The Galapagos grouper fishery: mostly dead, stunned, or in need of management regulations?

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFULLMENT OF THE
REQUIRMENT FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ZOOLOGY

October 2015

By

Paolo Usseglio

Dissertation Committee:

Alan Friedlander, Chairperson
Edward E. DeMartini
Kim Holland
Camilo Mora
Les Watling

Dedication

This dissertation represents the culmination of a long journey that started many years ago, in an island far, far away, when right out of school my parents refused to let me become a diving instructor and "gently" suggested that I first get a degree. When I finally did, and decided to go back to my idea of becoming a diving instructor, I met a rather unique marine scientist who showed me that there was much more to research that what you are taught in school. So off I went again into the halls of academia, where nerds thrive, fierce D&D and CS battles are fought, and had the good fortune to land in a lab that had the right mix of geniality, wit, and camaraderie.

To my parents, who have always guided me by example. Without their constant help, support, and "gentle" suggestions I would probably still be sitting under a palm tree reading Jules Verne (not that there is anything wrong with reading Jules Verne under a palm tree, but grad school has been way more fun).

Alan Friendlander made me see research and field work in a totally new perspective and encouraged me to get into grad school, starting me on this great adventure.

In a brilliant move, Peter Sale decided to give a kid from an island in the middle of nowhere a chance, and for that I am grateful.

While not always on the same spatiotemporal coordinates, I have always found support, and friendship with the band of misfits from the Sale lab "The Belize years". Paul Chittaro, Derek Hogan, and Camilo Mora.

Lastly, while this dissertation involved a lot of hard work, an even bigger part was done by my wife Esther Alvarez who had to put up with me during endless periods of grumpiness and frustration, which may, or may not, had been caused by coding in R. To her, my love and absolute devotion.

Just in case you were wondering, I did eventually become a diving instructor.

Acknowledgements

This dissertation represents a joint effort between the Fisheries Ecology Research Lab, University of Hawai'i, the Charles Darwin Foundation, and the Galapagos National Park Service, aimed at producing management regulations for bacalao in the Galapagos. The project was first conceived by Anna Schuhbauer, then at CDF, who set in motion the collaboration with Alan Friedlander to get the project started. Without her help and support this project would have never succeeded.

Field work could not have been accomplished without the help from Jorge Baque, Lena Heel, Isabel Haro, Johanna Zimmerhackel, staff at the CDF, Pelayo Salinas, and park rangers for help in fieldwork and sample processing. The artisanal fishers of Galapagos supported this research by helping us with samples and sharing their knowledge. Special thanks go to Don Gabino and Marco Gabino for their support, enthusiasm, and heaps and heaps of fresh ahi.

I would like to thank my advisor, Alan Friedlander, for his continuous support during this research. My sincere thanks also to the rest of my committee: Camilo Mora, Les Watling, Edward DeMartini and Kim Holland, for their insightful comments and encouragement, and also for the hard questions that helped widen my perspective.

I thank Thomas Helser and Delsa Anderl (Age and Growth Program, Research Ecology and Fisheries Management Division, Alaska Fisheries Science Center, NOAA Fisheries) for help with validation of age estimates, and Ryan S. Nichols and Matt Craig for help and guidance in otolith preparation and reading.

No words can convey the amount of gratitude I feel towards my fellow labmates. I thank Mary Donovan for help with length-weight models. Hal Koike has been pivotal in keeping my sanity, or helping me lose it. I still haven't figured that one yet. Kosta Stamoulis, for never loosing his cool when faced with my barrage of GIS related silly questions. Alex Filous, for company in long hours racing deadlines and an endless supply of ramen noodles and chimichangas. Without Eva Schemmel's help and guidance I would have never finish my histology samples. I thank Brian

Neilson for great surf sessions and awesome relaxing beer and freaks and geeks nights. Damiano Mauro and Aki Laruson for great friendship and keeping the D&D rolling. Adam Smith, pizza, and TMNT NES made “Paolo’s manor” feel like a castle.

All samples were collected under Galapagos National Park field permits PC-19-11, PC-24-13, and PC-25-14, and animal use approval was by the Animal Care & Use Committee, University of Hawaiʻi, protocol number 11-1284. Use of the interview data, collected and provided by the Charles Darwin Foundation, was excempt from federal regulations pertaining the protection of human research participants under permit CHS#22922 from the Human Studies Program at the University of Hawaiʻi.

Travel costs to Galapagos, sample processing, 10 acoustic tags, and receiver batteries were self-funded. The remaining acoustic tags, and support for processing materials and equipment were provided by the Fisheries Ecology Research Lab, University of Hawaiʻi. Additional funding came partly by grants awarded to Pelayo Salinas de León from the Lindblad Expeditions-National Geographic Joint Fund for Conservation and Research, The Galapagos Conservation Trust, The Mohammed Species Conservation Fund, The Disney Worldwide Conservation Fund and The Helmsley Charitable Trust.

.

Abstract

The Galapagos sailfin grouper *Mycteroperca olfax*, locally known as bacalao, is an important ecological, cultural, and economical resource in the Galapagos Archipelago. However, years of intensive fishing pressure have resulted clear signs of overfishing. Bacalao represent an important resource for which there is no management, but for which management cannot be implemented because of a lack of information on the current status of the fishery and inconsistencies in life history information. My research was, therefore, aimed at assessing life history and fisheries attributes for bacalao with the goal of providing management options for this species.

Longevity of bacalao is greater than previously reported, with a maximum recorded age of 21 years. Growth estimates showed bacalao to grow larger and slower than previously thought. Size at maturity was also estimated to be larger than previously accepted assessments. Current status of the bacalao fishery is worrisome as it is undergoing both recruitment and growth overfishing. The percentage of fish above size at maturity in the catch has dropped to an all time low, and Spawning Potential Ratio suggests that bacalao is facing imminent reproductive failure. Furthermore, over a 20-year period there have been declines in all of the stock health indicators, with 2012 being the lowest year on record. In lieu of management regulations specifically aimed at bacalao, the Galapagos Marine Reserve relies on no-take zones to provide protection from fishing. However, size of bacalao, catch rates, and catch composition were indistinguishable between areas open and closed to fishing. Bacalao showed high site fidelity and likely do not move outside no-take zones, and therefore poaching within these zones may contribute to the patterns observed. An evaluation of the knowledge of fishers of the current GMR zonation suggests that this lack of compliance due to unwitting poaching. My research has provided valuable information upon which management regulations for bacalao can be built, these should include slot limits, temporal closures, and adequate enforcement of no fishing areas.

Table of contents

List of tables

List of figures

Chapter I

Introduction

Worldwide annual fisheries landings that had been increasing from the turn of the century reached a peak in the early 50s and have exhibited a downward trend since (Pulvenis, 2012). This decrease in landings is, in part, the result of previously underexploited stocks becoming overexploited; the proportion of stocks estimated to be underexploited or moderately exploited dropped from 40% in the 70s to only 15% in 2008 (Pulvenis, 2012). While tropical coral reef fisheries represent only a small fraction of the total world fishery landings, they are considered to be among the most vulnerable to overexploitation (Russ, 1991). This susceptibility can be seen in the marked decline in some of the largest tropical fish species such as the bumphead parrotfish, the humphead wrasse and tropical groupers (Musick et al., 2000; Sadovy, 2002; Sadovy et al., 2003; Sadovy de Mitcheson et al., 2013). Within this group of species, groupers are a heavily targeted marine species that can be found in markets around the globe, usually demanding very high prices (Randall, 1987). Groupers are especially sensitive to fishing pressure due to life history characteristics such as slow growth, late onset of reproduction and high longevity (Randall, 1987; Beets & Hixon, 1994). They also form massive spawning aggregations where a large portion of the adult population can be at risk of exploitation (Sadovy de Mitcheson et al., 2008). According to the International Union for the Conservation of Nature (IUCN), over half of the assessed species of the Epinepheline groupers are currently listed as threatened.

Among the finfish for which a fishery exists in the Galapagos archipelago, the regionally endemic Sailfin grouper (Mycteroperca olfax), locally known as bacalao, is one of most iconic fishery species with great local cultural and economic importance. Bacalao is among the top predators on the reef (Okey et al., 2004), is fished locally and exported to the mainland where it is prepared in a traditional way and eaten during the Easter holiday, making it a culturally important food resource. The archipelago, made famous for its high number of endemic species (and for the observations conducted there on the voyage of the Beagle by Charles Darwin), lies 1000 km west of continental Ecuador in the Pacific Ocean. The archipelago comprises thirteen islands and over 100 islets (Snell, Stone & Snell, 1996) and within it lies the Galapagos Marine Reserve (GMR). The GMR was the first marine reserve established in Ecuador (in 1998), and was recognized in 2001 as a UNESCO World Heritage Site (Heylings, Bensted-Smith & Altamirano, 2002). The GMR encompasses an area of 133,000 km2, and while it has regulations pertaining to invertebrates and marine mammals, there are no regulations in place specifically aimed at the protection of finfish.

For decades, bacalao was the most important finfish species for Galapagos fishermen (Reck, 1983; Nicolaides et al., 2002). However, years of unregulated fishing for this vulnerable species suggests that overfishing of this important resource is occurring. Several factors imply that bacalao fisheries are being overexploited. For instance, the contribution of bacalao to the overall finfish landings in the Galapagos has dropped from nearly 100% in the 1940s to the current level of 17% (Reck, 1983; Nicolaides et al., 2002; Schiller et al., 2014), and total landings have declined between the 1970s and 2001 (Rodriguez, 1984; Ruttenberg, 2001; Gagern, 2009). However, some previous fishery studies suggested that the resource was being exploited at sustainable levels (Reck, 1983; Coello, 1989; Gagern, 2009). These previous studies are now outdated and their findings are in contrast with reconstructions of historical catch (Schiller et al., 2014). While there is no apparent consensus on the current status of the fishery, the very limited geographical range and a total lack of fisheries regulations have led IUCN to list bacalao as Vulnerable (VU) (Bertoncini et al., 2008).

Overfishing can have predictable effects in fish populations, for example the selective removal of larger fish results in a reduction of mean body size and population age stocks (Toresen, 1990; Haedrich & Barnes, 1997; Beets & Friedlander, 1999; Zwanenburg, 2000). Additionally, in sex changing species, the selective removal of one sex can affect sex ratios, which at low stock sizes can lead to a reduced production of eggs or offspring (depensation) (Bannerot et al., 1987; Huntsman & Schaaf, 1994). Studies have suggested that lack of or ineffective management structures are among the factors that contribute to the susceptibility of groupers to overfishing (Sadovy, 2001, 2002; Sadovy de Mitcheson et al., 2008).

Management strategies can therefore provide a respite from overexploitation, but as mentioned above, these do not exist for bacalao within the GMR.

Successful management regulations need to be based on accurate life history traits of the target species, and be adequately enforced. In the case of bacalao current information in life history is lacking, and often presenting conflicting results. Currently, the sexual pattern for bacalao has not been resolved, while previous studies claim the species to be a hermaphrodite (Rodriguez, 1984; Coello & Grimm, 1993), and this seems very likely, these claims are not supported by histological evidence. As a grouper that is recorded to attain a maximum size of 120 cm (Walford, 1937), maximum longevity of bacalao has been estimated between 7-11 years (Rodriguez, 1984; Gagern, 2009), which seems rather low for a Mycteropercid grouper, as congeners of similar maximum size reach 20-30 years (Heemstra & Randall, 1993). Lastly, various studies have provided contrasting estimates of size at sexual maturity that range from 47-67 cm TL (Rodriguez, 1984; Coello, 1989; Heemstra & Randall, 1993). These contrasting results can greatly influence fishery models. For example, underestimation of longevity leads to overestimation of growth and mortality rates (Mills & Beamish, 1980), which can in turn affect the outcome of population models used to formulate management for fish stocks (Tyler, Beamish & McFarIane, 1989; Reeves, 2003). These contrasting results highlight the need to further our knowledge of life history of bacalao to provide inputs upon which fishery management regulations can be built.

The only protection presently offered to bacalao is by small no-take areas on some islands, yet the extent of protection offered by these has yet to be demonstrated (Nicolaides et al., 2002). Effectiveness of an MPA is increased, among many other factors, by ensuring that the target species spends a significant amount of time within its boundaries (Afonso, Fontes & Santos, 2011). It follows that effective MPA's would be the ones that would encompass the target species home range with the result of reducing the possibility of the fish being caught outside its boundaries. But, in order to assess this effect, accurate estimates of site fidelity and home range are necessary; in the case of the Galapagos these are lacking for bacalao and would be an important part of studies assessing the effectiveness of MPAs.

Positive recovery of grouper populations has been seen following establishment of conservation strategies such as closures (Beets & Friedlander, 1999) and placement of MPA's (Hamilton, Potuku & Montambault, 2011). However, it is recognized that lack of compliance with zoning can erode the positive effects of MPAs (Kritzer, 2004). The process of implementation of the GMR zonation included a launch in 1999 without a complete zoning scheme, then a consensus approval of zonation in 2000 that lacked offshore boundaries, and the final physical demarcation of the zones not occurring until 2006 (Edgar, Barrett & Morton, 2004; Reyes & Murillo, 2007; Castrejón & Charles, 2013). Since the implementation of the zonation of the GMR, the offshore limits of each of the zones have still not been adequately marked, which has led to fishing in closed areas by fishers who were unaware of the zonation (Edgar et al., 2004). While lack of knowledge of the zonation, rather than a genuine attempt to violate regulations, can be a major reason for fishing in closed areas (McClanahan, 1999), it is necessary to assess fishers' knowledge of this zonation to tease these effects apart.

Fisheries management relies on fishery science and research in order to obtain the information necessary to create regulations, but there is a human dimension that involves fishers in the compliance of these regulations. Research efforts can involve fishers in joint activities ranging from cooperative approaches, where a fisher accompanies scientists, to collaborative approaches where fishers are included in all aspects of the research (Yochum, Starr & Wendt, 2011). If fishers are allowed to participate and engage in research, understand how scientific activities are carried out, and the reasons behind them, they will be more likely to accept the management suggestions derived from the research (Kaplan & McCay, 2004; Wiber et al., 2004; Pita, Pierce & Theodossiou, 2010; Mackinson et al., 2011). It is then necessary to evaluate the perceptions of fishers towards management regulation, their perception of their participation, and their views on how to manage resources, with the goals of including them in research activities that will result in the development of management regulations.

The previous paragraphs reflect the picture of the current state of bacalao in the Galapagos. Namely, the Galapagos has a very important ecological, cultural and economic species for which there is little, or conflicting, life history information. This confusion is compounded by the fact that there is no current effective management scheme and no information on current status of the fishery. It is possible that bacalao is a species that could gain respite from fishing pressure by means of small no-take areas throughout the archipelago, but as yet there are no data to show that this type of protection has any positive impact. Lastly, there is a community of fishers that exploit the resource who either don't know the current zonation scheme, or because they distrust scientists, choose to ignore current regulations.

This dissertation represents a joint effort between the Fisheries Ecology Research Lab, University of Hawai'i, the Charles Darwin Foundation, and the Galapagos National Park Service, aimed at producing management regulations for bacalao in the Galapagos. Given the identified knowledge gaps in bacalao this dissertation is divided into 5 sections as follow:

- Chapter 2: Assessing and validating basic life history traits of bacalao including age and growth, age and size at maturity and reproductive pattern.
- Chapter 3: Evaluate the current status of the bacalao fishery, and its trends over time.
- Chapter 4: Assess site fidelity of bacalao, determining the effect of no-take areas in the protection of bacalao, and assessing fishers' knowledge of the zonation scheme of the GMR.
- Chapter 5: Explore the views and perceptions of fishers towards management of resources, and their participation in it, in the Galapagos.

It is anticipated that this dissertation will provide sound science-based inputs that will become the base of management decisions aimed at enhancing stocks of bacalao and will serve as the template for future research efforts aimed at other commercially important species in the Galapagos.

References

Afonso P., Fontes J., Santos RS. 2011. Small marine reserves can offer long term protection to an endangered fish. Biological Conservation 144:2739–2744.

Bannerot SP., Fox Jr WW., Powers JE., Polovina J., Ralston S. 1987. Reproductive strategies and the management of groupers and snappers in the Gulf of Mexico and Caribbean. In: Tropical snappers and groupers: biology and fisheries management. Boulder, Colorado, USA: Westview Press, 561–606.

Beets J., Friedlander A. 1999. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, Epinephelus guttatus, in the US Virgin Islands. Environmental Biology of Fishes 55:91–98.

Beets J., Hixon MA. 1994. Distribution, persistence, and growth of groupers (Pisces: Serranidae) on artificial and natural patch reefs in the Virgin Islands. Bulletin of Marine Science 55:470–483.

Bertoncini AA., Gerhardinger LC., Sadovy YJ., Rocha L., Choat JH., Ferreira B., Craig M. 2008.Mycteroperca olfax. Available at www.iucnredlist.org (accessed May 12, 2015).

Castrejón M., Charles A. 2013. Improving fisheries co-management through ecosystem-based spatial management: The Galapagos Marine Reserve. Marine Policy 38:235–245.

Coello S. 1989. Consideration on the management of the Galapagos Bacalao fishery Myceroperca olfax (Jenys) (Pisces:Serranidae). Revista Pacifico Sur:705–709.

Coello S., Grimm AS. 1993. The reproductive biology of Mycteroperca olfax (Jenys) (Pisces: Serranidae): Protogyny and breeding season. Revista de Ciencias del Mar y Limnologia. 3:115–128.

Edgar GJ., Bustamante RH., Farina JM., Calvopina M., Martinez C., Toral-Granda MV. 2004. Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve. Environmental Conservation 31:212–218.

Edgar GJ., Barrett NS., Morton AJ. 2004. Biases associated with the use of underwater visual census techniques to quantify the density and size-structure of fish populations. Journal of Experimental Marine Biology and Ecology 308:269–290.

Gagern A von. 2009. Population dynamics and fisheries potential of the Galapagos grouper Mycteroperca olfax. Masters thesis Thesis. Germany: University of Bremen.

Haedrich RL., Barnes SM. 1997. Changes over time of the size structure in an exploited shelf fish community. Fisheries Research 31:229–239.

Hamilton RJ., Potuku T., Montambault JR. 2011. Community-based conservation results in the recovery of reef fish spawning aggregations in the Coral Triangle. Biological Conservation 144:1850–1858.

Heemstra PC., Randall JE. 1993. FAO species catalogue vol. 16 groupers of the world (family serranidae, subfamily epinephelinae): An annotated and illustrated catalogue of the grouper, rockcod, hind, coral grouper, and lyretail species known to date. Food and Agriculture Organization of the United Nations.

Heylings P., Bensted-Smith R., Altamirano M. 2002. Zonificación e historia de la Reserva Marina de Galápagos. In: Dan, Edgar GJ eds. Reserva Marina de Galápagos. Linea Base de la Biodiversidad. Fundación Charles Darwin y Servicio Parque Nacional de Galápagos, Santa Cruz, 10–22.

Huntsman GR., Schaaf WE. 1994. Simulation of the impact of fishing on reproduction of a protogynous grouper, the graysby. North American Journal of Fisheries Management 14:41–52.

Kaplan IM., McCay BJ. 2004. Cooperative research, co-management and the social dimension of fisheries science and management. Marine Policy 28:257–258.

Kritzer JP. 2004. Effects of noncompliance on the success of alternative designs of marine protected-area networks for conservation and fisheries management. Conservation Biology 18:1021–1031.

Mackinson S., Wilson DC., Galiay P., Deas B. 2011. Engaging stakeholders in fisheries and marine research. Marine Policy 35:18–24.

McClanahan TR. 1999. Is there a future for coral reef parks in poor tropical countries? Coral reefs 18:321–325.

Mills KH., Beamish RJ. 1980. Comparison of fin-ray and scale age determinations for lake whitefish (Coregonus clupeaformis) and their implications for estimates of growth and annual survival. Canadian Journal of Fisheries and Aquatic Sciences 37:534–544.

Musick JA., Harbin MM., Berkeley SA., Burgess GH., Eklund AM., Findley L., Gilmore RG., Golden JT., Ha DS., Huntsman GR., others 2000. Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). Fisheries 25:6–30.

Nicolaides F., Murillo JC., Toral V., Reck GK. 2002. Bacalao. In: Danulat E, Edgar GJ eds. Reserva marina de Galapagos: Linea base de la biodiversidad. Galapagos: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 146–165.

Okey TA., Banks S., Born AR., Bustamante RH., Calvopina M., Edgar GJ., Espinoza E., Farina JM., Garske LE., Reck GK., Salazar S., Shepherd S., Toral-Granda V., Wallem P. 2004. A trophic model of a Galapagos subtidal rocky reef for evaluating fisheries and conservation strategies. Ecological Modelling 172:383–401.

Pita C., Pierce GJ., Theodossiou I. 2010. Stakeholders' participation in the fisheries management decision-making process: Fishers' perceptions of participation. Marine Policy 34:1093–1102.

Pulvenis F. 2012. Fisheries and Aquaculture topics. The State of World Fisheries and Aquaculture (SOFIA). Topics Fact Sheets.

Randall JE. 1987. A preliminary synopsis of the groupers (Perciformes: Serranidae: Epinephelinae) of the Indo-Pacific region. In: Polovina J, Ralston S eds.

Tropical Snapper and Groupers, Biology and Fisheries Management. London: Westview Press. Inc., 89–189.

Reck GK. 1983. The coastal fisheries in the Galapagos Islands, Ecuador. Descriptions and consequences for management in the context of marine environmental protection and regional development. Doctoral thesis Thesis. Germany: Christian-Albrechts Univ.

Reeves S. 2003. A simulation study of the implications of age-reading errors for stock assessment and management advice. ICES Journal of Marine Science 60:314–328.

Reyes H., Murillo JC. 2007. Efforts to control illegal fishing activities in the Marine Reserve. In: CDF, GNP & INGALA ed. Galapagos Report 2006- 2007. Puerto Ayora, Ecuador, 23–30.

Rodriguez W. 1984. Estudio para evaluar las caracteristicas biologicas pesqueras de Mycteroperca olfax en las Islas Galapagos (Ecuador). Instituto Nacional de Pesca Boletin Tecnico 6:3–66.

