indicating the local exchange rate used.

Item	Budgeted Amount	Actual Amount	Difference	Comments
Meta-genomic assays	912	1462	-551	We outsourced most laboratory analyses for pathogen identification to an experienced aquaculture disease lab (Kennebec River Biosciences, Richmond, Maine, USA). Since the pathogen was very difficult to identify, a series of tests were required to rule out viral, fungal, and protozoan parasites before the bacterium Pantoea was found.
Histology sample preparation	456	332	124	Our collaborator on the project, Roxanna Smolowitz (Professor, Roger Williams University) was able to offset some of the costs associated with histological analyses through her research lab.
Electron microscopy sample preparation	182	0	182	Electron microscopy was not used due to the scarcity of samples.
Air travel from mainland	1216	1800	-584	A second trip was taken in December 2017 given the unusually strong La Niña event and it's potential effects as a mechanism of resilience against El Niño for Galapagos reef fish communities.
Dive boat rental (days)	3648	3000	648	Two trips were sponsored by the Charles Darwin Foundation and took place on Galapagos National Park boats as part of our inter-institutional collaboration.
GoPro underwater digital camera	456	350	106	We opted for the cheaper GoPro 4 model to reduce costs
Lodging (days)	1824	1824	0	Lodging prices were charged by the Charles Darwin Foundation as budgeted.
Food (days)	1368	1368	0	Food prices in Puerto Ayora were as budgeted.

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

There are two primary aims of this project moving forward. The first is most essential, which is to continue our monitoring programme without interruption. It has become clear that El Niño events are increasing in frequency and magnitude with the inexorable advance of climate change. These ENSOs can serve as a window into

the future, providing us a glimpse of what marine ecosystems may face in a warmer world. They also constitute the largest single threat to the sustained health and production of the Galapagos Marine Ecosystem. It is only through long-term, repeated monitoring programmes such as ours that the true nature of the effects of such climate perturbations can be ascertained. Indeed it is only the result of funding from the Rufford Foundation that we continued to monitor fish populations every 6 months since 2014, which led us to the discovery of disintegrating fish disease and allowed us to construct a baseline of fish populations to detect which species (planktivores) were most susceptible to decline during the 2015-16 El Niño.

The second important next step is to combine the observational inferences regarding the effects of climate change on fish populations that stemmed from this project, together with the insights into trophic and behavioral relationships that were elucidated in 2014-15 using funding from a 2nd Rufford Grant to Robert Lamb, to construct a mechanistic model of ecosystem functioning for the Galapagos Marine Reserve. This will entail using modern methods such as stable isotopes and meta-barcoding of gut contents to infer the diets of common reef fish and relate fluctuations in food availability (such as during El Niño) with population fluctuations. This will allow us to infer the direct causation of the effects of ENSOs on fish communities via the combined effects of disease and food limitation.

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

The Rufford Logo was featured in the following presentations given by Robert Lamb and Jon Witman:

• "Galapagos as a natural lab for understanding ENSO and Climate Change." International Climate Change Workshop for the Galapagos Islands. 10/2017.
• "El Niño causes habitat filtering and widespread disease in the Galapagos reef fish assemblage." Indopacific Fish Conference. 09/2017.
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Our Rufford-funded work has also been covered on a variety of news media outlets, including feature articles in National Geographic Magazine, Brown University, and our own blog at www.witmanlab.com/blog.

11. Please provide a full list of all the members of your team and briefly what was their role in the project.

Robert Lamb (Brown University) has been funding, planning, and executing marine research and conservation in Ecuador since 2005. Robert is fluent in Spanish, and used his extensive contacts in Galapagos to manage the team's research logistics. In addition, Robert has been performing surveys of fish abundances in the years leading up to El Niño, providing a baseline against which to compare population changes during this extreme climate forcing event. Robert also acted as a liaison between park managers and the broader scientific community, facilitating the transfer of ecological understanding into actionable conservation goals. Robert is currently writing a manuscript describing the fish disease outbreak.

Dr. Jon D. Witman (Professor, Brown University) is a community ecologist with 30+ years of experience as a research diver, professor, and conservation scientist. Jon is a research partner at the Charles Darwin Station, where we are stationed for dive work and research. Jon's 20 years of experience diving in the Galapagos Islands have established him as one of the premier experts on dynamics of marine ecosystems in the region. He organized field research trips, acquired outside funding to support our work, helped design field sampling protocols, and is currently writing a manuscript describing the fish disease outbreak.

Dr. Franz Smith (Data scientist, Sector Performance, New Zealand) is a former post-doctoral researcher in the Witman Lab and data scientist at the Charles Darwin Station. Franz is an expert diver and is a professional statistician with extensive experience in computational tools for ecological analysis and modeling. Franz assisted in field data collection, data analysis, and is currently writing the fish disease manuscript.

Dr. Roxanna Smolowitz (Professor, Roger Williams University) is a wildlife veterinarian who specializes in wildlife disease research for aquaculture. Roxanna brough her expertise and lab infrastructure for pathogen isolation and identification. She directed the pathological and histological analysis of infected fish specimens.

Jenifer Suarez (marine research specialist, Galapagos National Park) is a Galapagos native who was trained as a research diver at the Charles Darwin Station and now manages the department of applied marine research at the Galapagos National Park. Jenifer is an expert in taxonomic identification of Galapagos flora and fauna, and is well versed in underwater census techniques. Jenifer was essential for data collection as she is one of the most experienced divers in the Galapagos.

12. Any other comments?

We are immensely grateful to the Rufford Foundation for their continued support of our work in Ecuador.