Russ GR. 1991. Coral reef fisheries: effects and yields. In: Sale PF ed. The ecology of fishes on coral reefs. San Diego: Academic Press, 601–635.

Ruttenberg BI. 2001. Effects of artisanal fishing on marine communities in the Galapagos Islands. Conservation Biology 15:1691–1699.

Sadovy Y. 2001. The threat of fishing to highly fecund fishes. Journal of Fish Biology 59:90–108.

Sadovy Y. 2002. The vulnerability of reef fishes to exploitation. Fisheries Science 68:135–138.

Sadovy Y., Kulbicki M., Labrosse P., Letourneur Y., Lokani P., Donaldson TJ. 2003. The Humphead Wrasse, Cheilinus Undulatus: Synopsis of a Threatened and Poorly Known Giant Coral Reef Fish. Reviews in Fish Biology and Fisheries 13:327–364.

Sadovy de Mitcheson YS., Cornish A., Domeier M., Colin PL., Russell M., Lindeman KC. 2008. A Global Baseline for Spawning Aggregations of Reef Fishes. Conservation Biology 22:1233–1244.

Sadovy de Mitcheson Y., Craig MT., Bertoncini AA., Carpenter KE., Cheung WWL., Choat JH., Cornish AS., Fennessy ST., Ferreira BP., Heemstra PC., Liu M., Myers RF., Pollard DA., Rhodes KL., Rocha LA., Russell BC., Samoilys MA., Sanciangco J. 2013. Fishing groupers towards extinction: a global assessment of threats and extinction risks in a billion dollar fishery. Fish and Fisheries 14:119–136.

Schiller L., Alava JJ., Grove J., Reck G., Pauly D. 2014. The demise of Darwin's fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands: The demise of Darwin's fishes. Aquatic Conservation: Marine and Freshwater Ecosystems.

Snell HM., Stone PA., Snell HL. 1996. Geographical characteristics of the Galapagos Islands. Island of Biogeography:619–624.

Toresen R. 1990. Long-term changes in growth of Norwegian spring-spawning herring. Journal du Conseil: ICES Journal of Marine Science 47:48–56.

Tyler AV., Beamish RJ., McFarIane GA. 1989. Implications of age determination errors to yield estimates. In: Beamish RJ, McFarIane GA eds. Effects of ocean variability on recruitment and an evaluation on parameters used in stock assessment models. Canadian Special Publication Fisheries and Aquaculture. 27–35.

Walford LA. 1937. Marine game fishes of the Pacific coast from Alaska to the equator. Contrib. Santa Barbara Mus. Berkley, California: University of California Press.

Wiber M., Berkes F., Charles A., Kearney J. 2004. Participatory research supporting community-based fishery management. Marine Policy 28:459–468.

Yochum N., Starr RM., Wendt DE. 2011. Utilizing Fishermen Knowledge and Expertise: Keys to Success for Collaborative Fisheries Research. Fisheries 36:593–605.

Zwanenburg K. 2000. The effects of fishing on demersal fish communities of the Scotian Shelf. ICES Journal of Marine Science 57:503–509.

Chapter II

Improved estimates of age, growth and reproduction for the regionally endemic Galapagos sailfin grouper *Mycteroperca olfax* (Jenyns, 1840).

Abstract

The Galapagos Sailfin grouper, *Mycteroperca olfax*, locally known as bacalao and listed as vulnerable by the IUCN, is culturally, economically, and ecologically important to the Galapagos archipelago and its people. It is regionally endemic to the Eastern Tropical Pacific, and, while an important fishery resource that has shown substantial declines in recent years, to date no effective management regulations are in place to ensure the sustainability of the Galapagos fishery for this species. Previous estimates of longevity and size at maturity for bacalao are inconsistent with estimates for congeners, which brings into question the accuracy of prior estimates. We set out to assess the age, growth, and reproductive biology of bacalao in order to provide more accurate life history information to inform more effective fisheries management for this species. The oldest fish in our sample was 21 years old, which is 2-3 times greater than previously reported estimates of longevity. Parameter estimates for the von Bertalanffy growth function ($k= 0.11$, $L_\infty= 110$ cm TL, and $t_o= -1.7$ years) show bacalao to grow much slower and attain substantially larger asymptotic maximum length than previous studies. Mean size at maturity (as female) was estimated at 65.3 cm TL, corresponding to a mean age of 6.5 years. We found that sex ratios were extremely female biased (0.009 M:1F), with a large majority of the individuals in our experimental catch being immature (79%). Our results show that bacalao grow slower, live longer, and mature at a much larger size and greater age than previously thought, with very few mature males in the population. These findings have important implications for the fishery of this valuable species and provide the impetus for a long-overdue species management plan to ensure its long-term sustainability.

Introduction

The Galapagos Sailfin grouper, Mycteroperca olfax, has high cultural, economic, and ecological importance to the people and the marine ecosystem of the Galapagos Archipelago. It is one of the most sought after species in the artisanal hand-line fishery and is prized in its dried form for a traditional dish called "fanesca" that is consumed during Easter (Nicolaides et al., 2002). With a trophic level of 4.2, bacalao is the top demersal predator in the Galapagos (Okey et al., 2004). The species is likely a protogynous hermaphrodite (Rodriguez, 1984; Coello & Grimm, 1993), and it is regionally endemic to the Eastern Tropical Pacific (ETP), where it is commonly found throughout the Galapagos, and to lesser extent at Cocos Island, Costa Rica, and Malpelo Island off the west coast of Colombia (Grove & Lavenberg, 1997), although no fishery exists for this species at these locations

The artisanal hand-line fishery that targets M. olfax dates back to the late 1920s, when Norwegians introduced the butterfly method of salting and drying fish that gives bacalao (cod in Spanish) its name (Reck, 1983). Over the years bacalao has been one of the most sought after species, representing almost 100% of the finfish landings in the 1940s (Reck, 1983), to 89% of the total finfish catch in the 1970s, and only 17% in recent years (Reck, 1983; Nicolaides et al., 2002; Schiller et al., 2014). A very limited geographical range, and clear evidence of fisheries declines, have led the International Union for the Conservation of Nature (IUCN) to list bacalao as Vulnerable (VU) (Bertoncini et al., 2008).

Fishing regulations in the Galapagos Marine Reserve include a zonation scheme, with no-take areas (Heylings, Bensted-Smith & Altamirano, 2002), a licensing system, gear restrictions (e.g. spearfishing and long-lining), a ban on industrial fishing vessels, and a ban on capture and marketing of sharks (Castrejón et al., 2014). However, these regulations are poorly enforced and not well adhered to by many in the fishing community, which has resulted in overfishing of a number of prized species (Bustamante et al., 2000; Ruttenberg, 2001; Edgar et al., 2010). While bacalao has historically been the most important finfish fishery in the Galapagos, and despite suggestions of overfishing (Schiller et al., 2014), to date there are no management regulations specifically aimed at this fishery (e.g. total allowable catch, size limits, fishing seasons).

Fisheries are often managed to lessen the consequences of uncontrolled fishing, which can lead to the collapse of a fishery, economic inefficiency, loss of employment, habitat degradation or decreases in the abundance of rare species (Jennings, Kaiser & Reynolds, 2009). Fishery models use basic life history information (e.g., age, growth, reproduction) as inputs to determine how species respond to fishing. Models such as virtual population analysis are used to calculate mortality rates of age-based cohorts, making it critical to accurately assign the correct age to an individual of a given size. However in the case of bacalao previous studies have provided conflicting results, and many of the life history characteristics for this species remain uncertain. For example, the sexual pattern for this species has not been resolved, while previous studies claim the species to be hermaphroditic (Rodriguez, 1984; Coello & Grimm, 1993), these claims are not supported by histological analysis. In terms of longevity, otolith-derived age estimates range from 7 to 11 years (Rodriguez, 1984; Gagern, 2009), which seems low for a grouper that attains a maximum length of 120 cm TL. Similarly, various studies have provided dissimilar estimates of size at sexual maturity that range from 47-67 cm TL (Rodriguez, 1984; Coello, 1989; Heemstra & Randall, 1993). These contrasting results can influence fishery models. For example, underestimation of longevity leads to overestimation of growth and mortality rates (Mills & Beamish, 1980), which can in turn affect the outcome of population models used to formulate management for fish stocks (Tyler, Beamish & McFarlane, 1989; Reeves, 2003).

Because of the uncertainty in important life history parameters, our goal was to determine the longevity, growth rate, and size at maturity of bacalao in the Galapagos Islands in order to provide more accurate information for better management of this species.

Methods

Study site

The Galapagos Archipelago is located 1,000 km off the coast of Ecuador, and comprises thirteen islands and over 100 islets (Snell, Stone & Snell, 1996). The Galapagos Marine Reserve (GMR) encompasses approximately 133,000 km2 and was the first marine reserve established in Ecuador in 1998, being recognized in 2001 as a UNESCO World Heritage Site (Heylings, Bensted-Smith & Altamirano, 2002). While there is a ban on industrial fishing vessels in the GMR, artisanal fishing is allowed in fishing areas delimited by the GMR zonation scheme (Castrejón et al., 2014). Despite this status, artisanal fishing occurs throughout much of the archipelago.

Sample collection

Landings of bacalao were assessed at the fishing port of Pelican Bay on the island of Santa Cruz, which is the major landing port on the island. Measurements for every bacalao landed were taken, and opportunistic sampling of otoliths was performed. In addition, we conducted experimental fishing trips by accompanying local fishers. Fishers would select their regular spots around the islands of Santa Cruz, Santiago, Isabela, and Wolf (Fig. 1), and conduct fishing the same way as a typical commercial trip. All fish were processed (e.g: removal of otoliths and gonads and measurements) before the fisher took them to market. To ensure that our sampling represented the landings from the fishing community, fishers employed the traditional hook and line method, “empate”, which is homogeneously used among all fishers. Examination of results from previous studies shows that this fishing method captures bacalao from 19-100 cm TL, suggesting that gear selectivity did not affect size composition of the landings, and that the catch is representative of the population. Otoliths were collected in June 2011, February 2012, and from September 2012 to April 2013, whereas tissue samples for histological analysis were collected from October 2012 to February 2013, in order to coincide with the identified spawning period for this species (Coello & Grimm, 1993). All samples were collected under Galapagos National Park field permits PC-19-11, PC-24-13, and PC-25-14, and animal use approval by the Animal Care & Use Committee, University of Hawaiʻi, protocol number 11-1284.

Sample processing

Total (TL) and standard length (SL) of bacalao were measured to the nearest cm, and total weight was taken to the nearest gram. Sagittal otoliths were extracted from each fish, washed in water and cleaned in 95% ethanol prior to dry-storage. The right sagittal otolith was weighed to the nearest 0.1 g and its maximum length and width recorded to the nearest 0.1 mm. Otoliths were then fastened to a 2 x 2 cm square of plywood using acrylic glue, and a single transverse section, through the primordium, ~300 µm thick was cut at low speed using a Buehler™ IsoMet saw with two parallel blades separated by a shim. Sections were then mounted on glass slides using clear adhesive (Crystalbond™), ground for a few seconds with sand paper 400grit, polished with 15 µm lapping film, and viewed immersed in water against a dark background at low power on a dissecting microscope using two reflected light sources angled at 45 degrees. The number of clear bands observed in the transverse sections was counted, as well as the appearance of the outer margin (clear vs. opaque).

Gonads were removed from the fish and weighed to the nearest 0.1 g. A 0.5 mm transverse section from the middle of the gonad was cut and placed inside a tissue-embedding cassette before being fixed in 10% buffered formalin for 7 days, after which the samples were washed overnight in water to remove formaldehyde crystals, then worked up to 70% ethanol through a series of dilutions. Tissue samples were embedded in plastic resin (JB-4™) following previously established protocols (Sullivan-Brown, Bisher & Burdine, 2011). Embedded samples were sectioned into 3 µm slices using an automated microtome with a glass blade. Following sectioning, samples were mounted on glass slides, stained with toluidine blue and viewed under a dissecting microscope using transmitted light at 100x magnification (Olympus BX41, BX41TF). Samples were assigned to reproductive stages following key characteristics in the reproductive cycle previously proposed by Brown-Peterson et al. (2011) (Table 1).

Data analysis

Age and growth

Ageing consisted of assigning each fish a count of annual growth increments that comprised a ring of alternating clear and opaque sections. These were counted with no reference to time of collection or fish length. Each otolith was read twice by a single observer, and the coefficient of variation (CV) was calculated (Campana, Annand & McMillan, 1995). For otoliths where the CV was greater than 10%, the otolith was read a third time. If no consensus was reached among counts, or if the otolith appeared irregular, or had poorly defined growth increments, the otolith was discarded from all further analyses. Validation of the first increment width was conducted by performing daily increment counts.

Growth was modeled using the von Bertalanffy growth function (Bertalanffy, 1938):

$$Lt=L_{\infty}(1\text{-}e\text{-}k(t\text{-}t_o))+\varepsilon$$

Where Lt is the predicted mean length at age t, L_{∞} is the asymptotic mean length, k is the Brody growth coefficient, t_0 is the theoretical age at which length is 0, and ε denotes the belief that residuals would be distributed normally about the expected growth line (Haddon, 2010). Estimated ages were adjusted to decimal age by assigning a birth date for all fish set at October 1st, which was the beginning of the spawning season. Starting parameters for the model were determined using a Ford-Walford plot, model parameters were estimated using nonlinear (weighted) least-squares by means of the NLS function in R. Confidence intervals for the resulting model parameter estimates were calculated via bootstrapping with 1000 iterations. These analyses were conducted using the R package FSA (Ogle, 2015).

The length–weight relationship for bacalao was obtained by fitting the power function $W= aL^b$ to weight and length data where: W is the total wet weight, L total length, and a and b are empirically derived constants. Length and weight data were log (natural) transformed, and transformation bias of the scale parameter was corrected using $a=\exp(b)*\exp(\sigma^2/2)$ as a correction factor, where b is the intercept parameter of the model, and σ2 is the estimated residual variance of the regression model (Hayes, Brodziak & O'Gorman, 1995).

Reproduction

The adult sex ratio was calculated using all sexually mature females and males. A chi square test was used to assess whether sex ratios differed significantly from 1:1. Mean size at sexual maturity (L50) was calculated by fitting a logistic model to the proportion of mature fish binned in 5 cm size classes. The logistic model follows the formula: $\log(p/1-p)=a+\beta TL$, where p is the probability of being mature, TL is total length, and a and β are fitting constants. Proportion of mature fish were fitted by iteratively reweighted least squares (IWLS) using the GLM function in R (R Development Core Team, 2013). Confidence intervals for the predicted model parameters were estimated via bootstrapping with 1000 iterations. Mean age at first maturity was estimated using the same method. Additionally, an estimate of L50 was obtained from the empirical relationship between L50 and $L\infty$ derived using the equation $\log L50 = 0.9469 * \log L\infty - 0.1162$ (Froese, 2000). Gonadosomatic index (GSI) was calculated as $GSI=(GW/SW)*100\%$, where GW is the wet gonad weight, and SW is the somatic weight, or gonad free body weight, this metric was calculated only for mature fish.

All analyses were done using the statistical software R (R Development Core Team, 2013). Data manipulation was performed using the reshape package (Wickham, 2007), and graphing was conducted with the package ggplot2 (Wickham, 2009).

Results

Sampling of landings at the fishing port, as well as samples taken from fishers, resulted in a total of 297 bacalao, with a mean TL of 49.8 cm (±11.1 sd), with a size range from 18 to 100 cm TL (Fig.2). The length (TL cm) to weight (g) relationship, calculated from these samples, resulted in estimates for a=5.47e^{-6} and b=3.158, the coefficient of determination of the log transformed data (natural log) was r^2=0.94.

Unpublished reports from the Charles Darwin Foundation that monitored bacalao during the peak fishing times for the 2011 fishing season (January and August-November) resulted in a total of 277 fish landed at the port of Pelican Bay. Our sampling of 297 bacalao is therefore representative of the fishery landings as a whole.

Age and growth

From the collected otoliths, only 198 were readable and used for growth analysis. Sectioned sagittal otoliths, when viewed under a dissecting microscope with reflected light, showed alternating clear and opaque bands (Fig. 3). Validation of the first annuli, by counting daily rings, was limited by the number of readable rings in the sample analyzed. While it was not possible to read the section nearest the core, an estimate of 280 days was produced by interpolating unreadable spaces with the mean width of the observable bands. The first annuli was estimated to occur at ~ 511 μm from the core.

Growth modeling and length at age

Age estimates from otoliths ranged from 1-21 years. The estimated von Bertalanffy growth model parameters were k= 0.11 (0.09 - 0.15 95% CI), L_∞= 110 cm (TL) (99 - 125% CI), and t_o= -1.7 years (-2.3 - -1.2 95% CI) (Fig. 4).

Reproduction

Sampling of bacalao during the reproductive season (October-February) resulted in 116 fish with a size range between 34 and 81 cm TL and a mean TL of

51.4 cm (±10.4 sd) (Fig. 5). The sex ratio was significantly female skewed ($\chi^2 = 112$, $p < 0.01$), with 0.009 males per female.

Immature fish represented 79% of the sampled individuals (n=92) (Fig. 6a) and had a mean TL of 48.9 (±8.3 sd) cm. Mature bacalao, including fish that were developing, spawning capable or that were regressing and whose ovaries contained regenerating oocyte stages (Fig. 6b,c), represented the remaining 21% of the samples (n=24). These fish had a mean TL of 60.6 (±11.3 sd) cm. There was only one male in our samples (Fig. 6d), with a size of 81 cm TL. Due to the high occurrence of immature females in our sample collection, we were not able to obtain enough mature samples to accurately determine spawning peaks or spawning times. GSI reached the highest value for the month of December, when seawater temperatures started warming up, however we did not have samples for the month of January (Fig. 7).

Size at which 50% of the population reached sexual maturity (L_{50}) was estimated from the logistic regression model as 65.3 cm TL (61.3-74.9 95% CI), while age at maturity was 6.5 years (5.7- 7.8 95% CI, Fig.8). The empirical equation proposed by (Froese, 2000) estimated size at maturity for females as 65.6 cm TL (49.5 – 86.9 se). Since we only sampled one male, it was not possible to estimate size or age at sex change.

Discussion

Our estimates of maximum age of bacalao (21 years) were two to three times higher than those previously reported. The large proportion of immature individuals in our samples, as well as the low number of larger individuals, and highly biased sex ratio suggests that the resource has undergone, and is probably still experiencing, severe overfishing. We have provided more accurate estimates of size-at-age, growth, and size and age at sex change of bacalao, and these estimates should be urgently incorporated into management plans for this species.

Age and growth

Previous age estimates of bacalao ranged between 7 and 11 years (Rodriguez, 1984; Gagern, 2009). Longevity for other mycteropercids such as *Mycteroperca bonaci* (Max TL 150 cm) is 34 years, while M. macrolepis (Max TL 145 cm) and *M. phenax* (Max TL 107 cm) reach 22 and 21 years, respectively (Froese & Pauly, 2015). Our maximum recorded age of 21 years is closer to what would be expected of a mycteropercid grouper, and while our biggest fish was only 100 cm TL, bacalao is reported to reach 120 cm TL (Walford, 1937), suggesting that it is likely that longevity for this species is closer to 30 years. Differences in age between our study and previous works very likely stem from difficulties in reading bacalao otoliths. Rodriguez (1984) reported that 90% of the otoliths collected were considered unreadable due to the presence of a large number of false rings, or the lack of rings that he attributed to demineralization. Similarly, Gagern (2009) reported finding a large number of rings that he presumed were formed on a monthly basis. It was clear in the present study that bacalao otoliths are not necessarily easy to interpret, but we found that cross-sections can be read more easily using a dissecting microscope with reflected light against a dark background than with transmitted light and a compound microscope. Both Rodriguez (1984) and Gagern (2009) employed transmitted light and a compound microscope for their readings.

Estimation of age and growth in marine teleosts is useful for a variety of purposes such as estimating mortality (Pauly, 1980), predicting responses to exploitation (Jennings, Reynolds & Mills, 1998; Jennings, Kaiser & Reynolds, 2009), and developing fisheries management arrangements (Frisk, Miller & Dulvy, 2005). However, inaccurate estimates of these key parameters can result in models that do not accurately represent exploitation of the species. For instance, in the case of the orange roughy (*Hoplostethus atlanticus*), initial estimates of longevity were 24 years, while later validated estimates were nearly 100 years (Andrews, Tracey & Dunn, 2009), resulting in dramatically different estimates of natural mortality and exploitation rates (Tracey & Horn, 1999). It is important to note, however, that our estimates of growth parameters are based on sampling that is limited in smaller (<20 cm TL) and larger (>65 cm TL) individuals, so caution is needed in the use of these data and their application. Additional sampling in the future focusing on these size gaps may generate more robust estimates. Nonetheless, large individuals in particular are notoriously rare due to the overfishing experienced by the species.

Reproduction

While this study aimed to resolve some of the uncertainties regarding reproduction of bacalao, logistic constraints as well as the inherent difficulty in securing enough samples of reproductive age individuals precludes final conclusions in many aspects. We were not able to collect any transitional individuals that would resolve the sexual pattern for the species. While there have been suggestions that bacalao is protogynous (Rodriguez, 1984; Coello & Grimm, 1993), these studies relied on gross morphology of the gonads, rather than histology, which is known to produce inaccurate estimates of reproductive size (West, 1990) and even of sexual identity in protogynous groupers (DeMartini, Everson & Nichols, 2011). Because detailed microscopic examination of gonads is necessary to determine the sexual pattern in most fishes (Sadovy & Shapiro, 1987), these findings cannot be considered conclusive.

Most groupers are monandric protogynous hermaphrodites, maturing as females and then switching to males (Smith, 1959; Thompson & Munro, 1974;

Collins et al., 1987; Sadovy, Figuerola & Roman, 1992), however there are exceptions such as the Nassau grouper (Sadovy & Colin, 1995; Chan & Sadovy, 2002). While the pattern for bacalao is still unresolved, it is likely that the species is protogynous and follows monandry. These assumptions are supported by the observable patterns of a lack of males at smaller sizes, and the severely skewed sex ratios observed by us and other authors in the past. However, it is important to stress that until histological evidence is provided, the sexual pattern should remain unresolved. The conundrum lies in that the observed pattern of very low abundance of larger size classes will only be exacerbated by continued heavy fishing pressure.

Reproductive periodicity in bacalao has been suggested to peak in the months of October-January (Coello & Grimm, 1993) , and December and April (Rodriguez, 1984) .While logistical constraints restricted our sampling to the period of October-February, the GSI attained the highest values in the month of December. Additionally, the first recorded evidence of a spawning aggregation for bacalao was in the month of November (Salinas-de-León, Rastoin & Acuña-Marrero, 2015). Although there is not clear consensus on reproductive periodicity, sufficient information exists to establish a closed season from October to April, which would protect bacalao during much of the spawning season.

Information on size at maturity for bacalao has been highly contradictory, with Coello (1989) reporting size at maturity at 47.5 cm TL, and Rodriguez (1984) reporting it at 63 cm TL. However, both of these studies used macroscopic examination, which is known to produce inaccurate estimates as discussed above. Fishbase (Froese & Pauly, 2015), reports 67 cm, citing Heemstra and Randall (1993) as the source, we however, did not find any reference to size at maturity for bacalao in the latter paper. Our sampling was focused during the peaks of reproduction for the species to ensure that the maximum amount of mature individuals were collected, and found a size at maturity larger than those previously reported (65 cm TL). Our estimates are consistent with those published by Rodriguez (1984), and the empirical estimates derived from the equation of Froese (65 cm) (Froese, 2000), although it is recognized that the predictive model of Froese (2000) has a high level of uncertainty.

Bacalao has been suggested to have experienced severe overfishing as early as the 1950s (Reck, 1983), which could have resulted in fishing induced changes in life history (Conover & Munch, 2002; Baskett et al., 2005; Enberg et al., 2012; Sharpe, Wandera & Chapman, 2012). Evidence of overfishing includes a decrease in mean landed size since the 1970s (Reck, 1983; Nicolaides et al., 2002), a marked increase in the proportion of immature fish in landings from 35% in 1993 (Coello & Grimm, 1993) to 73% in our study, and an overall decline in the catch from 89% of the total finfish catch in the 1970's to only 17% in recent years (Reck, 1983; Nicolaides et al., 2002; Schiller et al., 2014). However, the decline in contribution of bacalao to the overall catch is partially a result of diversification of the fisheries and a shift to pelagic species such as tuna and wahoo (Schiller et al., 2014), that reflects the preference for these species by the local tourist industry and export market, which may mask the effect of overfishing. While this market preference can explain some of the declines, the effect of artisanal fishing in the declines of bacalao has already been demonstrated for the Galapagos (Ruttenberg, 2001). Lacking reproductive biology data from earlier periods (before the 1950s) will make it impossible to resolve the reproductive patter for a non-exploited population.

Fishery effects on bacalao quite likely also include impacts on the adult sex ratio and size-at-sex change. The highly skewed sex ratio we observed (0.015 M:F) is consistent with those previously reported (0.021: Coello & Grimm, 1993; 0.017: (Reck, 1983), suggesting that the adult sex ratio had likely been altered by fishing down of the larger bacalao prior to the 1980s, especially by targeting spawning aggregations (Salinas-de-León, Rastoin & Acuña-Marrero, 2015). Although there has not been a decline in catch rates in the bacalao fishery over time (Nicolaides et al., 2002), this might represent expansion of the fishery to new unfished areas. In the 1980s fishers reported that larger fish were caught mostly on "far" offshore banks such as Banco San Luis, which is located only 30 km from the main fishing port on Santa Cruz Island (Reck, 1983). In contrast, the largest fish in our study, as well as 2 additional males sampled for otoliths were caught at Wolf Island, located in the far north bio-region of the GMR, nearly 300 km from Santa Cruz Island.

Size-selective fishing mortality typically results in the differential loss of larger and older males in protogynous groupers (Sadovy, 1996). Major implications of severely skewed sex ratios include reduction in the probability that females will survive to sex change (Armsworth, 2001), loss of productivity due to sperm limitation (Bannerot et al., 1987; Koenig et al., 1996), and ultimately reproductive failure as males become too rare to effectively mate with females (Allee effect) (Bannerot et al., 1987; Huntsman & Schaaf, 1994).

Conclusions

Protogynous species have been suggested to be at particular risk of overexploitation, even when fishing mortality rates are low (Huntsman & Schaaf, 1994; Alonzo & Mangel, 2004; Heppell et al., 2006). This is especially relevant in an area such as the Galapagos where there are no management regulations specific to bacalao (e.g. allowable catch, size limits, fishing seasons). While the sexual pattern of bacalao remains unresolved, it is likely that the species is hermaphroditic, therefore, and heeding the precautionary approach, conservative management approaches for the species should include a mix of control over catch and fishing effort such as slot limits (Heppell et al., 2005), seasonal closures during reproductive season, and realized no-take spatial closures (Beets & Friedlander, 1999; Sadovy, 2001; Sadovy & Domeier, 2005; Heppell et al., 2006; De Mitcheson et al., 2008). Currently, the only protection for bacalao occurs in no-fishing zones which are yet to show positive evidence of protection (Nicolaides et al., 2002).

The results from this paper provide needed inputs for fisheries models in order to determine adequate levels of catch and fishing effort that would ensure the long term sustainability of the bacalao fishery and reduce current levels of discards and bycatch associated with it (Zimmerhackel et al., 2015). Creating management regulations, however, is often easier than implementing them. This is especially true in developing countries (McClanahan, Maina & Davies, 2005; King, 2013), where using collaborative approaches is necessary to ensure compliance to management regulations (Yochum, Starr & Wendt, 2011; Usseglio, Schuhbauer & Friedlander, 2014). By working with the local fishing community to develop more accurate estimates of age, growth, and reproduction of bacalao, our results are more credible to them, and therefore more likely to be accepted in any future management decisions.

References

Alonzo SH., Mangel M. 2004. The effects of size-selective fisheries on the stock dynamics of and sperm limitation in sex-changing fish. *Fishery Bulletin* 102:1–13.

Andrews AH., Tracey DM., Dunn MR. 2009. Lead–radium dating of orange roughy (*Hoplostethus atlanticus*): validation of a centenarian life span. *Canadian Journal of Fisheries and Aquatic Sciences* 66:1130–1140.

Armsworth PR. 2001. Effects of fishing on a protogynous hermaphrodite. *Canadian Journal of Fisheries and Aquatic Sciences* 58:568–578.

Bannerot SP., Fox Jr WW., Powers JE., Polovina J., Ralston S. 1987. Reproductive strategies and the management of groupers and snappers in the Gulf of Mexico and Caribbean. In: *Tropical snappers and groupers: biology and fisheries management.* Boulder, Colorado, USA: Westview Press, 561–606.

Baskett ML., Levin SA., Gaines SD., Dushoff J. 2005. Marine reserve design and the evolution of size at maturation in harvested fish. *Ecological Applications* 15:882–901.

Beets J., Friedlander A. 1999. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, Epinephelus guttatus, in the US Virgin Islands. *Environmental Biology of Fishes* 55:91–98.

Bertalanffy L von. 1938. A quantitative theory of organic growth. *Hum. BioI. 10 (2): 181* 213.

Bertoncini AA., Gerhardinger LC., Sadovy YJ., Rocha L., Choat JH., Ferreira B., Craig M. 2008.*Mycteroperca olfax*. *Available at www.iucnredlist.org* (accessed May 12, 2015).

Brown-Peterson NJ., Wyanski DM., Saborido-Rey F., Macewicz BJ., Lowerre-Barbieri SK. 2011. A standardized terminology for describing reproductive development in fishes. *Marine and Coastal Fisheries* 3:52–70.

Bustamante RH., Reck GK., Ruttenberg BI., Polovina J. 2000. The Galápagos spiny lobster fishery. In: Phillips BF, Kittaka J eds. *Spiny lobsters: fisheries and culture*. Oxford, UK: Blackwell Science Ltd, 210–220.

Campana SE., Annand MC., McMillan JI. 1995. Graphical and Statistical Methods for Determining the Consistency of Age Determinations. *Transactions of the American Fisheries Society* 124:131–138.

Castrejón M., Defeo O., Reck G., Charles A. 2014. Fishery science in Galapagos: From a resource-focused to a social–ecological systems approach. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 159–185.

Chan TTC., Sadovy Y. 2002. Reproductive biology, age and growth in the chocolate hind, *Cephalopholis boenak* (Bloch, 1790), in Hong Kong. *Marine and Freshwater Research* 53:791–803.

Coello S. 1989. Consideration on the management of the Galapagos Bacalao fishery *Myceroperca olfax* (Jenys) (Pisces:Serranidae). *Rev. Pacifico Sur*:705–709.

Coello S., Grimm AS. 1993. The reproductive biology of *Mycteroperca olfax* (Jenys) (Pisces: Serranidae): Protogyny and breeding season. *Rev. Cien. Mar. Limn.* 3:115–128.

Collins MR., Waltz CW., Roumillat WA., Stubbs DL. 1987. Contribution to the life history and reproductive biology of gag, *Mycteroperca microlepis* (serrandidae), in the South Atlantic bight. *South Carolina State Documents Depository*.

Conover DO., Munch SB. 2002. Sustaining fisheries yields over evolutionary time scales. *Science* 297:94–96.

DeMartini EE., Everson AR., Nichols RS. 2011. Estimates of body sizes at maturation and at sex change, and the spawning seasonality and sex ratio of the endemic Hawaiian grouper (*Hyporthodus quernus*, F. Epinephelidae). *Fishery Bulletin* 109:123–134.

Edgar GJ., Banks SA., Brandt M., Bustamante RH., Chiriboga A., Earle SA., Garske LE., Glynn PW., Grove JS., Henderson S., Hickman CP., Miller KA., Rivera F., Wellington GM. 2010. El Niño, grazers and fisheries interact to greatly elevate extinction risk for Galapagos marine species. *Global Change Biology* 16:2876–2890.

Enberg K., Jorgensen C., Dunlop ES., Varpe O., Boukal DS., Baulier L., Eliassen S., Heino M. 2012. Fishing-induced evolution of growth: concepts, mechanisms and the empirical evidence. *Marine Ecology-an Evolutionary Perspective* 33:1–25.

Frisk MG., Miller TJ., Dulvy NK. 2005. Life histories and vulnerability to exploitation of elasmobranchs: inferences from elasticity, perturbation and phylogenetic analyses. *Journal of Northwest Atlantic Fishery Science* 37:27–45.

Froese R. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. *Journal of Fish Biology* 56:758–773.

Froese R., Pauly D. 2015.FishBase. Available at www.fishbase.org, version (08/2015).

Gagern A von. 2009. Population dynamics and fisheries potential of the Galapagos grouper *Mycteroperca olfax*. Masters thesis Thesis. Germany: University of Bremen.

Grove JS., Lavenberg R. 1997. *The fishes of the Galápagos islands*. Stanford University Press.

Haddon M. 2010. Modelling and quantitative methods in fisheries. Boca Raton, FL: CRC press.

Hayes DB., Brodziak JK., O'Gorman JB. 1995. Efficiency and bias of estimators and sampling designs for determining length-weight relationships of fish. *Canadian Journal of Fisheries and Aquatic Sciences* 52:84–92.

Heemstra PC., Randall JE. 1993. FAO species catalogue vol. 16 groupers of the world (family serranidae, subfamily epinephelinae): An annotated and illustrated catalogue of the grouper, rockcod, hind, coral grouper, and lyretail species known to date. Food and Agriculture Organization of the United Nations.

Heppell SS., Heppell SA., Read AJ., Crowder LB. 2005. Effects of fishing on long-lived marine organisms. *Marine conservation biology: the science of maintaining the sea's biodiversity. Island Press, Washington, DC*:211–231.

Heppell SS., Heppell SA., Coleman FC., Koenig CC. 2006. Models to compare management options for a protogynous fish. *Ecological Applications* 16:238–249.

Heylings P., Bensted-Smith R., Altamirano M. 2002. Zonificación e historia de la Reserva Marina de Galápagos. In: Dan, Edgar GJ eds. *Reserva Marina de Galápagos. Linea Base de la Biodiversidad.* Fundación Charles Darwin y Servicio Parque Nacional de Galápagos, Santa Cruz, 10–22.

Huntsman GR., Schaaf WE. 1994. Simulation of the impact of fishing on reproduction of a protogynous grouper, the graysby. *North American Journal of Fisheries Management* 14:41–52.

Jennings S., Kaiser M., Reynolds JD. 2009. *Marine fisheries ecology*. United Kingdom: John Wiley & Sons.

Jennings S., Reynolds JD., Mills SC. 1998. Life history correlates of responses to fisheries exploitation. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 265:333–339.

King M. 2013. Fisheries biology, assessment and management. Oxford: John Wiley & Sons.

Koenig CC., Coleman FC., Collins LA., Sadovy Y., Colin PL. 1996. Reproduction in gag (*Mycteroperca microlepis*)(Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. In: *Biology, fisheries and culture of tropical groupers and snappers. ICLARM Conf. Proc. 48*. 307–323.

McClanahan TR., Maina J., Davies J. 2005. Perceptions of resource users and managers towards fisheries management options in Kenyan coral reefs. *Fisheries Management and Ecology* 12:105–112.

Mills KH., Beamish RJ. 1980. Comparison of fin-ray and scale age determinations for lake whitefish (*Coregonus clupeaformis*) and their implications for estimates of growth and annual survival. *Canadian Journal of Fisheries and Aquatic Sciences* 37:534–544.

De Mitcheson YS., Cornish A., Domeier M., Colin PL., Russell M., Lindeman KC. 2008. A Global Baseline for Spawning Aggregations of Reef Fishes. *Conservation Biology* 22:1233–1244.

Nicolaides F., Murillo JC., Toral V., Reck GK. 2002. Bacalao. In: Danulat E, Edgar GJ eds. *Reserva marina de Galapagos: Linea base de la biodiversidad*. Galapagos: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 146–165.

Ogle DH. 2015.FSA: Fisheries Stock Analysis. *Available at http://fishr.wordpress.com/fsa/*

Okey TA., Banks S., Born AR., Bustamante RH., Calvopina M., Edgar GJ., Espinoza E., Farina JM., Garske LE., Reck GK., Salazar S., Shepherd S., Toral-Granda V., Wallem P. 2004. A trophic model of a Galapagos subtidal rocky reef for evaluating fisheries and conservation strategies. *Ecological Modelling* 172:383–401.

Pauly D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *Journal du Conseil* 39:175–192.

R Development Core Team. 2013. R: A language and environment for statistical computing. *Foundation for statistical computing, Vienna, Austria* Ver 3.0.2.

Reck GK. 1983. The coastal fisheries in the Galapagos Islands, Ecuador. Descriptions and consequences for management in the context of marine environmental protection and regional development. Doctoral thesis Thesis. Germany: Christian-Albrechts Univ.

Reeves S. 2003. A simulation study of the implications of age-reading errors for stock assessment and management advice. *ICES Journal of Marine Science* 60:314–328.

Rodriguez W. 1984. Estudio para evaluar las caracteristicas biologicas pesqueras de *Mycteroperca olfax* en las Islas Galapagos (Ecuador). *Instituto Nacional de Pesca Boletin Tecnico* 6:3–66.

Ruttenberg BI. 2001. Effects of artisanal fishing on marine communities in the Galapagos Islands. *Conservation Biology* 15:1691–1699.

Sadovy YJ. 1996. Reproduction of reef fishery species. In: Polunin NVC, Roberts CM eds. *Reef fisheries*. Chapman and Hall, London: Springer, 15–59.

Sadovy Y. 2001. The threat of fishing to highly fecund fishes. *Journal of Fish Biology* 59:90–108.

Sadovy Y., Colin PL. 1995. Sexual development and sexuality in the Nassau grouper. *Journal of Fish Biology* 46:961–976.

Sadovy Y., Domeier M. 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. *Coral Reefs* 24:254–262.

Sadovy Y., Figuerola M., Roman A. 1992. Age and growth of red hind *Epinephelus guttatus* in Puerto Rico and St. Thomas. *Fishery Bulletin* 90:516–528.

Sadovy Y., Shapiro DY. 1987. Criteria for the diagnosis of hermaphroditism in fishes. *Copeia*:136–156.

Salinas-de-León P., Rastoin E., Acuña-Marrero D. 2015. First record of a spawning aggregation for the tropical eastern Pacific endemic grouper *Mycteroperca olfax* in the Galapagos Marine Reserve: *mycteroperca olfax* spawning aggregation. *Journal of Fish Biology*:n/a–n/a.

Schiller L., Alava JJ., Grove J., Reck G., Pauly D. 2014. The demise of Darwin's fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands: The demise of Darwin's fishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

Sharpe DMT., Wandera SB., Chapman LJ. 2012. Life history change in response to fishing and an introduced predator in the East African cyprinid *Rastrineobola argentea*. *Evolutionary Applications* 5:677–693.

Smith CL. 1959. Hermaphroditism in some serranid fishes from Bermuda. *Pap. Michigan Acad. Sci* 44:111–119.

Snell HM., Stone PA., Snell HL. 1996. Geographical characteristics of the Galapagos Islands. *Island of Biogeography*:619–624.

Sullivan-Brown J., Bisher ME., Burdine RD. 2011. Embedding, serial sectioning and staining of zebrafish embryos using JB-4 resin. *Nat. Protocols* 6:46–55.

Thompson R., Munro JL. 1974. The biology, ecology and bionomics of the hinds and groupers, Serranidae. In: Munro JL ed. *Caribbean coral reef fishery resources*. Manila, Philipines: ICLARM, Makati, 59–93.

Tracey DM., Horn PL. 1999. Background and review of ageing orange roughy (*Hoplostethus atlanticus* , Trachichthyidae) from New Zealand and elsewhere. *New Zealand Journal of Marine and Freshwater Research* 33:67–86.

Tyler AV., Beamish RJ., McFarIane GA. 1989. Implications of age determination errors to yield estimates. In: Beamish RJ, McFarIane GA eds. *Effects of ocean variability on recruitment and an evaluation on parameters used in stock assessment models*. Can. Spec. Publ. Fish. Aquat. Sci.i.

Usseglio P., Schuhbauer A., Friedlander A. 2014. Collaborative Approach to Fisheries Management as a Way to Increase the Effectiveness of Future Regulations in the Galapagos Archipelago. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 187–202.

Walford LA. 1937. Marine game fishes of the Pacific coast from Alaska to the equator. Contrib. Santa Barbara Mus. *Nat. Hist., Univ. Calif. Press, Berkeley. xxix* 69.

West G. 1990. Methods of assessing ovarian development in fishes - a review. *Australian Journal of Marine and Freshwater Research* 41:199–222.

Wickham H. 2007. Reshaping data with the reshape package. *Journal of Statistical Software* 21.

Wickham H. 2009. ggplot2: elegant graphics for data analysis. Springer, New York.

Yochum N., Starr RM., Wendt DE. 2011. Utilizing Fishermen Knowledge and Expertise: Keys to Success for Collaborative Fisheries Research. *Fisheries* 36:593–605.

Zimmerhackel JS., Schuhbauer AC., Usseglio P., Heel LC., Salinas-de-León P. 2015. Catch, bycatch and discards of the Galapagos Marine Reserve small-scale handline fishery. *PeerJ* 3:e995.

Tables

Table 1 Reproductive stages, histological features, and maturity rating used to assess the maturity of female bacalao. Stages follow key milestones in the reproductive cycle (modified from (Brown-Peterson et al,. 2011)).

Phase	Histological features	Maturation
Immature (never spawned)	Small ovaries, often clear, blood vessels indistinct. Only oogonia and primary growth oocytes present. No atresia or muscle bundles. Thin ovarian wall and little space between oocytes.	Immature
Developing (ovaries developing but not yet ready to spawn)	Enlarging ovaries, blood vessels becoming more distinct. Primary growth, cortical alveolar, vitellogenic stages 1 or 2. No evidence of vitellogenic stage 3 or postovulatory follicles.	Mature
Spawning capable	Large ovaries, blood vessels prominent, Vitellogenic stage 3 oocytes and postovulatory follicles present. Early stage maturation oocytes might be present. Atresia or early vitellogenic oocytes might be present.	Mature
Regressing	Atresia at any stage, postovulatory follicles present. Blood vessels prominent. Some cortical alveolar and or vitellogenic oocytes stages 1 or 2 present.	Mature
Regenerating	Small ovaries, blood vessels reduced but present. Only oogonia and primary growth oocytes present. Muscle bundles, enlarged blood vessels, thick ovarian wall, atresia, old degenerating postovulatory follicles, may be present.	Mature

Figures

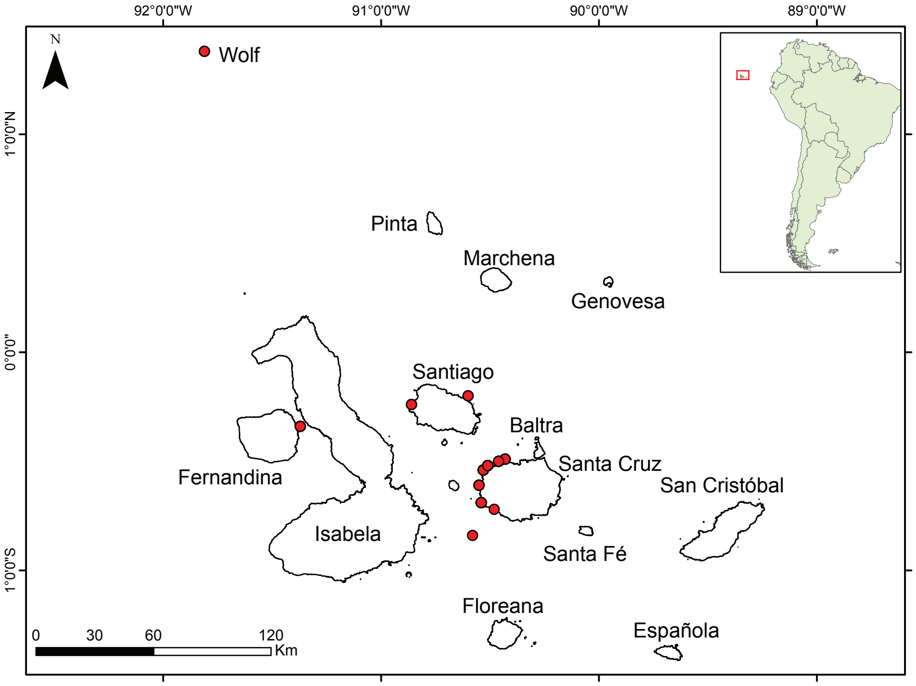


Figure 1 Study area of the Galapagos archipelago, red dots represent sampling sites; inset map shows the location of the Galapagos archipelago.

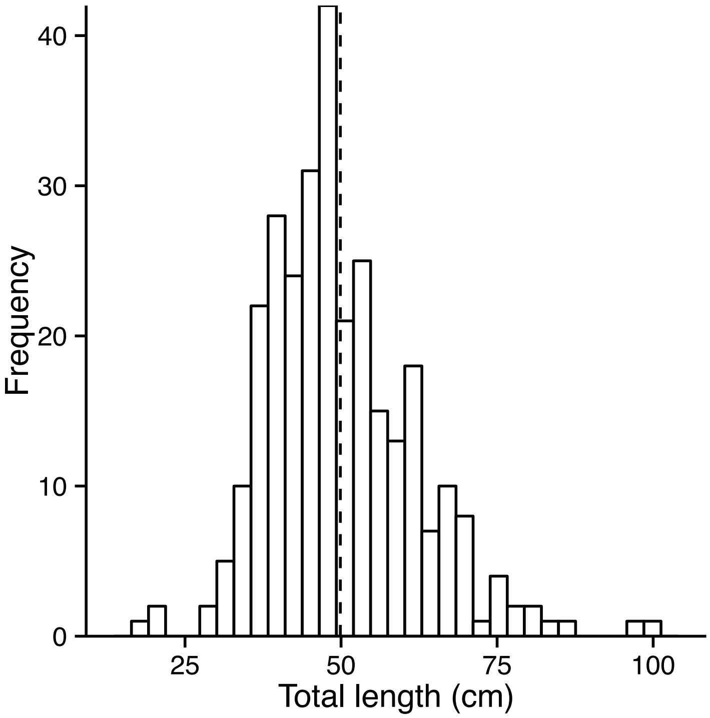


Figure 2 Size composition of bacalao sampled from landings at the fishing ports, as well as samples taken by artisanal fishers (n= 297). Black dashed line represents mean TL (49.8 cm ± 11.1 sd).

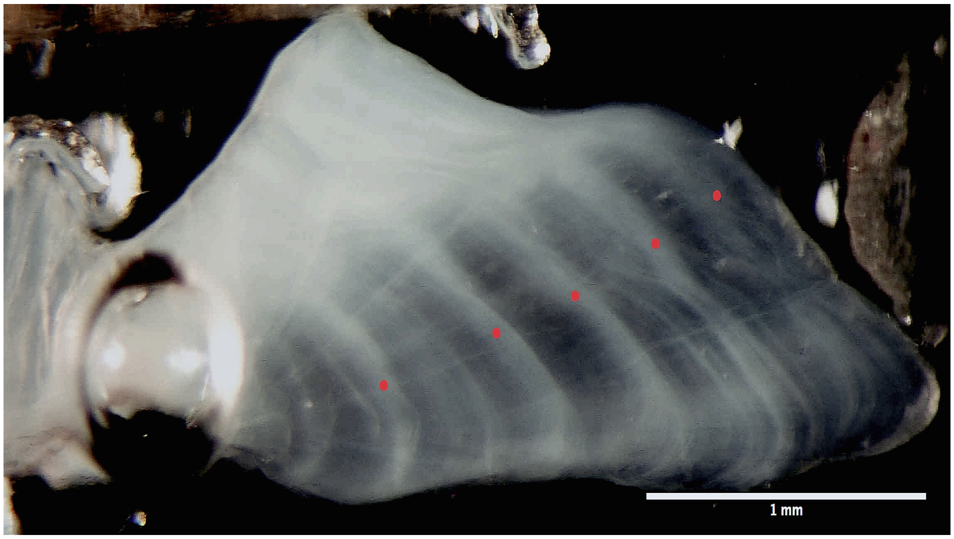


Figure 3 Photomicrograph of an otolith cross section from a 49 cm, 5 year old bacalao, as viewed through a dissecting scope against a dark background with reflected light from two sources placed at opposing sides at a 45 degree angle. Red dots represent yearly rings.

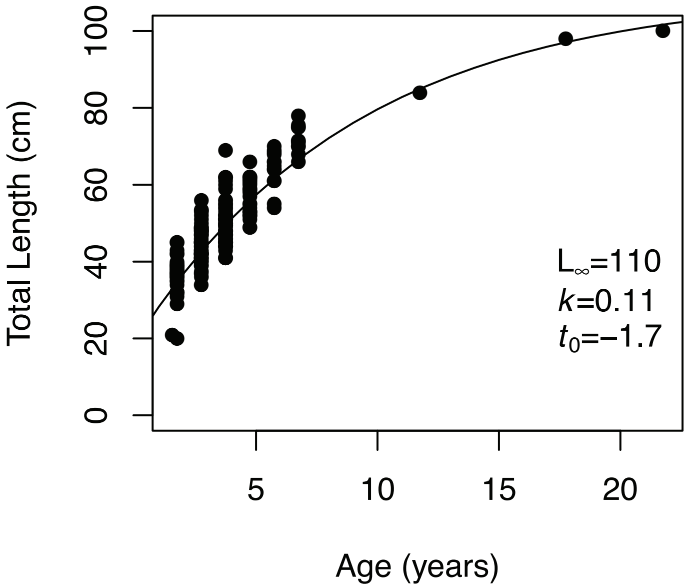


Figure 4 The von Bertalanffy growth function fit to size at age data for bacalao in the Galapagos (n=198).

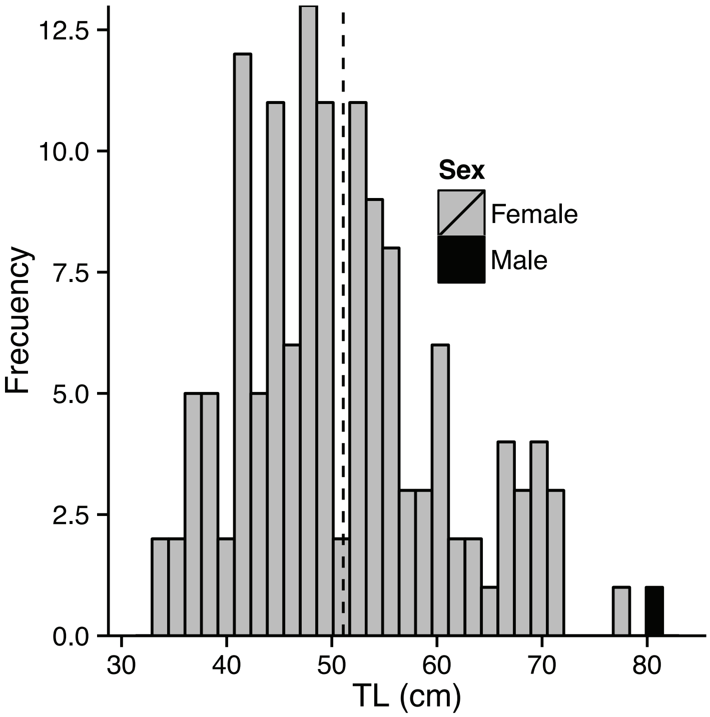


Figure 5 Size composition of bacalao sampled for gonads, by sex (n= 116). Black dashed line represents mean TL (51.4 cm ±10.4 sd).

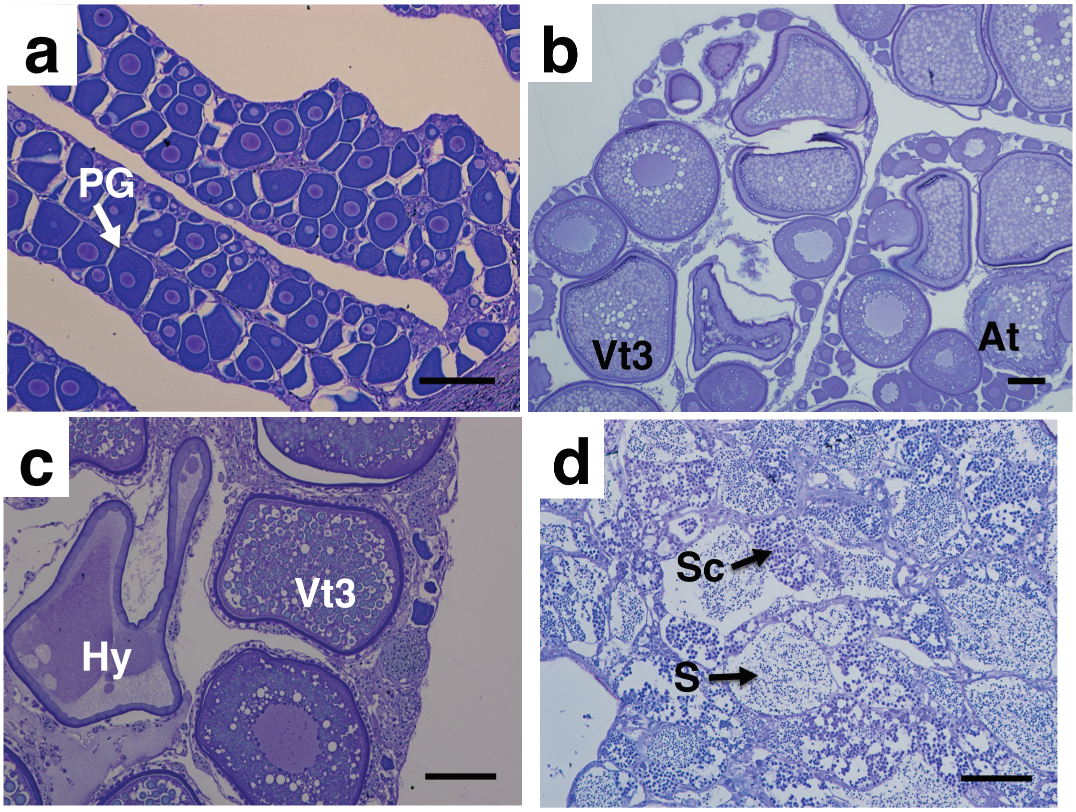


Figure 6 Photomicrograph of toluidine blue stained gonad cross sections of *Mycteroperca olfax*: a) immature 46 cm TL female exhibiting primary growth oocytes (PG), b) spawning capable 70 cm TL female with oocytes in vitellogenic stage 3 (Vt3) and atresia (At), c) spawning capable 84 cm TL female with oocytes in vitellogenic stage 3 (Vt3) and hydrated (Hy), d) male 98 cm TL with spermatocrypts (Sc), and spermatozoa (S). Scale bars 100 μm.

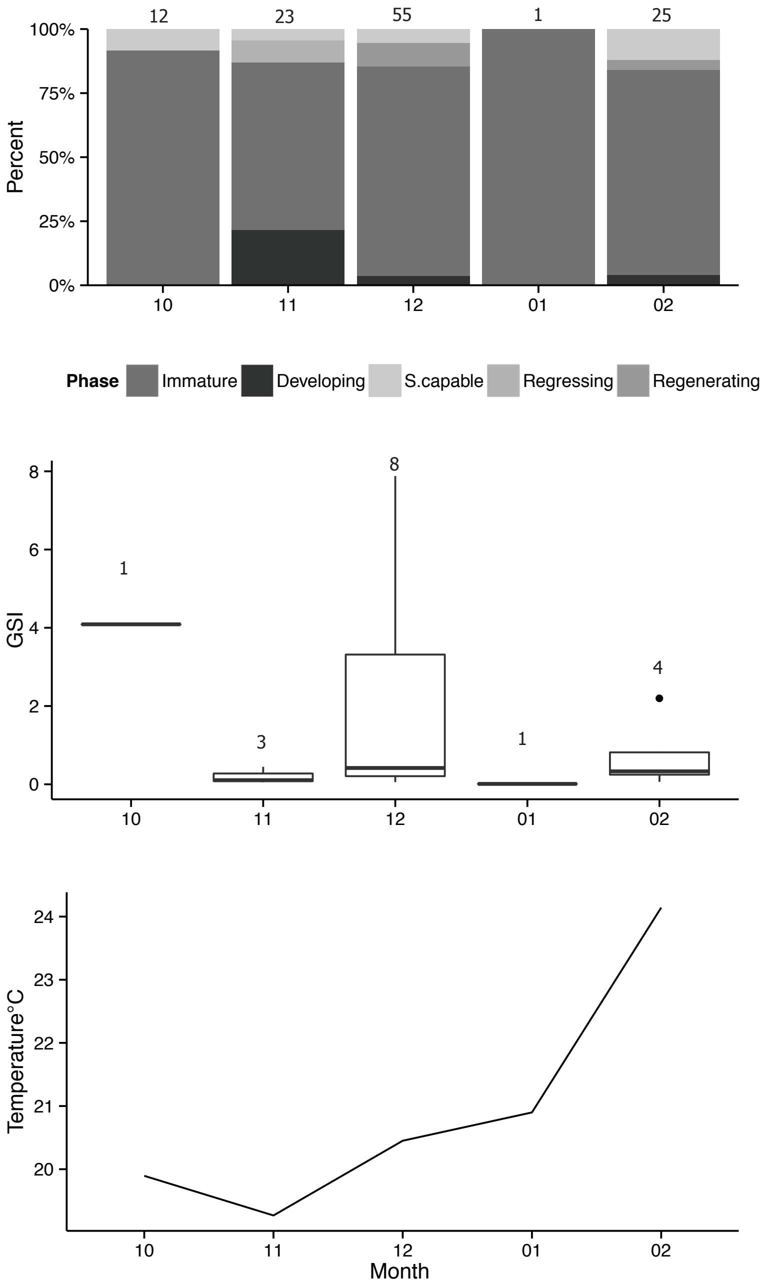


Figure 7 Top: Proportion of developmental stages of *Mycteroperca olfax* sampled by month, top number represents the n for each month. Middle: Box and whisker plot of gonadosomatic index (GSI) for fish sampled, line represents the median, box are the lower and upper quartiles (25% and 75%), points represent the outliers, and numbers above represent the number of mature fish per month. Bottom: Mean water temperature at the island of Santa Cruz.

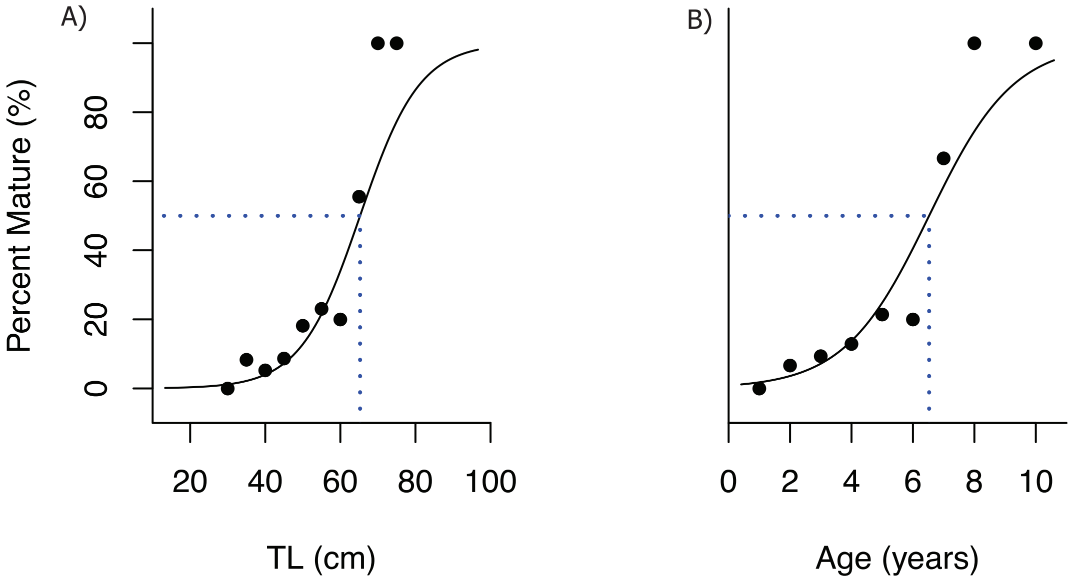


Figure 8 Maturity ogives for female bacalao (n = 116), (A) size (TL) at which 50% of the population matures (L50 = 65.3 cm TL, 95% CI [61.3–74.9]), (B) age at which 50% of the population matures (6.5 years, 95% CI [5.7–7.8]). Blue dashed lines represent size and age at which 50% of the population matures; black line is the resulting logistic model, black circles are proportions of categorized values.

Chapter III

So long and thanks for all the fish: overexploitation of the regionally endemic Galapagos grouper *Mycterperca olfax* (Jenyns, 1840).

Abstract

The regionally endemic Galapagos sailfin grouper, locally known as bacalao, is one of the most highly prized finfishes within the Galapagos Marine Reserve (GMR). Concerns of overfishing, coupled with a lack of fishing regulations aimed at the species raises concerns about the current state of this resource. We assessed the status of the bacalao fishery using three simple indicator: (1) percent of fish below reproductive size (L_m); (2) percent of fish within the optimum length interval (L_{opt}); and (3) percent of megaspawners in the catch. The most recent landings show that the vast majority of the bacalao caught (97.5%, n = 356) were below L_m, the number of fish within the L_{opt} interval was extremely low (2.5%, n = 9), and there were no megaspawners. Historical data show a declining trend in all three indicators. Bacalao fully recruit to the fishery at 52 cm TL, which is well below the size at which 50% of the population matures. The Spawning Potential Ratio is 0.14, strongly suggesting eminent reproductive failure. Our results suggest the need for bacalao-specific management regulations that should include minimum (65 cm TL) and maximum (78 cm TL) landing sizes, and closed season from October to January. These regulations will likely have negative impacts on the livelihoods of fishers in the short term, emphasizing the need to develop alternative sources of income in parallel with the development of new fishing regulations.

Introduction

Encompassing an area of approximately 133.000 km^2, the Galapagos Marine Reserve (GMR) lies 1000 km off the coast of Ecuador. It was the first marine reserve to be established in Ecuador and in 2001 was enshrined as a UNESCO World Heritage Site (Heylings, Bensted-Smith & Altamirano, 2002). High levels of immigration resulted in a population rapid increase from 1,500 people in the 1950s, to over 25,000 in 2010 (INEC, 2011). Commercial fishing started in the Galapagos Islands in the 1940s, when the regionally endemic Galapagos sailfin grouper (*Mycteroperca olfax*, locally called bacalao) comprised nearly the entire catch (Reck, 1983). Bacalao is one of the most iconic species targeted by fishers, with high cultural and economic value. Since the beginning of the fishery, bacalao have been salted and consumed during the eastern holiday in a traditional dish called "fanesca" (Reck, 1983). Landings of this species comprised nearly the entire finfish catch in the 1940s, but declined to < 17% by 2000 (Reck, 1983; Nicolaides et al., 2002). Groupers comprised 89% of landings in the late 1970s, of which bacalao accounted for 36% (Reck, 1983), but by the late 1990s, the catch had shifted to various other species (Andrade & Murillo, 2002). Despite indications of overexploitation of groupers in the GMR, fisheries management is directed only towards sea cucumbers and lobster. Fishing regulations for finfishes include a zonation scheme, with no-take areas, a licensing system, gear restrictions (e.g. spearfishing and long-lining), a ban on industrial fishing vessels, and a ban on capture and marketing of sharks (Castrejón et al., 2014), however there are no specific management regulations for bacalao. Due to its restricted range, and clear evidence of fisheries declines, bacalao has been listed as Vulnerable (VU) by the International Union for Conservation of Nature (IUCN) (Bertoncini et al., 2008).

Fisheries data within the GMR has been collected sporadically and there are important gaps in the time series. Fisheries data was collected prolifically between the 1970's and 1980's, resulting in scientific papers and reports which included bacalao as a main focus, this momentum was interrupted in the 1980's with the decrease of governmental funding led by the international oil price drop (Castrejón et al., 2014). Due to the exponential growth of the fishing sector, primarily led by the illegal expansion of the sea cucumber fishery, the Charles Darwin Foundation started the Galapagos Fishery Monitoring Program, which was later referred to as the Participatory Fisheries Monitoring Program (PIMPP) collected spatially explicit finfish fishery data during the years of 1997-2006 (Castrejón et al., 2014). The most recent data set of bacalao fisheries was done in 2009 (Gagern, 2009). However, biases in estimation of life history parameters of bacalao (Usseglio et al., 2015) cast doubt on previous stock assessments were the fishery was assessed to be within the limit of yield per recruit estimates (Reck, 1983; Coello, 1989).

Lack of good time series data is a common occurrence in developing countries, which has led to the development of an array of length-based methods that are used to understand the dynamics of fish populations (Hordyk et al., 2014). Because of the availability of length information on the bacalao fishery, and because of the high commercial, cultural, and ecological importance of bacalao, this study is aimed at assessing the current state of the fishery, with the goals of producing suggestions for the management of this fishery.

Methods

Permission statement

This research was conducted under permits PC-19-11, PC-24-13, and PC-25-14 from the Galapagos National Park, animal use approval by the Animal Care & Use Committee, University of Hawaiʻi, protocol number 11-1284.

Data sources

We assessed changes in three overfishing indicators overtime, as well as the current status of the bacalao stock. Samples for the year 2012 were collected by accompanying local fishers on commercial fishing trips, data for 2010-2011 was collected by sampling of landings conducted by staff from the Charles Darwin Foundation at the fishing port on the island of Santa Cruz. Historical data for the period 1983-2009 was obtained from published reports and unpublished databases.

Fishing trips

We accompanied local fishers on fishing targeting bacalao using the traditional artisanal method locally called "empate", which consists of a main line of twisted nylon, connected to a 2 m long leader made of 45 kg test monofilament. At intervals of 50 cm, three 50 cm long whips of monofilament 23 kg test are attached, and to each of these whips a single fishing hook, typically number 9 (4.5 cm long by 2.5 cm wide) is attached. The entire rig is weighted with a 1 kg lead weight. During our trips bait consisted primarily of yellowfin tuna (*Thunnus albacares*), but also included several species of bycatch such as other smaller groupers, grunts, and snappers.

We fished at several locations in the islands of Isabela, Santa Cruz, and Santiago (Fig 9.), where most of the fishing targeting bacalao occurs during the months of April to June 2012. Fishers chose the fishing sites on each island based on their Local Ecological Knowledge (LEK), which ensured that our sampling was consistent with contemporary artisanal fishing activities. In areas closed to fishing, and through express permission given by the National Park, fishers used the locations they frequented before the GMR zonation was implemented. Fishing trips included two fishers, each with an empate rigged with 3 hooks. Each trip started at daybreak, and went on until ca. 16:00 h, leaving enough time to return to port before dark. At each fishing site, a GPS coordinate was taken and as fish were caught an observer recorded their Total Length (TL) to the nearest cm and the time of capture.

Landings in Santa Cruz

We conducted fishery-dependent sampling by measuring bacalao landed at the port of Pelican Bay on the island of Santa Cruz during the fishing seasons from November 2010 to January 2011, and August-November 2011. Sampling consisted of recording the site of capture, vessel information, and size and weight of each landed fish. Samples of landed fish were obtained from the islands of Santiago, Santa Cruz, Isabela, Floreana, Marchena, Rabida, and Santa Fe (Fig 9).

Historical data

Historical size data on bacalao were obtained for the years 1983 from (Rodriguez, 1984), the period 1997-2003 from the (PIMPP) database (source CDF), and 2009 from the work of (Gagern, 2009).

Data Analysis

Status of bacalao artisanal fishery

The status of the bacalao artisanal fishery was assessed by means of three simple indicators (Froese, 2004): 1) percentage of mature fish in the catch (Lm), 2) percentage of fish caught at optimum length (Lopt), and 3) percentage of old large fish (megaspawners) in the catch (Froese, 2004). Size at first maturity for bacalao was estimated at 65.3 by (Usseglio et al., 2015). Optimum length at catch is the length where the maximum yield and revenue can be obtained from a fish (Froese, 2004), and was estimated using the empirical relationships between optimum length and L infinity (L_{∞}), derived from the equation (L_{opt}<-(10^(1.0421*log10(L_{∞})-0.2742))) (Froese, 2000). Using the obtained optimum length, we calculated the optimum length interval as fish caught within ± 10% optimum length (Froese, 2004).

Lastly, megaspawners are defined as old and large fish in the catch, and were defined as fish of a size larger than optimum length +10% (Froese, 2004).

In a healthy stock it would be expected that: (1) all fish caught would be larger than the size of first maturity (a large percentage of the catch below size at maturity would suggest recruitment overfishing), (2) a very large proportion of the catch would be within the optimum length interval (the inverse would suggest growth overfishing), and (3) there would be very few megaspawners in the catch (Froese, 2004). For megaspawners, however, values of 30–40% represent a healthy age structure in a population where there is no maximum size limit (Froese, 2004), such as is the case for bacalao in the GMR.

Fishery assessment

Spawning potential ratio (SPR)

Because of the lack of good long-term fisheries data available for bacalao, we used a length-based approach to estimate spawning potential ratio (SPR) and fishery selectivity to assess the current bacalao stock status from data collected in 2011-2012.

SPR is derived by estimating the actual average lifetime production of mature eggs per recruit (P) at an equilibrium population density in the absence of any density-dependent suppression of maturation or fecundity (Goodyear, 1993). It was estimated following the methods outlined in (Hordyk et al., 2014), which require as an input length composition data, the ratio between natural morality (M) and growth rate (k) M/k, length infinity (L_∞), and the coefficient of variation of length infinity (CVL_∞), SPR is then calculated as:

$$SPR = \frac{P_{fished}}{P_{unfished}}$$

where P is potential fecundity, and:

$$P_{fished} = \sum_a \begin{cases} E_a & for\ a = 0 \\ e^{-Z_{a-1}a_1}E_a & for\ 0 < a \leq a_{max} \end{cases}$$

$$P_{unfished} = \sum_{a} E_a e^{-M_a}$$

Where a is age, E is egg production at age a, Z_a is total mortality at age a, and M_a is maturity at age a.

While an estimate for k exists for bacalao (Usseglio et al., 2015), no such estimate exists for an unfished population of bacalao. As a proxy, we used reports from a congener (*Mycterperca venenosa*) of m=0.29 reported by (Thompson & Munro, 1978). Simulation results from Prince et al (Prince et al., 2014), indicate predictable patterns in life-history ratios and the M/k parameter, and our best knowledge of bacalao's life history. Our estimate of M/k was 2.7, which corresponds to simulation results from (Prince et al., 2014), that indicate predictable patterns in life-history ratios and the M/k parameter for fish with indeterminate growth and that reproduces at a relatively later stage of their life cycle, such as bacalao.

Fishery selectivity

A selectivity curve was modeled following the methods in (Hordyk et al., 2014), assuming that selectivity was asymptotic and size dependent following the equation:

$$S_l = \frac{1}{1 + e^{-\ln(19)(l - l_{s50})/l_{s95} - l_{s50}}}$$

where s_l is selectivity at length l, l_{s95} and l_{s50} are the lengths at 50 and 95% selectivity.

The ratio of fishing to total mortality (F/M) was estimated with the equation:

$$Z_a = M + S_a + F$$

Where Z_a is total mortality at age a, M is the instantaneous rate of annual natural mortality, and Sa is the selectivity at age a.

Mortality

Instantaneous total mortality (Z) was estimated following the analysis of a catch curve following the methods outlined by (Chapman & Robson, 1960). An age frequency distribution for bacalao landings was constructed and catch plotted against age, for catch curve analysis only the ages on the descending limb of the curve following peak catch were included (Smith et al., 2012). The Chapman-Robson estimate of annual survival (S) is given by the equation:

$$S = \frac{T}{1 - T - \frac{1}{n}}$$

Where n is the total recorded age of fish on the descending limb of the catch curve, and *T* is the sum of recoded ages of fish on the descending limb of the curve. An estimate of Z is obtained following the equation proposed by (Hoenig, Lawing & Hoenig, 1983):

$$Z = -\log(S) - \frac{(n-1)(n-2)}{n(T+1)(N+T-1)}$$

The above analysis was conducted using the R package FSA (Ogle, 2015).

Generational turnover rate

We estimated the average time required for a new generation to replace the last generation by calculating the mean generational turnover rate following the methods proposed by (Gaillard et al., 2005) and applied to fish by (Depczynski & Bellwood, 2006), as given by the equation:

$$\overline{GT} = AM + \frac{T_{max} - AM}{2}$$

Where AM is age at maturity in females, and T_{max} is maximum age, both of these estimates were obtained from (Usseglio et al., 2015).

Historical changes in the fishery

We assessed the change over time in four metrics used to describe the bacalao fishery of: mean TL of landed fish, percent of fish above Lm, percent of fish within the Lopt interval, and percent megaspawners in the catch. Trends of each of these metrics over time were assessed by means of a least square linear regressions of each of the indicators over the time-series, these regressions were then followed by an F-test.

Results

Current status of the bacalao artisanal fishery in the GMR

Samples collected by fishing during the year 2012 resulted in a total of 365 bacalao from 43 sites from around the islands of Isabela, Santa Cruz, and Santiago, with an overall mean TL of 45.5 cm (± 8.2 sd), and a range from 20 to 73 cm TL.

The reported maximum length for bacalao is 120 cm TL (Heemstra & Randall, 1993). We previously estimated a length at maturity of 65.3 cm TL, and L_∞ of 110 (Usseglio et al., 2015). Based on these values, L_{opt} was calculated as 71.3 cm TL (60.3-84.3 se). The Lopt interval (10% ± Lopt) was between 64.2 and 78.4 cm TL, and megaspawners (Lopt + 10%) were those fish > 78.4 cm TL.

A low proportion of the bacalao landed (2.5%, n=9) were above size at reproductive maturity (Lm), the number of fish within the Lopt interval was very low (2.5%, n=9), and there were no megaspawners in the landings (Fig 10).

At an island level, the indicators performed similarly, with low percentages of bacalao catch above size of maturity, very low percentages of fish within the optimal capture interval, and no megaspawners (Table 2).

Fishery assessment

Using an M/k ratio of 2.7, we calculated an SPR for 2012 of 0.14, and an F/M ratio of 1.07. The size at which 50% of the bacalao recruit to the fishery was 39.3 cm TL, and 100% are recruited to the fishery at 52 cm TL (Fig. 11), meaning that 100% of the population is being fished before reaching sexual maturity, suggesting severe recruitment overfishing. Annual survival rate (S) was estimated at 57.1 (1.7 se), and instantaneous total mortality (Z) at 0.56 (0.14 se). Using an estimate of age at first maturity of 6.5 years, and a maximum observed age of 21 years (Usseglio et al., 2015), the generational turnover time for bacalao was of 13.7 years.

Historical changes in the fishery

Historical data from previously studies yielded 1,299 bacalao in 1983 and 663 in 2009. In addition, the PIIMP dataset recorded a total of 2,335 bacalao for the period 1997-2003 (Table 3). Lopt, Lm, and megaspawners all showed declines over time, with 2012 being the lowest value observed in the dataset. Mean TL of bacalao showed a decreasing not significant trend ($F_{1,9}$=3.99, p>0.05. R^2=0.2) (Table 3, Fig 12). Percentage of bacalao larger than size at maturity declined, with 2012 being the lowest in the time series by an order of magnitude and was marginally significant ($F_{1,9}$=5.06, p=0.05. R^2=0.3) (Fig 13). Similarly, percent of the catch within the L_{opt} interval showed a declining trend with the year 2012 being the lowest value of the dataset by an order of magnitude ($F_{1,9}$=2.11, p>0.05. R^2=0.1) (Fig 13). And lastly, the proportion of megaspawners was consistently low for all of the years analyzed, declining to zero for the year 2012 ($F_{1,9}$=3.67, p>0.05. R^2=0.21) (Fig 13).

Discussion

Results from the evaluation of the biological indicators (e.g., TL, Lm, Lopt, % megaspawners) used to assess the current status of the bacalao artisanal fishery in the Galapagos archipelago, along with declining trends in all of these over a 20-year span suggests that, at present, this fishery is undergoing both recruitment and growth overfishing. The percentage of fish above size at maturity has dropped to an all time low, and SPR suggests that bacalao is facing imminent reproductive failure. Currently the GMR does not have management regulations specific to bacalao, relying only on no-take areas that have yet to show positive results of effect on bacalao (Nicolaides et al., 2002). Our results highlight the immediate need to establish management regulations for this species in the Galapagos.

Population declines in bacalao have been linked to the shift in composition of the fisheries landings, with bacalao dropping from almost all of the landings at the beginning of the fishery in the 1940s to less than 17% in recent years (Reck, 1983; Schiller et al., 2014). This pattern, however, can be a reflection of two things: a change in the preference of fishers for offshore species, such as tuna and wahoo, unrelated to abundance of bacalao, or that these changes were triggered because of drops in the abundance of bacalao. Reconstruction of landings in the Galapagos show that serranids, as a group, declined sharply in the late 80s, about the time when other species increased their contribution to total landings (Schiller et al., 2014). The role of bacalao in this decline is hard to judge as the inshore fisheries labeled a rather large group of species comprising other groupers as bacalao (Nicolaides et al., 2002). While there is no direct data that would explain the exact nature of the change in targeted species, the coincidence of decline in groupers and increase of offshore species seems like a plausible explanation that overfishing played a role. Our results suggest that over a 20-year period there have been declines in all of the indicators used to assess the status of the fishery, strongly suggesting that declines in the landings of bacalao are the likely reason behind the change in shift of targeted species.

Fisheries tend to target larger, older individuals over smaller and younger, with larger fish being more likely to be caught than smaller ones, under this scenario when larger fish are removed from the population the mean size of the landings will decline, as it has been seen in multiple overexploited stocks (Haedrich & Barnes, 1997; Beets & Friedlander, 1999; Zwanenburg, 2000). While the correlation in our analysis of mean TL trend was not significant, this can be a reflection of the variability observed in the data. However, it is clear that mean landed size in bacalao has decreased considerably and that the latest data point is also the lowest. Fisheries for bacalao started in the 1940s but to data no data from this period survives, it is likely the average size of the population was much larger, and that the population had already gone through severe overfishing by the beginning of our data series in the 80s.

Large and old individuals, megaspawners, would be expected to represent 30–40% of the age structure in a healthy population where there are no maximum size limit, or fishing selectivity (Froese, 2004). This pattern was not evident in any of the observed years in the dataset, with the megaspawner metric being the lowest across all years, supporting the hypothesis that most of the overfishing for bacalao occurred in the early days of the fishery and before the beginning of the dataset in the 1980s. The pattern of very low large individuals in the population has the consequence of reducing reproductive potential. Given that fecundity increases exponentially with female weight (McIntyre & Hutchings, 2003), smaller individuals have reduced reproductive potential (Scott, Marteinsdottir & Wright, 1999), and egg size and early survival of larvae is reduced in young females (Trippel, 1998). Bacalao is fully recruited to the fishery at a size considerably smaller than size at maturity, which results in the severely skewed sex ratios observed since the 1980s (Reck, 1983; Coello & Grimm, 1993; Usseglio et al., 2015). Early recruitment to the fishery leads to a reduction in the probability that females will survive to sex change (Armsworth, 2001), loss of productivity due to sperm limitation (Bannerot et al., 1987; Koenig et al., 1996), and ultimately reproductive failure as males become too rare to effectively mate with females (Allee effect) (Bannerot et al., 1987; Huntsman

& Schaaf, 1994). Reproductive success of bacalao is practically non-existent. While SPRs < 0.4 are considered adverse for many species (Clark, 2002), our result of 0.14, the long generational time of 14 years, the very high total mortality, low survival estimate of only 57% yearly, and that the peak harvest season for bacalao coincidences with peak spawning (Coello & Grimm, 1993; Nicolaides et al., 2002) place the population at risk of imminent reproductive failure.

At present there are no management regulations aimed specifically at bacalao in the GMR. While there have been management proposals in the past (Coello, 1989), these have been largely ignored, placing present day protection of bacalao solely within the GMR zonation scheme, which has yet to be evaluated in terms of bacalao, but that seems to have little positive effect (Nicolaides et al., 2002). The bacalao fishery in Galapagos should follow conservative management approaches that should include a mix of control over catch and fishing effort, seasonal closures, and effective no-take spatial closures.

The way forward

The GMR is no stranger to fisheries collapses, as exemplified by the sea cucumber, and lobster fisheries, but it has also witnessed riots and violence when regulations are implemented (Finchum, 2002). There is an obvious need to include fishers in decision making (Usseglio, Schuhbauer & Friedlander, 2014), keeping in mind that the most effective regulations will need to be stringent given the current state of the resources, and will not be popular.

Our results strongly suggested that the bacalao fishery in the GMR is in a critical condition and facing imminent reproductive failure, and while a total closure until the stock recovers would be highly advisable, we recognize that this might not be feasible, as it will negatively impact the livelihood of a large number of of fishers and their families. We therefore, suggest bacalao-specific management regulations be developed in conjunction with fishers. These should at least include:

- Minimum landing size of bacalao ≥ to L_{50} (65 cm TL)
- Maximum landing size of bacalao ≤ to size of megaspawners (78 cm TL)

- Closed season from October to January during peak spawning

In addition to the above regulations, it would be advisable to re-evaluate the existing no-take areas within the GMR in terms of essential fish habitat for bacalao. The final site selection of the conservation zones (no-take zones) in the GMR was mostly based on expert opinion, with the main goal of protecting a range of sites representative of different shallow habitats in each of the five locally recognized biogeographic zones. However, (Edgar et al., 2004) notes that there was limited use of technical data on shallow benthic biodiversity, when compared to locations with a previous use for tourism or fisheries. The above hints at a need to incorporate juvenile nursery habitat, spawning aggregation sites, and essential fish habitat for adults in the design of no take zones specific for bacalao. Movements forwards in this direction is the discovery of the first spawning aggregation site for bacalao within the GMR (Salinas-de-León, Rastoin & Acuña-Marrero, 2015).

It is understandable that enacting these regulations will have negative impacts on the livelihoods of fishers from the GMR, emphasizing the need of working with them to develop alternative sources of income in parallel to the development of fishing regulations, which is plausible as over 60% of fishers interviewed in the GMR responded that they would be willing to adopt income alternatives different than fishing (Usseglio, Schuhbauer & Friedlander, 2014). However, it is essential to recognize the choices facing the conservation, fishing, and community-at-large of the Galapagos Archipelago between managing their resources wisely or avoiding political and social conflict, the former would ensure resilience of an important cultural, economic, and biological resource, while the latter would result in what Pauly aptly named “Malthusian overfishing” (Pauly, 1990).

References

Andrade R., Murillo JC. 2002. Lisas. In: Danulat E, Edgar GJ eds. *Reserva Marina de Galápagos. Línea Base de*. Santa Cruz: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 166–175.

Armsworth PR. 2001. Effects of fishing on a protogynous hermaphrodite. *Canadian Journal of Fisheries and Aquatic Sciences* 58:568–578.

Bannerot SP., Fox Jr WW., Powers JE., Polovina J., Ralston S. 1987. Reproductive strategies and the management of groupers and snappers in the Gulf of Mexico and Caribbean. In: *Tropical snappers and groupers: biology and fisheries management.* Boulder, Colorado, USA: Westview Press, 561–606.

Beets J., Friedlander A. 1999. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, Epinephelus guttatus, in the US Virgin Islands. *Environmental Biology of Fishes* 55:91–98.

Bertoncini AA., Gerhardinger LC., Sadovy YJ., Rocha L., Choat JH., Ferreira B., Craig M. 2008.*Mycteroperca olfax*. *Available at www.iucnredlist.org* (accessed May 12, 2015).

Castrejón M., Defeo O., Reck G., Charles A. 2014. Fishery science in Galapagos: From a resource-focused to a social–ecological systems approach. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 159–185.

Chapman D., Robson DS. 1960. The analysis of a catch curve. *Biometrics*:354–368.

Clark WG. 2002. F 35% revisited ten years later. *North American Journal of Fisheries Management* 22:251–257.

Coello S. 1989. Consideration on the management of the Galapagos Bacalao fishery *Myceroperca olfax* (Jenys) (Pisces:Serranidae). *Revista Pacifico Sur*:705–709.

Coello S., Grimm AS. 1993. The reproductive biology of *Mycteroperca olfax* (Jenys) (Pisces: Serranidae): Protogyny and breeding season. *Revista de Ciencias del Mar y Limnologia.* 3:115–128.

Depczynski M., Bellwood DR. 2006. Extremes, plasticity, and invariance in vertebrate life history traits: insights from coral reef fishes. *Ecology* 87:3119–3127.

Edgar GJ., Bustamante RH., Farina JM., Calvopina M., Martinez C., Toral-Granda MV. 2004. Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve. *Environmental Conservation* 31:212–218.

Finchum R. 2002. The beliefs & perceptions of fishermen regarding management actions, regulations, and the protection of the Galapagos marine reserve. Master's thesis Thesis. USA: Colorado State University.

Froese R. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. *Journal of Fish Biology* 56:758–773.

Froese R. 2004. Keep it simple: three indicators to deal with overfishing. *Fish and Fisheries* 5:86–91.

Gagern A von. 2009. Population dynamics and fisheries potential of the Galapagos grouper *Mycteroperca olfax*. Masters thesis Thesis. Germany: University of Bremen.

Gaillard J -M., Yoccoz NG., Lebreton J -D., Bonenfant C., Devillard S., Loison A., Pontier D., Allaine D. 2005. Generation Time: A Reliable Metric to Measure Life-History Variation among Mammalian Populations. *The American Naturalist* 166:119–123.

Goodyear CP. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. In: Smith SJ, Hunt JJ, Rivard D eds. *Risk Evaluation and Biological Reference Points for Fisheries Management*. Canadian Special Publications of Fisheries Aquatic Sciences. 67–81.

Haedrich RL., Barnes SM. 1997. Changes over time of the size structure in an exploited shelf fish community. *Fisheries Research* 31:229–239.

Heemstra PC., Randall JE. 1993. *FAO species catalogue vol. 16 groupers of the world (family serranidae, subfamily epinephelinae): An annotated and illustrated catalogue of the grouper, rockcod, hind, coral grouper, and lyretail species known to date*. Food and Agriculture Organization of the United Nations.

Heylings P., Bensted-Smith R., Altamirano M. 2002. Zonificación e historia de la Reserva Marina de Galápagos. In: Dan, Edgar GJ eds. *Reserva Marina de Galápagos. Linea Base de la Biodiversidad.* Fundación Charles Darwin y Servicio Parque Nacional de Galápagos, Santa Cruz, 10–22.

Hoenig JM., Lawing WD., Hoenig NA. 1983. Using mean age, mean length and median length data to estimate the total mortality rate. *ICES CM* 500:23.

Hordyk A., Ono K., Valencia S., Loneragan N., Prince J. 2014. A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. *ICES Journal of Marine Science*.

Huntsman GR., Schaaf WE. 1994. Simulation of the impact of fishing on reproduction of a protogynous grouper, the graysby. *North American Journal of Fisheries Management* 14:41–52.

INEC. 2011. *Proyecciones-poblacionales*. Instituto Nacional de Estadísticas y Censos.

Koenig CC., Coleman FC., Collins LA., Sadovy Y., Colin PL. 1996. Reproduction in gag (*Mycteroperca microlepis*)(Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. In: *Biology, fisheries and culture of tropical groupers and snappers. ICLARM Conf. Proc. 48*. 307–323.

McIntyre TM., Hutchings JA. 2003. Small-scale temporal and spatial variation in Atlantic cod (*Gadus morhua*) life history. *Canadian Journal of Fisheries and Aquatic Sciences* 60:1111–1121.

Nicolaides F., Murillo JC., Toral V., Reck GK. 2002. Bacalao. In: Danulat E, Edgar GJ eds. *Reserva marina de Galapagos: Linea base de la biodiversidad*. Galapagos: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 146–165.

Ogle DH. 2015.FSA: Fisheries Stock Analysis. *Available at http://fishr.wordpress.com/fsa/*

Pauly D. 1990. On Malthusian overfishing. *NAGA, The ICLARM quarterly* 13:2–4.

Prince J., Hordyk A., Valencia SR., Loneragan N., Sainsbury K. 2014. Revisiting the concept of Beverton -Holt life-history invariants with the aim of informing data-poor fisheries assessment. *ICES Journal of Marine Science*.

Reck GK. 1983. The coastal fisheries in the Galapagos Islands, Ecuador. Descriptions and consequences for management in the context of marine environmental protection and regional development. Doctoral thesis Thesis. Germany: Christian-Albrechts Univ.

Rodriguez W. 1984. Estudio para evaluar las caracteristicas biologicas pesqueras de *Mycteroperca olfax* en las Islas Galapagos (Ecuador). *Instituto Nacional de Pesca Boletin Tecnico* 6:3–66.

Salinas-de-León P., Rastoin E., Acuña-Marrero D. 2015. First record of a spawning aggregation for the tropical eastern Pacific endemic grouper *Mycteroperca olfax* in the Galapagos Marine Reserve: *mycteroperca olfax* spawning aggregation. *Journal of Fish Biology*.

Schiller L., Alava JJ., Grove J., Reck G., Pauly D. 2014. The demise of Darwin’s fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands: The demise of Darwin’s fishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

Scott B., Marteinsdottir G., Wright P. 1999. Potential effects of maternal factors on spawning stock-recruitment relationships under varying fishing pressure. *Canadian Journal of Fisheries and Aquatic Sciences* 56:1882–1890.

Smith MW., Then AY., Wor C., Ralph G., Pollock KH., Hoenig JM. 2012. Recommendations for catch-curve analysis. *North American Journal of Fisheries Management* 32:956–967.

Thompson R., Munro JL. 1978. Aspects of the biology and ecology of Caribbean reef fishes: Serranidae (hinds and groupers). *Journal of Fish Biology* 12:115–146.

Trippel EA. 1998. Egg size and viability and seasonal offspring production of young Atlantic cod. *Transactions of the American Fisheries Society* 127:339–359.

Usseglio P., Friedlander AM., DeMartini EE., Schuhbauer A., Schemmel E., Salinas-de-León P. 2015. Improved estimates of age, growth and reproduction for the regionally endemic Galapagos sailfin grouper *Mycteroperca olfax* (Jenys,1840). *PeerJ* 3:e1270:21.

Usseglio P., Schuhbauer A., Friedlander A. 2014. Collaborative Approach to Fisheries Management as a Way to Increase the Effectiveness of Future Regulations in the Galapagos Archipelago. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 187–202.

Zwanenburg K. 2000. The effects of fishing on demersal fish communities of the Scotian Shelf. *ICES Journal of Marine Science* 57:503–509.

Tables

Table 2 Total number of bacalao caught, percentage of the catch above size of maturity (Lm) and percent of catch within the optimum length interval (Lopt).

	Total fish	% above Lm	% within Lopt
Isabella	217	1.4	2.3
Santa Cruz	86	3.5	4.6
Santiago	62	4.8	4.8

Table 3 Total numbers and mean TL (cm) of bacalao sampled during the years 1983, 1997-2003, 2009, 2011, and 2012 in the GMR.

Year	N	TL cm (sd)
1983	1299	54.7 (11.5)
1997	331	56.9 (14.6)
1998	544	53.4 (12.3)
1999	160	52.5 (13.4)
2000	264	49.6 (11.4)
2001	553	53.2 (13.4)
2002	292	49.8 (13.3)
2003	191	53.3 (10.2)
2009	663	53 (11.6)
2011	314	52.2 (10.7)
2012	365	45.5 (8.2)

Figures

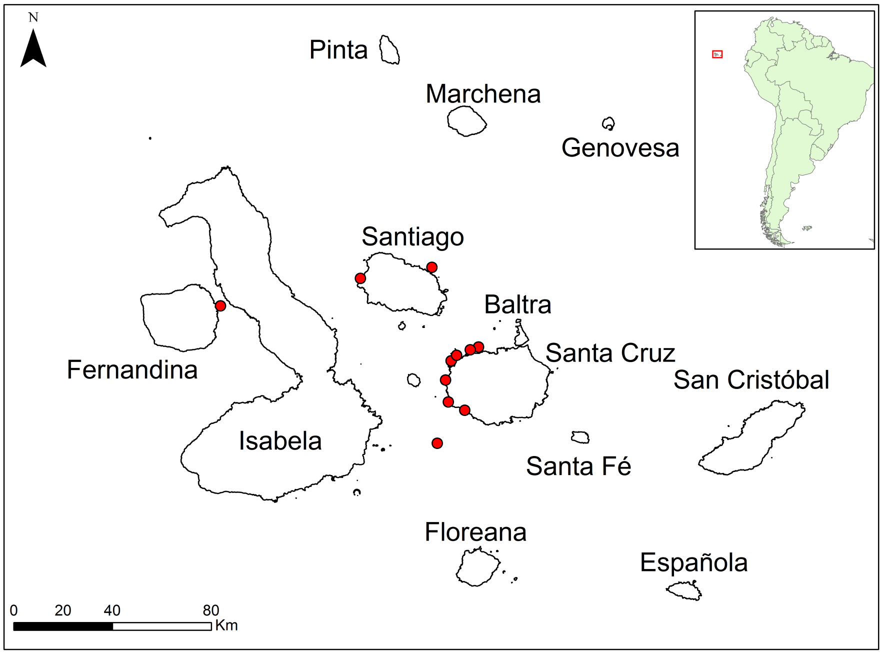


Figure 9 Study area of the Galapagos archipelago, inset map shows location of the Galapagos Archipelago Red circles represent fishing spots.

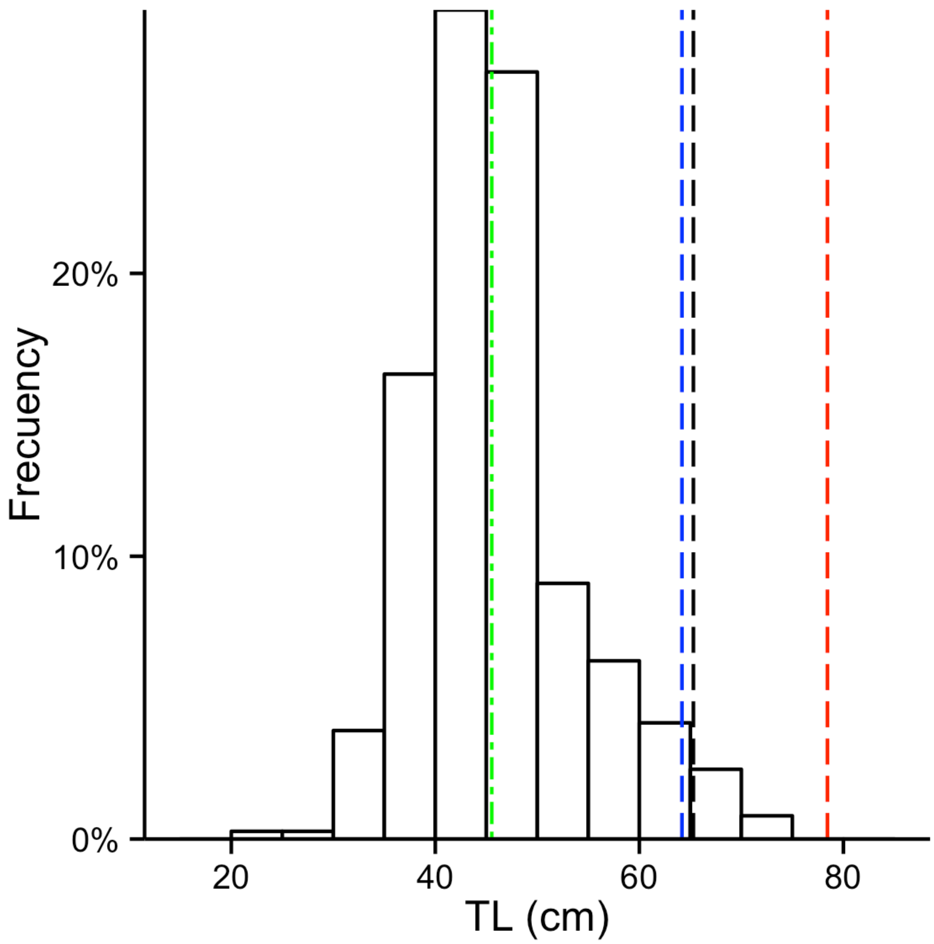


Figure 10 Size frequency distribution of bacalao caught during experimental fishing, and landed on the port of Santa Cruz (n=365). Dot-and-dash green line represents the mean TL (cm), black dotted line represents size of maturity (L_m), blue line represents the lower limit of the optimal length interval (L_{opt}), and red line represents both the upper limit of the optimal length interval, at the size at which bacalao larger than it are considered megaspawners.

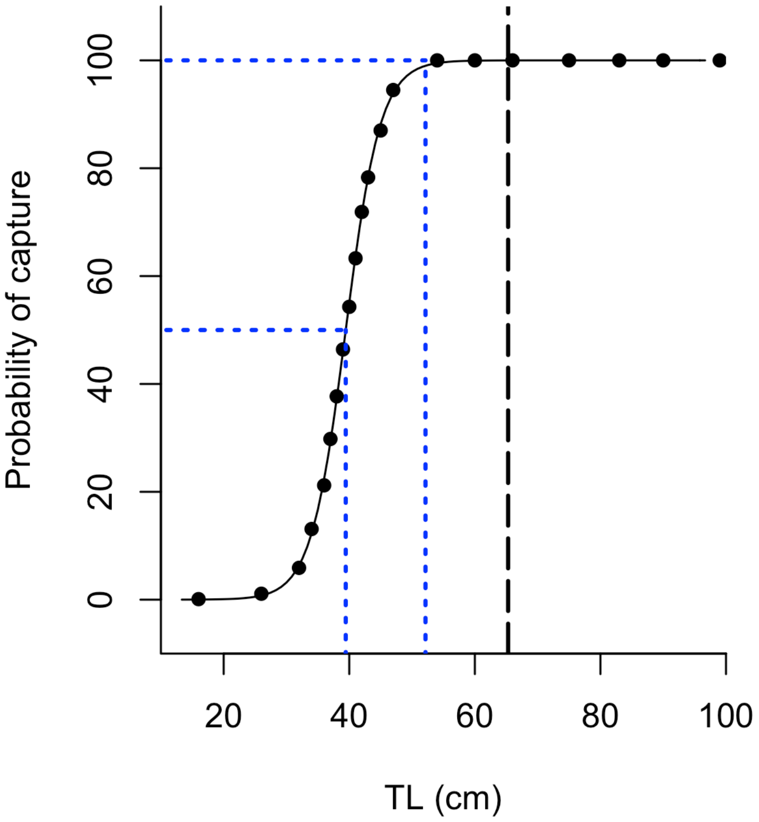


Figure 11 Selectivity of bacalao from length data collected in 2012. Red line represents the logistic selectivity model, blue lines represents size at 50% and 100% recruitment to the fishery, and black double dotted line represents size at which 50% of the population reaches sexual maturity.

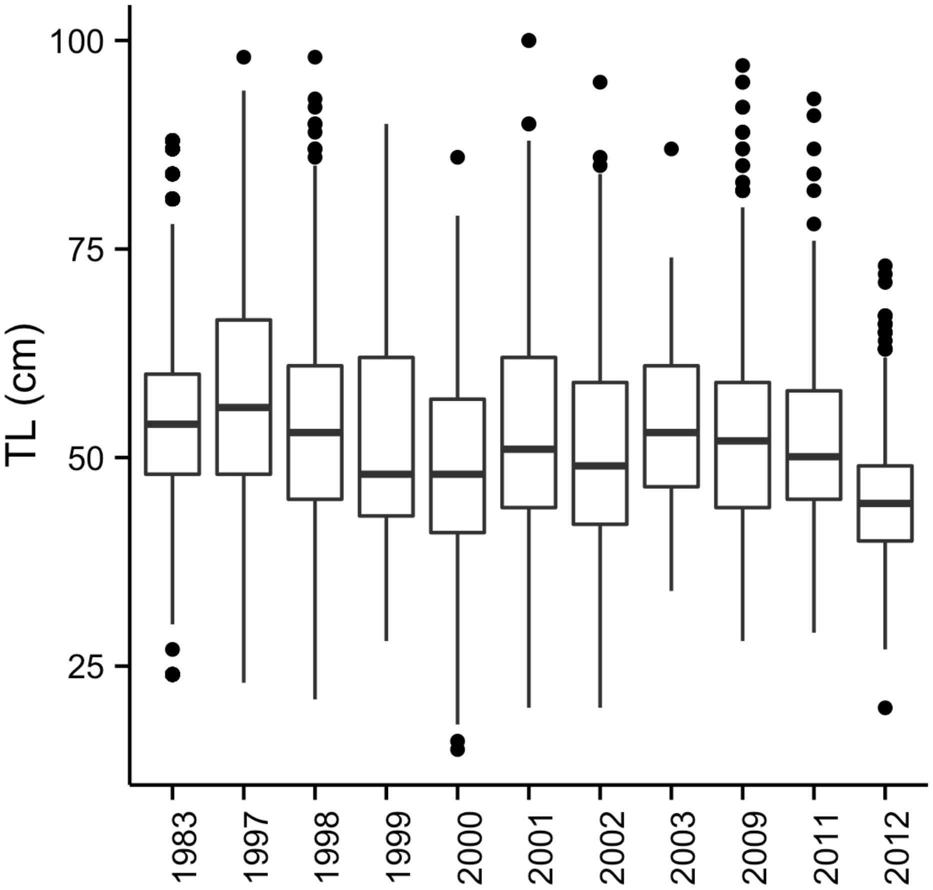


Figure 12 Mean TL(cm) for bacalao caught in the GMR in the years 1983, 1997-2003 (PIMMP monitoring program) and data collected in this study (2011, 2012). Box represents the top and lower percentiles (75%, 25%) while the centerline represents the median, the whiskers represent 1.5 IQR, and the dots represent outliers.

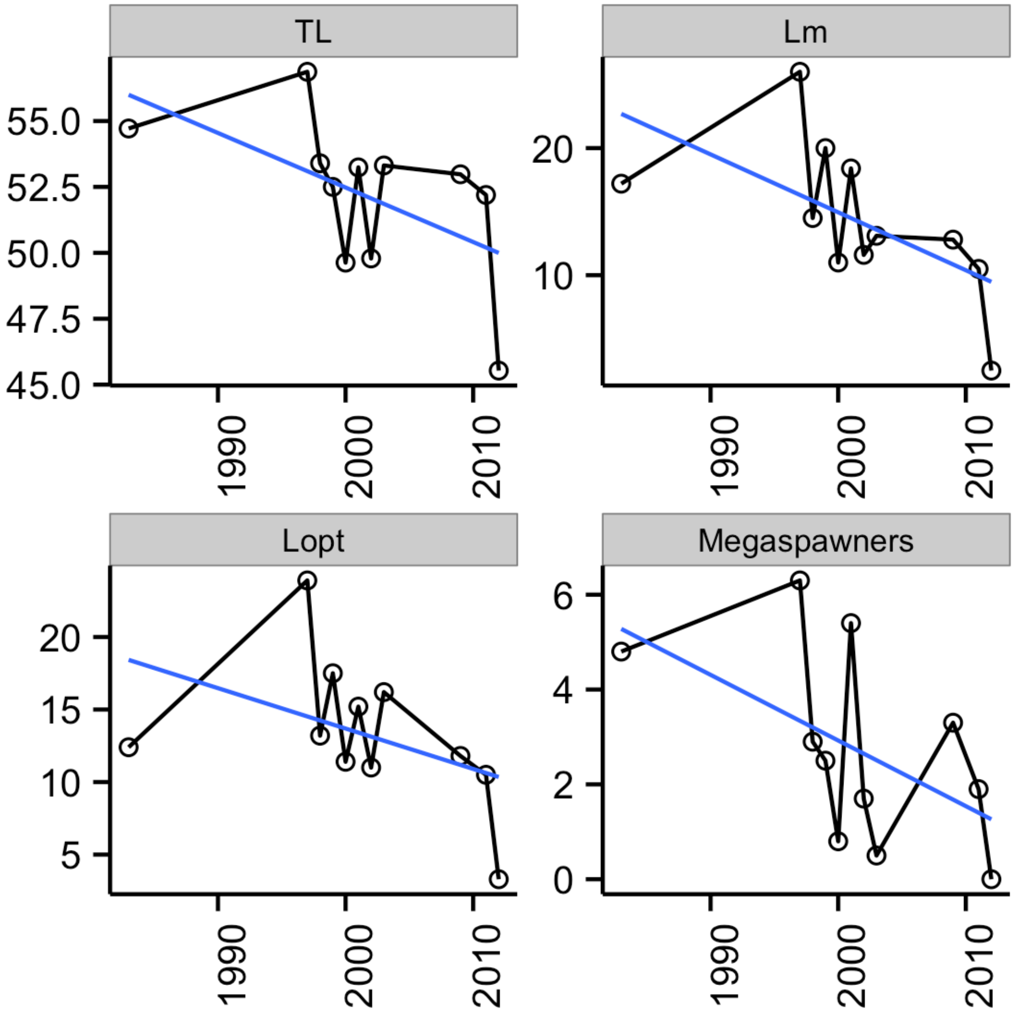


Figure 13 Trend analysis by least square linear regression for total length (cm)(TL), percentage of fish above reproductive maturity (L_m), percentage of fish within the optimum length interval (L_{opt}), and percent megaspawners for bacalao measured by Rodriguez (1983), as part as the PIMMP project (1997-2013) and this study (2011, 2012).

Chapter IV

Do no-fishing zones within the Galapagos Marine Reserve constitute sanctuary for the regionally endemic Galapagos grouper *Mycterperca olfax* (Jenyns, 1840)

Abstract

The regionally endemic Galapagos sailfin grouper (*Mycteroperca olfax)* is a highly prized fish for the artisanal fishers in the Galapagos archipelago that is listed as Vulnerable (VU) by the IUCN due to its restricted geographical range and evidence of fisheries declines. Fishing regulations for finfishes within the Galapagos Marine Reserve include a zonation scheme, with no-take areas, a licensing system, gear restrictions, a ban on industrial fishing vessels, and a ban on capture and marketing of sharks, yet there are no specific management regulations for bacalao, making the no-take areas the only respite from fishing pressure for the species. Currently there is no consensus on the effect of the no-take areas for bacalao, we therefore set out to evaluate this effect in terms of catch and size differences of fish. We additionally looked at patterns of home fidelity and explored knowledge of zonation of the marine reserve by local fishers. We found that there was no identifiable effect in the size or composition of the landings of bacalao among areas, with similar results for CPUE and the metrics used to assess the status of the fishery. Bacalao showed relatively high site fidelity that suggests movement at the scale of 1000s of meters. The lack of discernible protected area effect suggests that fish inside the reserves are still under fishing pressure. We found that there is a general lack of knowledge of the zonation scheme by fishers, which could result in unwitting poaching inside protected areas. Lack of enforcement and community support can explain the lack of observed effect. Fishers perceive that that they should be more involved in scientific research aimed at advising fisheries, and that such involvement via intensive education programs might result in increased commitment to regulations and preventing non-compliance.

Introduction

Since the 1940s the regionally endemic Galapagos sailfin grouper (*Mycteroperca olfax*, locally called bacalao) has been a highly prized fish for the artisanal fishers of the Galapagos archipelago. While landings of this species comprised nearly the entire catch during the beginnings of the fishery (Reck, 1983), current landing compositions place the contribution of bacalao at 17% of the total (Schiller et al., 2014). This shift in composition of landings, along with a restricted geographical range and evidence of fisheries declines have led the IUCN (International Union for Conservation of Nature) to list bacalao as Vulnerable (VU) (Bertoncini et al., 2008).

The Galapagos archipelago, encompassing an area of approximately 133.000 km^2, encloses the Galapagos Marine Reserve (GMR), which was the first marine reserve to be established in Ecuador and in 2001 was included in the UNESCO World Heritage Sites (Heylings, Bensted-Smith & Altamirano, 2002). Within the GMR fishing regulations for finfishes include a zonation scheme, with no-take areas, a licensing system, gear restrictions (e.g. spearfishing and long-lining), a ban on industrial fishing vessels, and a ban on capture and marketing of sharks (Castrejón et al., 2014). However, there are no specific management regulations for bacalao (e.g. total allowable catch, size limits, fishing seasons, or selectivity regulations for the hook and line fishery). Currently, approximately 75% of the GMR is open to fishing, with 8% of the marine area in no-fishing zones (but allowing tourism), 12% in conservation zones (scientific research with permit only), and 5% in specially managed zones (e.g. Ports). Extractive uses are prohibited in the conservation and tourism zones, although many fishers are unaware of or do not abide by established no-fishing boundaries, resulting in poor compliance with zonation ((Murillo et al., 2002)).

In lieu of fishery management regulations, bacalao relies on the effect of these no-fishing areas to get a respite from fishing pressure; However, the effect of these areas have yet to show positive results (Nicolaides et al., 2002). Positive effects of protection in marine fish include increases in biomass, higher densities, and fish of larger size (Rakitin & Kramer, 1996; Bohnsack, 1998; Roberts et al., 2001; Galal, Ormond & Hassan, 2002; Pelletier et al., 2005a). Nevertheless, these positive effects are subject to time spanned since the protection was enabled (Claudet et al., 2008), reserve size (Afonso, Fontes & Santos, 2011), and protection from fishing (Kritzer, 2004).

Because of the high commercial, cultural, and ecological importance of bacalao for the Galapagos, this study is aimed at evaluating the effect of the no-take areas in terms of bacalao, assessing the degree of site fidelity of the species, and exploring the knowledge of the zonation scheme by fishers. It is expected that these results will provide baseline information needed by the management authorities in the Galapagos to help enact bacalao-specific regulations.

Methods

We assessed the effectiveness of the current zonation of the GMR for bacalao by comparing the landings from fishing activities between areas open and closed to fishing. The current zonation of the island includes five zones: ports, conservation, fishing, tourism and special use (Castrejón & Charles, 2013) (Fig. 14). Extractive use is allowed in the fishing zone, and it is forbidden in the conservation and tourism zones. For the purposes of this study we lumped the conservation and tourism zones, where fishing is banned, and will refer to them henceforth as the closed zone. Fishing areas will be referred to as the open zone.

Because MPA's have a social component, we explored fisher's perceptions and knowledge of the current zonation scheme of the GMR by means of semi-structured interviews.

Fishing trips

We accompanied local fishers on fishing trips aimed at catching bacalao. Across all trips fishers employed the traditional artisanal hand-line method locally called "empate". We fished at locations in both the open and the closed zones off the islands of Isabela, Santa Cruz, and Santiago (Fig 14), where most of the fishing targeting bacalao occurs. Site location was selected based on fishers Local Ecological

Knowledge (LEK), which ensured that our sampling was consistent with contemporary artisanal fishing activities. In areas closed to fishing, fishers used the locations they frequented before the GMR zonation was implemented. Fishing around the island of Isabela was done by opportunistically accompanying fishers on their daily trips; Therefore, we do not have as many sites in the closed area for this island.

We fished during the months of April to June 2012, from daybreak until ca. 16:00 h. At each of the GMR zones (open vs. closed), fishers were asked to conduct fishing activities as they normally would; We only asked them to use boundaries set in the GPS to ensure that they stayed within a given zone for a given period of time. Fishing activities involved 2 fishers, each with an empate rigged with 3 hooks. At each of the selected fishing sites a GPS coordinate was taken, and as fish were caught and landed an observer recorded their Total Length (TL) to the nearest centimeter and the time of capture. Fishers kept the catch, which was later taken by them to market.

Interviews

In order to examine the perceptions of fishers towards the GMR zonation we used questionnaire-based interviews. Fishers were approached at the main landing sites on the islands of Santa Cruz and San Cristobal between February and April 2012. Previous conversation with fishers and other scientists highlighted fishers' aversion towards long interviews. We therefore designed a semi-structured and standardized questionnaire composed of 11 questions that took ca. 20 minutes to complete.

Maps are a good way of interacting with fishers (Bergmann et al., 2004) and are valuable for collecting information on LEK (Friedlander et al., 2003), (Bergmann et al., 2004). We tested knowledge of the zonation of the GMR with the aid of a blank map, where fishers were asked to draw the zonation scheme around the island they normally fished. A drawback of this approach is the inability to discern between a null answer arising from lack of knowledge, and a null answer resulting from inability to identify landmarks on the map; In other words does a blank answer represent an inability of the fisher to read the landmarks on the map and orient himself, or does it mean that the fisher does not know where a given feature is on a map? In order to deal with this issue we asked fishers to indicate their usual fishing and bait collecting spots, allowing us to assess whether a fisher could properly orientate himself on the map.

Trained Charles Darwin Foundation personnel administered the questionnaire by approaching fishers at the landing dock and asking permission to conduct an interview. Based on previous work with fishers and the Galapagos National Park rangers, we found that fishers were easier convinced to participate when approached by personal not directly involved with the management authorities; Furthermore, interviewers participating in this survey had previously gained the fishers' trust by working closely with them and by guaranteeing their answers would be anonymous. To ensure an adequate number of responses we used the snowball sampling technique (Goodman, 1961), where following each survey the interviewed fisher was asked to suggest a fellow fisher to be interviewed. These individuals were then sought out, asked to participate in the interview, and asked to recommend another fellow fisher to participate in the survey. In no instance did any fisher refuse to cooperate in our surveys.

Acoustic monitoring

We employed an array of acoustic monitoring receivers (Vemco™ VR2W) setup on the islands of Santa Cruz and Bartolome (Fig 14). At each monitoring station a single receiver was moored 5 m off the bottom, and left to listen continuously along a single channel (69 kHz) for the presence of coded pulse acoustic transmitters. The acoustic transmitters employed in this study included Vemco V9-2H (estimated battery life 150 days), V9-2L (estimated battery life 313 days), V13-1L (estimated battery life 625 days), and V13-1H (estimated battery life 539 days), each with a detection range of ~200m. Each acoustic transmitter emits a pulse of closely spaced “pings” at 69 kHz at ~60 second intervals, and each pulse uniquely identifies a transmitter. A successful detection comprised the receiver decoding a given pulse, which was in turn stored in the receiver’s memory and included the date and time, as well as the acoustic transmitter’s unique identification.

Acoustic arrays on each island were set across different habitat types. For the island of Santa Cruz all receivers were located in areas characterized by low habitat structure but with occurrences of smaller pockets of high rugosity areas (rocky structure). Since fishers look for these areas of higher rugosity with an eco-sounder to target bottom fish, we used the same areas to evaluate patterns of site fidelity in bacalao. We setup a total of 6 acoustic monitoring stations at Santa Cruz, ranging in depth from 15-20m. Because we were interested in differences in patterns of site fidelity among habitat types, we deployed a second array comprising 4 receivers off the island of Bartolome; This array was deployed along a dropoff habitat at depths ranging 14-18m. One of the acoustic arrays was range tested using V13-1H and V13-1L tags, set to pulse every 15 seconds. The tags were secured to a line and dropped at distances of 50m, 150m, and 200m away from the receiver and left at each location for an hour, the starting and end times of each test were recorded, and percent detections received were calculated as the percentage of recorded detections over the number expected during the deployment time.

Bacalao were acoustically tagged on four opportunities off the island of Santa Cruz during the months of December 2010, February 2011, June 2011, and December 2012, and on one opportunity at the island of Bartolome on April 2013. At each of the acoustic stations, in the vicinity of the acoustic receiver within (~50 m), we fished for bacalao from a fisher skiff using hand line. Captured fish were slowly brought to the surface, placed in containers full of sea water with an aerator, their air bladder was vented using a 17 gauge hypodermic needle, and left to recover for ~15 minutes. Once recovered, fish were taken from the holding tank and placed on a padded mat and wrapped in a wet towel that covered the eyes and left the abdomen exposed. Transmitters were inserted in the fish through a small incision performed in the abdominal wall, with the size of the incision dependent on transmitter size. The incision was closed with surgical sutures. Fish were then placed back in the holding tank and left to recover for another ~10 min, after which fish were gently moved overboard and held until they swam away. Total handling time outside of the water for the surgical procedure was ~90 seconds.

Data Analysis

Status of the stock between open and closed areas

We assessed the status of the bacalao stock in areas open and closed to fishing using the three simple indicators proposed by Froese (2004), which were: 1) percentage of mature fish in the catch, 2) percentage of fish of optimum length in the catch, and 3) percentage of mega-spawners in the catch (Froese, 2004). To calculate the percentage of mature fish in the catch we used the estimate of L50 of 65.3 cm obtained from Usseglio et al., (2015). Optimum length at catch, as defined by Froese (2004), is the length were the maximum yield and revenue can be obtained from each fish, and was estimated using the empirical relationships between optimum length and L infinity (L∞), derived from the equation (Lopt<-(10^(1.0421*log10(L∞)-0.2742))) (Froese, 2000). Using an estimate of Loo of 110 (Usseglio et al., 2015) resulted in an estimate for Lopt of 71.3cm TL (60.2-84.4 ± se). This size was used to calculate the optimum length interval, defined by (Froese, 2004) as fish within ± 10% optimum length, (64.2 and 78.4 cm TL). Lastly, the proportion of mega-spawners, referring to the fraction of old and mature fish in the total catch and was defined as fish of a size larger than optimum length plus 10% by Froese (2000), or the upper limit of the L_{opt} interval (78.4 cm TL).

These indicators helped us characterize the stocks of bacalao given that in a healthy stock it would be expected that most fish caught are larger than the size of median maturity, that a very large proportion of the catch is within the optimum length interval, and that there are 30–40% mega-spawners in the landings. The values for megaspawners represent a healthy age structure in a population where there is no fishery maximum size limit, and no size specific gear selectivity (Froese, 2004), such as is the case for the bacalao artisanal fishery within the GMR.

The proportions estimated for each of the above indicators at each of the islands and zones were compared by multiple chi square tests.

Catch Per Unit Effort (CPUE)

Catch per unit of effort (CPUE) for each of the sampling sites was calculated as CPUE=C/h, where C is total catch and h is the fishing time in hours. We expressed CPUE as KG*Fisher^{-1}*Hour^{-1}. We used these data to test the hypothesis that there were significant differences in CPUE between open and closed zones. For this we used a factorial ANOVA in which island and zone were factors and CPUE was the response variable. Normality of the ANOVA residuals was assessed graphically by means of quantile-quantile plots, and tested for statistical significance by means of a Shapiro-Wilk's test. Non-normality of the residuals led to log+1 transformation of raw data to achieve normality. Post hoc comparisons, of the log-transformed data were assessed by means of a Tukey test.

Size differences

Differences in size class distributions of bacalao between open and closed zones were assessed using a 2-sample Kolmogorov–Smirnov test. Additionally, a chi square test of homogeneity was performed by lumping landings in 10 cm size class bins and comparing the proportion per bin among zones for the same island. Lastly, significant differences in the mean size of bacalao caught in open and closed zones was tested by means of a factorial ANOVA, where TL was the response variable and island and zone were factors.

Awareness of zonation

The maps drawn by fishers' were scored as low, medium, or high quality depending on their level of knowledge of the zonation of the GMR. Fishers who either left the map blank, or failed to correctly geographically identify any of the zonation areas were scored as low. Medium levels of knowledge to fisher maps were those on which zonation was drawn in wrong areas, or labeling of zones was wrong (e.g., a tourism zone labeled as a conservation area), but at least some of the zoned areas were identified and labeled correctly. High ratings were given to maps for fishers who drew zonation that agreed with the actual location and zoning type for the GMR. The percentage of each level of fishers' knowledge of GMR zoning was calculated by island and Pearson's Chi square test for differences among fishers.

All analyses were performed using the statistical software R (Ver 3.0.2) (R Development Core Team, 2013), plotting was done using the package ggplot2 (Wickham, 2009), and data manipulation was done using the package reshape (Wickham, 2007).

Acoustic monitoring

Residency times for bacalao were calculated as the total of number of days the fish was detected over the total number of days the fish remained at large, where our threshold for detections was setup as one successful detection per day. Median residency time between islands was compared by means of a Wilcoxon signed-rank test. Diel and temporal patterns of behavior were explored using the Fast Fourier Transformation (FFT) to decompose time series data into component frequencies that are then visualized to identify dominant patterns in a plot of components versus period. FFT was applied for data summarized by hour for each bacalao.

Permission statements

This research was conducted under permits PC-19-11, PC-24-13, and PC-25-14 from the Galapagos National Park, animal use approval by the Animal Care & Use Committee, University of Hawai'i, protocol number 11-1284, use of interview data provided by the Charles Darwin Foundation was except from federal regulations pertaining the protection of human research participants under permit CHS#22922 from the Human Studies Program at the University of Hawai'i.

Results

Status of the stock between open and closed areas

We fished a total of 365 bacalao at 43 sites around the islands of Isabela, Santa Cruz, and Santiago (Table 4). Overall mean TL of bacalao caught in the fishing trips was 45.5 cm (± 8.2 sd), with a range from 20 to 73 cm TL.

Overall, the percentage of fish above size of maturity was very low, with no significant differences in proportions ($\chi^2_{(1,\,n=365)}$ = 0.075, p>0.05) between the closed (2.1% n=2) and open (2.7% n=7) zones. The percentage of fish within the Lopt interval was very low, and the proportions were not significantly different ($\chi^2_{(1,\,n=365)}$ = 0.01, p>0.05) closed zones (2.1% n=2) vs. open zones (3.7% n=10). And lastly, there were no mega-spawners in any of the zones.

The proportion of mature bacalao, and fish within the L_{opt} interval in the catch as a function of islands and zones is plotted on Fig 15; there were no significant differences in the proportion of fish above size of maturity within the catch for the island of Santa Cruz ($\chi^2_{(1,\,n=365)}$ = 0.05, p>0.05), and Santiago ($\chi^2_{(1,\,n=365)}$ = 0.02, p>0.05). The island of Isabela could not be tested because the closed zone had zero fish above size at maturity. In terms of the percentage of fish within the optimal length interval, the proportions between open and closed zones were not significantly different for the island of Santa Cruz ($\chi^2_{(1,\,n=365)}$ = 3.5, p>0.05), Santiago ($\chi^2_{(1,\,n=365)}$ = 0.4, p>0.05), and the island of Isabela could not be tested because the closed zone had zero fish within this range.

CPUE among zones

CPUE across all islands and zones ranged between 1.6 and 6.1 kg*fisher^{-1}*hour^{-1}. Mean CPUE for the island Isabela was higher in the open zone (2.8 Kg*Fisher^{-1}*Hour^{-1} ±3.4 sd) than the closed zone (2.4 kg*fisher^{-1}*hour^{-1} ± 2.4 sd). Similarly, the island of Santiago had higher CPUE in the zone open than the closed zone (6.1 kg*fisher^{-1}*hour^{-1} ±3.8 sd vs. 3.1 kg*fisher^{-1}*hour^{-1} ± 4.4 sd). Conversely, the island of Santa Cruz exhibited a reverse pattern with higher CPUE in the closed zone (3.9 $kg*fisher^{-1}*hour^{-1}$ ± 3.9 sd) than the open zone (1.7 $kg*fisher^{-1}*hour^{-1}$, ± 1.6 sd) (Fig. 16).

The factorial ANOVA of log transformed CPUE data resulted in no significant differences in CPUE among islands ($F_{2,1}=1.9$, $p>0.05$), zones ($F_{1,2}=0.1$, $p>0.05$), or the interaction term ($F_{2,51}=2.9$, $p>0.05$).

Size class analysis of landings

The larger bacalao were caught on the open zones in all three islands (Table 1), ANOVA resulted in significant differences in mean TL among islands ($F_{2,1}=4.7$, $p<0.05$), with the islands of Isabela and Santiago being significantly different ($p<0.05$), however there were no significant differences in mean TL between zones ($F_{1,2}=1$, $p>0.05$), or the interaction term between island and zone ($F_{2,359}=0.1$, $p>0.05$). The KS test resulted in no significant differences in size class distributions between closed and open zones for the islands of Isabela (D=0.11, $p>0.05$), Santa Cruz (D=0.17, $p>0.05$), and Santiago (D=0.2, $p>0.05$) (Fig 17). The chi square test of homogeneity resulted in no significant difference in the proportion of fish in each size bin class between open and closed zones for the islands of Santa Cruz ($\chi^2_{(4, n=365)} = 0.12$, $p>0.05$), Santiago ($\chi^2_{(4, n=365)} = 0.13$, $p>0.05$), and Isabela ($\chi^2_{(4, n=365)} = 0.1$, $p>0.05$).

Awareness of zonation

Our interviews comprised a total of 26% of the active registered fishers in the GMR (104 of 400). Most of the interviewed fishers resided on San Cristobal (58%, n=60), followed by Santa Cruz (40%, n=42), and Isabela (2%, n=1). Only three fishers live on the island of Floreana and logistical and cost constraints precluded us from interviewing them. Of the fishers interviewed, 42% were born in the Galapagos Islands, while the remaining 58% originated from mainland Ecuador. Fishers' ages ranged from 19 to 80 yrs (mean = 42 ± 11.3 sd). Due to the small number of fishers interviewed on Isabela, we focused our analysis on the islands of San Cristobal and Santa Cruz.

Knowledge of zonation

Of the 104 surveys, 17 maps were left blank for both fishing grounds and zonation and were, therefore, not included in the analysis. There was no significant difference between islands in fishers' ability to locate their fishing and bait collecting grounds with 95% of fishers in San Cristobal and 93% in Santa Cruz correctly identifying these on the map ($\chi^2_{(1,\, n=87)}$=0.03, p=0.84). When asked if the different management zones were easy to find using the current zonation, 87% of fishers responded positively, 10.8% said that zones were not easy to find, and the remaining 2.2% did not answer. Even though the majority of fishers on both islands thought that the zones were easy to find (San Cristobal 82.5% vs. Santa Cruz 94.3%), there were significant differences between islands in the proportion of fishers who thought that the zones were not easy to find (San Cristobal 15.8% vs. Santa Cruz 5.8%) ($\chi^2_{(1,\, n=87)}$=8.22, p=0.04).

When asked to draw the locations of the conservation, fishing, tourist, and special use areas in the GMR on the same map, 49.4% of interviewed fishers exhibited low knowledge of zonation, 33.7% medium knowledge, and the remaining 16.9% good knowledge. At an island level, there were significant differences in the proportion of fishers who exhibited no knowledge of zonation (San Cristobal 56.9% vs. Santa Cruz 37.9%)($\chi^2_{(1,\, n=87)}$=9.7, p=0.007).

Acoustic monitoring

A total of 64 bacalao were tagged, 49 off the island of Santa Cruz and 15 off the island of Bartolome (Table 5). Range testing resulted in between 2-10 % detections at a distance of 200m from the receiver (Table 6). For the island of Bartolome we had 2 sets of tags: one set of new tags from a new order and tags that had been recovered by fishers and were being re-deployed. We noticed that all of the tags from a same order (new tags) had very low detection rates (Table 5, fish gr-49-2 through gr_58), when compared to the older tags (Table 5, fish gr_60 through gr_64). Residency rates were significantly different between these sets of data with the new set 11.2%(±14.4 sd) and the old tags 68.9%(±27.2 sd) ($\chi^2_{(1,\, n=15)}$=35.5,

$p<0.01$),which makes us suspect transmitter failure in these new tags. We therefore, removed these tags from further analysis.

At an island level, study length days for Santa Cruz ranged from 134-625 (Fig. 18), and for Bartolome it was 242 days (Fig. 19). Residency rates overall were of 43.8% (±33.8% sd), with an island-level residency for Santa Cruz of 48% (±33.1% sd), and 68.9% (±27.2% sd) for Bartolome. There was a significant difference in median residency time between Santa Cruz and Bartolome ($W = 52.5$, $p < 0.05$). Fish at Santa Cruz remained within a given receiver, while fish at Bartolome moved among receivers (Fig 20). Diel patterns for fish at both islands suggested the highest peaks of activity at 24-hour intervals, followed by minor peaks at 8 and 12-hour intervals. These intervals coincide with higher detections during the day (Fig. 21).

For the island of Santa Cruz, three of the acoustically tagged individuals were recaptured, fishers captured fish gr_43 and the last detection corresponds to the same day it showed at the market. Fish gr_20 and gr_34 were recaptured while fishing at the same location at which they were tagged.

Discussion

Management of the artisanal fisheries that target finfish within the GMR rely mostly on small no fishing zones for the protection of these species. One of the traditionally most important species is the Galapagos sailfin grouper (bacalao), whose fishery has shown evidence of overexploitation (Reck, 1983; Coello, 1989; Ruttenberg, 2001; Schiller et al., 2014). To date, the effect of protection that bacalao receives from the zonation scheme within the GMR is still unclear (Nicolaides et al., 2002). We found that there was no identifiable effect in the size or composition of the landings of bacalao among areas, with similar results for CPUE and the metrics used to assess the status of the fishery. High estimates of size fidelity for bacalao suggest that fish have relatively restricted movements, and therefore that fish inside the reserves are still under fishing pressure. Limited enforcement capacity by local authorities, as well as a general lack of knowledge of the zonation scheme by fishers could explain the lack of effect detected.

No-take reserves have been shown to be successful in protecting groupers, as was reported by Beets & Friedlander (1999), who found an increase in size and improvement in sex ratios for a small bodied Caribbean grouper. Similarly, Galal, Ormond & Hassan (2002) found increases in mean length for groupers of the genus *Mycteroperca.* While effective MPA's have been shown to include higher densitie, and fish of larger size than adjacent non-protected areas (Rakitin & Kramer, 1996; Bohnsack, 1998; Galal, Ormond & Hassan, 2002; Pelletier et al., 2005b), this was not evident in our results. While it is recognized that the amount of sampling days limited our ability to see effects in the CPUE, differences in size composition should have been apparent. The lack of clear differences in the size composition of landings between the open and closed areas suggests no apparent effect of the GMR zonation on bacalao. This lack of effect can be the result of several factors, among which, and based in our objectives, we can assess the relative importance of: time of establishment of the MPA, size of the MPA, enforcement and compliance.

Effect of protection in groupers has been suggested to take between 4-5 years, as shown by García-Charton et al. (2008) for the Mediterranean. The current zonation scheme of the GMR has been in place since 2006 (Castrejón & Charles, 2013), so it would be expected for effects of protection to be evident. The three metrics used to assess overfishing, at a broad level, resulted in no significant differences in the proportion of the landings below size of maturity or within the L_{opt} interval among open and closed areas. Furthermore, there were no mega-spawners in any of the zones. This lack of positive effect of no-take zones suggests that these fish are still under fishing pressure, as fishing selectively targets larger individuals (Erzini et al., 2006), and therefore fish size is a good indicator of fishing pressure (Pelletier et al., 2005b), (Götz et al., 2013).

If the time since establishment of the reserve encompasses the time for results to show, then a possibility is that reserve size might be an issue. While the relative magnitude of the effect of a protected area has been suggested to be dependent on reserve size and age (Claudet et al., 2008), for groupers even small reserves have been shown to have positive effects (Afonso, Fontes & Santos, 2011). Our results from the acoustic sampling show that bacalao are relatively sedentary, and they move at scales of roughly a kilometer. Significant differences in residency rates among islands are related to the setup of the acoustic arrays at each island. At Santa Cruz there were no fish that appeared in a receiver different than the one in which they were tagged, given that receivers were 2-8 km away from each other. For Bartolome, receivers were 300-600m away from each other, and it was possible to detect movement of fish among these receivers at scales of ~ 1 km. While small in area, the existing no-fishing zones within the GMR are at scales larger than 1 Km, suggesting that fish movement is not likely to explain the lack of zonation success.

In addition to home range, protection from fishing has been suggested as being more important than other factors (such as habitat) in explaining the patterns of abundance for some fisheries species (Abesamis, Russ & Alcala, 2006), (Friedlander, Brown & Monaco, 2007). Lack of compliance with zoning can erode the positive effects of MPAs (Kritzer, 2004), which can in turn be the likely factor explaining the lack of no-take area effectiveness observed in our study. In the Galapagos, (Ruttenberg, 2001) found significantly lower biomass of commercial fisheries species, particularly bacalao, among areas that were heavily fished compared to lightly fished areas. Lack of effectiveness of the GMR zonation in protecting bacalao can result from a variety of factors that can include lack of enforcement and lack of compliance.

The GMR is a large area of > 133,000 km^2, and effectively enforcing zoning across this large expanse would require considerable resources in both infrastructure and personnel. Information on enforcement is scarce and outdated. However, as of 2007 there were 49 park personnel to operate 11 vessels and 2 remote bases, with 32 unfilled positions suggesting lack of resources for enforcement activities (Reyes & Murillo, 2007). Enforcement operations have historically focused on preventing poaching and illegal exploitation of sea cucumbers, rather than enforcing coastal zoning compliance with most of the fishing related infractions related to ocean going vessels carrying shark fins, or shark bodies (Reyes & Murillo, 2007). Little capacity to appropriately enforce the extent of the GMR would leave compliance of the zoning in the hands of the fishers themselves. Assessing the level of enforcement of regulations within the GMR is beyond the scope of this paper, but the available information suggests that this area could be improved on.

Lack of knowledge of the zonation rather than a genuine attempt to violate regulations can be a major reason for fishing in closed areas (McClanahan, 1999). Our results show that while fishers reported that the different zones were easy to find (87%), when given a blank map, only 16.9% of respondents exhibited good knowledge of the zonation, suggesting that this lack of knowledge of zonation can lead to fishing inside the no-take areas. This low awareness of zonation could arise from the implementation process, which included a launch in 1999 without a complete zoning scheme, then a consensus approval of zonation in 2000 lacking offshore boundaries, with a final physical demarcation of the zones not occurring until 2006 (Edgar et al., 2004), (Reyes & Murillo, 2007), (Castrejón & Charles, 2013). Since the implementation of the zonation of the GMR, the offshore limits of each of the zones have still not been adequately marked. This lack of demarcation has led to fishing in closed areas by fishers who were unaware of the zonation (Edgar et al., 2004). For example, Murillo et al. (2002), estimated that ca. 10% of sites fished for sea cucumbers within the GMR were within areas closed to fishing. While illegal in the Galápagos, spearfishing is still practiced (Ruttenberg, 2001). During this study we noted fishing with spearguns and surface supplied air inside the no-take zone off the island of Santiago, and anecdotal evidence from other fishers we spoke to during this study confirms that this fishing practice is still common in the Galapagos. Spearfishing can be extremely effective at removing large quantities of groupers from an area, as shown by Hamilton, Potuku & Montambault (2011), who estimated that over two consecutive nights spearfishers removed 30% of a large spawning aggregation of squaretail grouper (*P. areolatus*) in the Solomon Islands.

Our results failed to provide conclusive evidence of positive impacts of the current GMR zoning for bacalao, suggesting that fish within the closed areas are still under fishing pressure. One of the main reasons given as to why MPAs fail to achieve conservation objectives stems from the lack of enforcement and community support (Gjertsen, 2005), especially in a reserve as large as the GMR, with a zonation scheme that spans the whole archipelago. While the lack of knowledge of zonation observed by us can result in fishers unknowing fishing in closed areas within the GMR, Castrejón & Charles (2013) suggested that the biggest challenge to the effectiveness of the zoning of the GMR is the re-establishment of credibility and legitimacy of the reserve and its management. While fishers are involved in the management of the GMR, as they have a representative in the Inter-Institutional Management Authority (IMA), the maximum decision making body in the GMR, they perceive that they should be more involved in scientific researched aimed at advising fisheries (Usseglio, Schuhbauer & Friedlander, 2014). This perception of a need to be more involved in research can result in an increase the sense of belonging of stakeholders in the community, increase levels of communication, strengthen trust, and foster educational opportunities (Viteri & Chávez, 2007; Usseglio, Schuhbauer & Friedlander, 2014). Involvement of fishers through intensive education programs can result in increased commitment to regulations and prevent non-compliance (Svensson, Rodwell & Attrill, 2010).

References

Abesamis RA., Russ GR., Alcala AC. 2006. Gradients of abundance of fish across no-take marine reserve boundaries: evidence from Philippine coral reefs. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16:349–371.

Afonso P., Fontes J., Santos RS. 2011. Small marine reserves can offer long term protection to an endangered fish. *Biological Conservation* 144:2739–2744.

Beets J., Friedlander A. 1999. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, Epinephelus guttatus, in the US Virgin Islands. *Environmental Biology of Fishes* 55:91–98.

Bergmann M., Hinz H., Blyth R., Kaiser M., Rogers S., Armstrong M. 2004. Using knowledge from fishers and fisheries scientists to identify possible groundfish “Essential Fish Habitats.” *Fisheries Research* 66:373–379.

Bertoncini AA., Gerhardinger LC., Sadovy YJ., Rocha L., Choat JH., Ferreira B., Craig M. 2008.*Mycteroperca olfax*. *Available at www.iucnredlist.org* (accessed May 12, 2015).

Bohnsack JA. 1998. Application of marine reserves to reef fisheries management. *Australian Journal of Ecology* 23:298–304.

Castrejón M., Defeo O., Reck G., Charles A. 2014. Fishery science in Galapagos: From a resource-focused to a social–ecological systems approach. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 159–185.

Castrejón M., Charles A. 2013. Improving fisheries co-management through ecosystem-based spatial management: The Galapagos Marine Reserve. *Marine Policy* 38:235–245.

Claudet J., Osenberg CW., Benedetti-Cecchi L., Domenici P., García-Charton J-A., Pérez-Ruzafa Á., Badalamenti F., Bayle-Sempere J., Brito A., Bulleri F., Culioli J-M., Dimech M., Falcón JM., Guala I., Milazzo M., Sánchez-Meca J., Somerfield PJ., Stobart

B., Vandeperre F., Valle C., Planes S. 2008. Marine reserves: size and age do matter. *Ecology Letters* 11:481–489.

Coello S. 1989. Consideration on the management of the Galapagos Bacalao fishery *Myceroperca olfax* (Jenys) (Pisces:Serranidae). *Revista Pacifico Sur*:705–709.

Edgar GJ., Bustamante RH., Farina JM., Calvopina M., Martinez C., Toral-Granda MV. 2004. Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve. *Environmental Conservation* 31:212–218.

Erzini K., Gonçalves JMS., Bentes L., Moutopoulos DK., Casal JAH., Soriguer MC., Puente E., Errazkin LA., Stergiou KI. 2006. Size selectivity of trammel nets in southern European small-scale fisheries. *Fisheries Research* 79:183–201.

Friedlander A., Nowlis JS., Sanchez JA., Appeldoorn R., Usseglio P., McCormick C., Bejarano S., Mitchell-Chui A. 2003. Designing effective marine protected areas in seaflower biosphere reserve, colombia, based on biological and sociological information. *Conservation Biology* 17:1769–1784.

Friedlander AM., Brown E., Monaco ME. 2007. Defining reef fish habitat utilization patterns in Hawaii: comparisons between marine protected areas and areas open to fishing. *Marine Ecology-Progress Series* 351:221–233.

Froese R. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. *Journal of Fish Biology* 56:758–773.

Froese R. 2004. Keep it simple: three indicators to deal with overfishing. *Fish and Fisheries* 5:86–91.

Galal N., Ormond RFG., Hassan O. 2002. Effect of a network of no-take reserves in increasing catch per unit effort and stocks of exploited reef fish at Nabq, South Sinai, Egypt. *Marine and freshwater Research* 53:199–205.

García-Charton JA., Pérez-Ruzafa A., Marcos C., Claudet J., Badalamenti F., Benedetti-Cecchi L., Falcón JM., Milazzo M., Schembri PJ., Stobart B., Vandeperre F., Brito A., Chemello R., Dimech M., Domenici P., Guala I., Le Diréach L., Maggi E., Planes S. 2008. Effectiveness of European Atlanto-Mediterranean MPAs: Do they accomplish the expected effects on populations, communities and ecosystems? *Journal for Nature Conservation* 16:193–221.

Gjertsen H. 2005. Can Habitat Protection Lead to Improvements in Human Well-Being? Evidence from Marine Protected Areas in the Philippines. *World Development* 33:199–217.

Goodman LA. 1961. Snowball sampling. *The Annals of Mathematical Statistics* 32:148–170.

Götz A., Kerwath SE., Attwood CG., Götz A. 2013. A step-by-step framework to assess benefits of established temperate marine protected areas. *South African Journal of Science* 109:1–9.

Hamilton RJ., Potuku T., Montambault JR. 2011. Community-based conservation results in the recovery of reef fish spawning aggregations in the Coral Triangle. *Biological Conservation* 144:1850–1858.

Heylings P., Bensted-Smith R., Altamirano M. 2002. Zonificación e historia de la Reserva Marina de Galápagos. In: Dan, Edgar GJ eds. *Reserva Marina de Galápagos. Linea Base de la Biodiversidad.* Fundación Charles Darwin y Servicio Parque Nacional de Galápagos, Santa Cruz, 10–22.

Kritzer JP. 2004. Effects of noncompliance on the success of alternative designs of marine protected-area networks for conservation and fisheries management. *Conservation Biology* 18:1021–1031.

McClanahan TR. 1999. Is there a future for coral reef parks in poor tropical countries? *Coral reefs* 18:321–325.

Murillo JC., Martinez P., Toral V., Hearn A. 2002. Pepino de mar. In: Danulat E, Edgar GJ eds. *Reserva marina de Galapagos: Linea base de la biodiversidad*. Galapagos: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 176–196.

Nicolaides F., Murillo JC., Toral V., Reck GK. 2002. Bacalao. In: Danulat E, Edgar GJ eds. *Reserva marina de Galapagos: Linea base de la biodiversidad*. Galapagos: Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, 146–165.

Pelletier D., García-Charton JA., Ferraris J., David G., Thébaud O., Letourneur Y., Claudet J., Amand M., Kulbicki M., Galzin R. 2005a. Designing indicators for assessing the effects of marine protected areas on coral reef ecosystems: A multidisciplinary standpoint. *Aquatic Living Resources* 18:15–33.

Pelletier D., García-Charton JA., Ferraris J., David G., Thébaud O., Letourneur Y., Claudet J., Amand M., Kulbicki M., Galzin R. 2005b. Designing indicators for assessing the effects of marine protected areas on coral reef ecosystems: A multidisciplinary standpoint. *Aquatic Living Resources* 18:15–33.

Rakitin A., Kramer DL. 1996. Effect of a marine reserve on the distribution of coral reef fishes in Barbados. *Marine ecology progress series. Oldendorf* 131:97–113.

R Development Core Team. 2013. R: A language and environment for statistical computing. *Foundation for statistical computing, Vienna, Austria* Ver 3.0.2.

Reck GK. 1983. The coastal fisheries in the Galapagos Islands, Ecuador. Descriptions and consequences for management in the context of marine environmental protection and regional development. Doctoral thesis Thesis. Germany: Christian-Albrechts Univ.

Reyes H., Murillo JC. 2007. Efforts to control illegal fishing activities in the Marine Reserve. In: CDF, GNP & INGALA ed. *Galapagos Report 2006- 2007*. Puerto Ayora, Ecuador, 23–30.

Roberts CM., Bohnsack JA., Gell F., Hawkins JP., Goodridge R. 2001. Effects of marine reserves on adjacent fisheries. *Science* 294:1920–1923.

Ruttenberg BI. 2001. Effects of artisanal fishing on marine communities in the Galapagos Islands. *Conservation Biology* 15:1691–1699.

Schiller L., Alava JJ., Grove J., Reck G., Pauly D. 2014. The demise of Darwin's fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands: The demise of Darwin's fishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

Svensson P., Rodwell LD., Attrill MJ. 2010. The perceptions of local fishermen towards a hotel managed marine reserve in Vietnam. *Ocean & Coastal Management* 53:114–122.

Usseglio P., Friedlander AM., DeMartini EE., Schuhbauer A., Schemmel E., Salinas-de-León P. 2015. Improved estimates of age, growth and reproduction for the regionally endemic Galapagos sailfin grouper *Mycteroperca olfax* (Jenys,1840). *PeerJ* 3:e1270:21.

Usseglio P., Schuhbauer A., Friedlander A. 2014. Collaborative Approach to Fisheries Management as a Way to Increase the Effectiveness of Future Regulations in the Galapagos Archipelago. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 187–202.

Viteri C., Chávez C. 2007. Legitimacy, local participation, and compliance in the Galápagos Marine Reserve. *Ocean & Coastal Management* 50:253–274.

Wickham H. 2007. Reshaping data with the reshape package. *Journal of Statistical Software* 21.

Wickham H. 2009. *ggplot2: elegant graphics for data analysis*. Springer, New York.

Tables

Table 4 Number of sampling sites per island and zone within island, total number of bacalao caught at each site, mean tl (sd), maximum and minimum landed size of bacalao fished in the islands of Isabela, Santa Cruz and Santiago.

Island	Zone	Sites (n)	N	Mean TL (sd)	Max TL (cm)	Min TL (cm)
Isabela	Closed	4	21	44.2 (±6.9)	59	27
Isabela	Open	10	196	44.7 (±7.9)	71	20
Santa Cruz	Closed	8	49	44.9 (±7.9)	72	30
Santa Cruz	Open	12	37	46.54 (±10.1)	73	35
Santiago	Closed	4	27	47.69(±6.7)	66	35
Santiago	Open	5	35	48.81(±8.4)	67	32

Table 5 Bacalao tagged with acoustic transmitters in the islands of Santa Cruz and Bartolome.

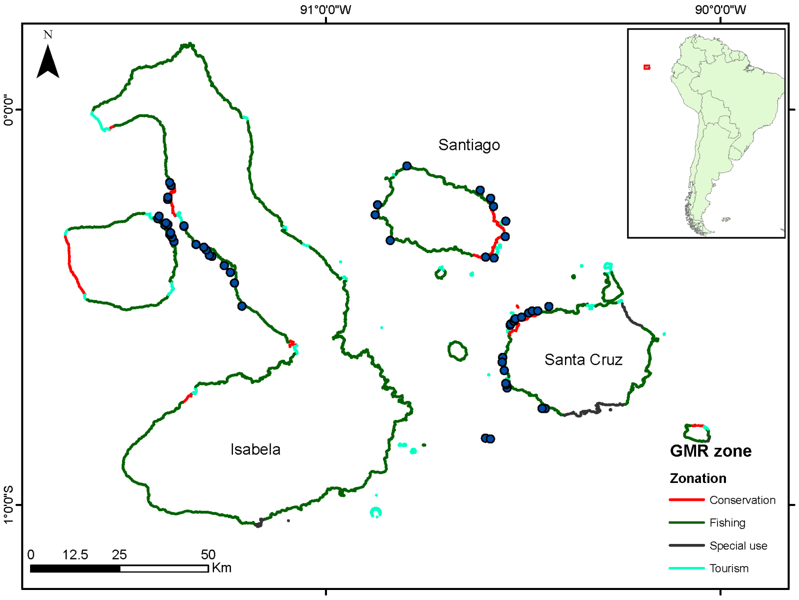
Island	ID	Tag type	TL (cm)	Days at large (truncated to battery life)	Residency (%)
Santa Cruz	gr_01	V9-2H	47	150	56.7
	gr_02	V13-1L	45.5	625	55.7
	gr_03	V13-1L	58.5	421	2.6
	gr_04	V13-1L	52	625	23.7
	gr_05	V13-1L	50.5	625	99.9
	gr_06	V13-1L	65	466	12.7
	gr_07	V13-1L	52.5	521	39.0
	gr_08	V13-1L	56	465	53.1
	gr_09	V13-1L	38	625	50.9
	gr_10	V13-1L	53	426	100.0
	gr_11	V13-1L	51	465	48.2
	gr_12	V13-1L	52.5	625	99.5
	gr_13	V13-1L	43.5	625	95.4
	gr_14	V13-1L	57	519	0.2
	gr_15	V13-1L	52	519	38.0
	gr_16	V13-1L	38.5	519	12.5
	gr_17	V13-1L	57.5	520	77.5
	gr_18	V9-2L	48	313	70.9
	gr_19	V9-2L	42	313	1.0
	gr_20	V9-2L	42	313	85.6
	gr_21	V9-2L	59	313	51.4
	gr_22	V13-1H	36.5	539	27.5
	gr_23	V9-2L	47	313	27.2
	gr_24	V9-2L	47.5	313	27.2
	gr_25	V9-2L	42.5	313	26.5
	gr_26	V9-2L	41	313	47.3
	gr_27	V9-2L	41.5	313	6.1
	gr_28	V9-2L	32.5	313	47.3
	gr_29	V9-2L	52.5	313	80.2
	gr_30	V9-2L	44	313	23.6
	gr_31	V9-2L	39	313	0.3
	gr_32	V9-2L	35	313	41.9
	gr_33	V9-2L	49	313	27.2
	gr_34	V9-2L	42	313	86.3
	gr_35	V9-2L	46	313	35.1

Island	ID	Tag type	TL (cm)	Days at large (truncated to battery life)	Residency (%)
Bartolome	gr_36	V9-2L	53.5	313	45.7
	gr_37	V13-1H	42	234	0.9
	gr_38	V13-1H	61	134	5.2
	gr_39	V13-1H	55	234	0.4
	gr_40	V13-1H	52	426	98.8
	gr_41	V13-1H	53	429	32.9
	gr_42	V13-1H	45	135	47.4
	gr_43	V13-1H	63	417	97.4
	gr_44	V13-1H	42	429	35.4
	gr_45	V13-1H	48	426	95.5
	gr_46	V13-1L	65	436	100.0
	gr_47	V13-1L	52	436	99.3
	gr_48	V13-1L	45.5	436	74.5
	gr_49_1	V13-1L	48	429	40.8
	gr_49_2	V13-1H	50	429	40.8
	gr_50	V13-1H	53	242	6.6
	gr_51	V13-1H	47	242	5.4
	gr_52	V13-1H	56	242	34.7
	gr_53	V13-1H	54	242	0.4
	gr_54	V13-1H	53	242	11.2
	gr_55	V13-1H	55	242	2.9
	gr_56	V13-1H	47	242	5.8
	gr_57	V13-1H	52	242	2.1
	gr_58	V13-1H	48	242	2.1
	gr_60	V13-1H	46	242	100.0
	gr_61	V13-1H	49	242	50.6
	gr_62	V13-1H	51	242	93.7
	gr_63	V13-1H	47	242	36.8
	gr_64	V13-1H	50	242	63.6

Table 6 Range test for Vemco V13-1 tags for the islands of Santa Cruz and Bartolome

	Santa Cruz		**Bartolome**
	High	**Low**	**High**
50m	100	90	100
150m	42	8	44
200m	3	2	10

Figures



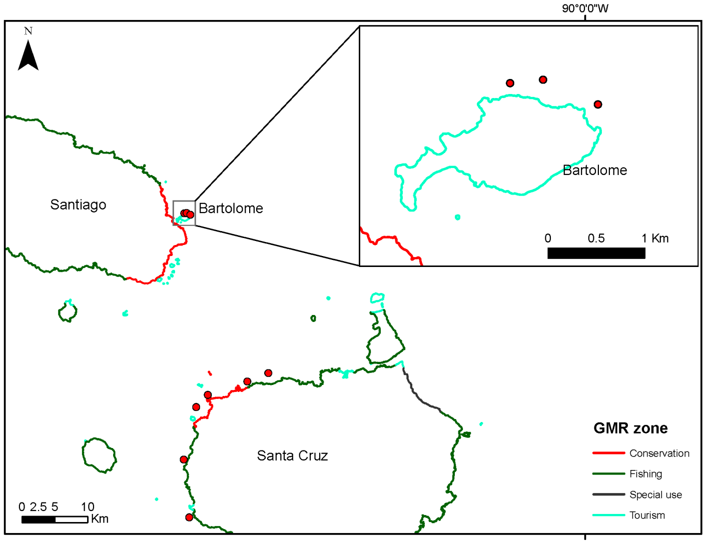


Figure 14 Top: Study area, inset map location of the GMR. Blue dots represent fishing sites, lines along shore represent zonation of the GMR. Inset map: Location of the Galapagos archipelago in relation to South America. Bottom: Location of the acoustic receivers in the islands of Santa Cruz and Bartolome. Inset map: Close up of the receiver array in the island of Bartolome.

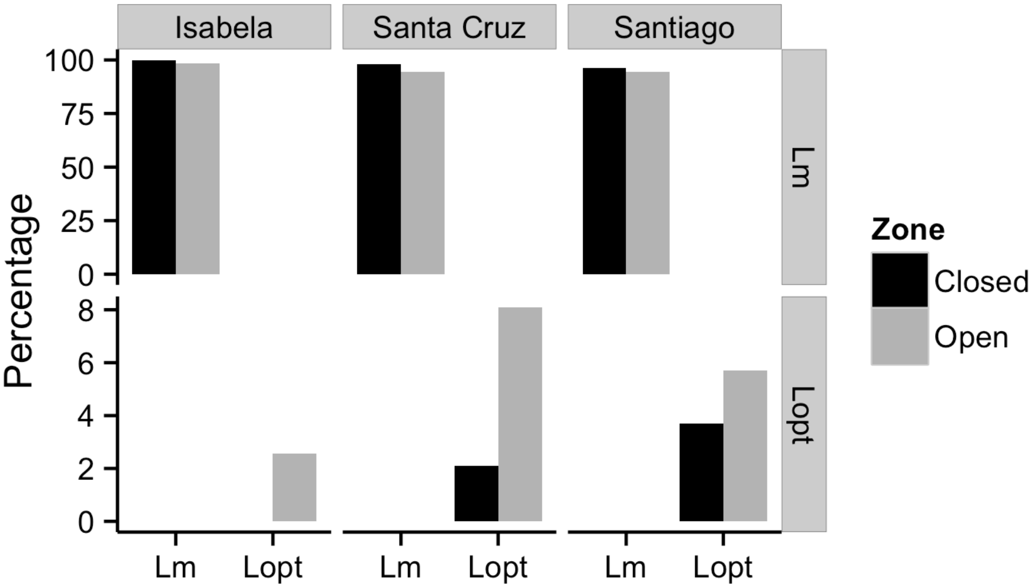


Figure 15 Indicators used to assess the state of the bacalao stocks among the islands of Isabela, Santa Cruz and Santiago. Lm=percent of the catch below size at maturity, Lopt=fish within the optimal fishing interval.

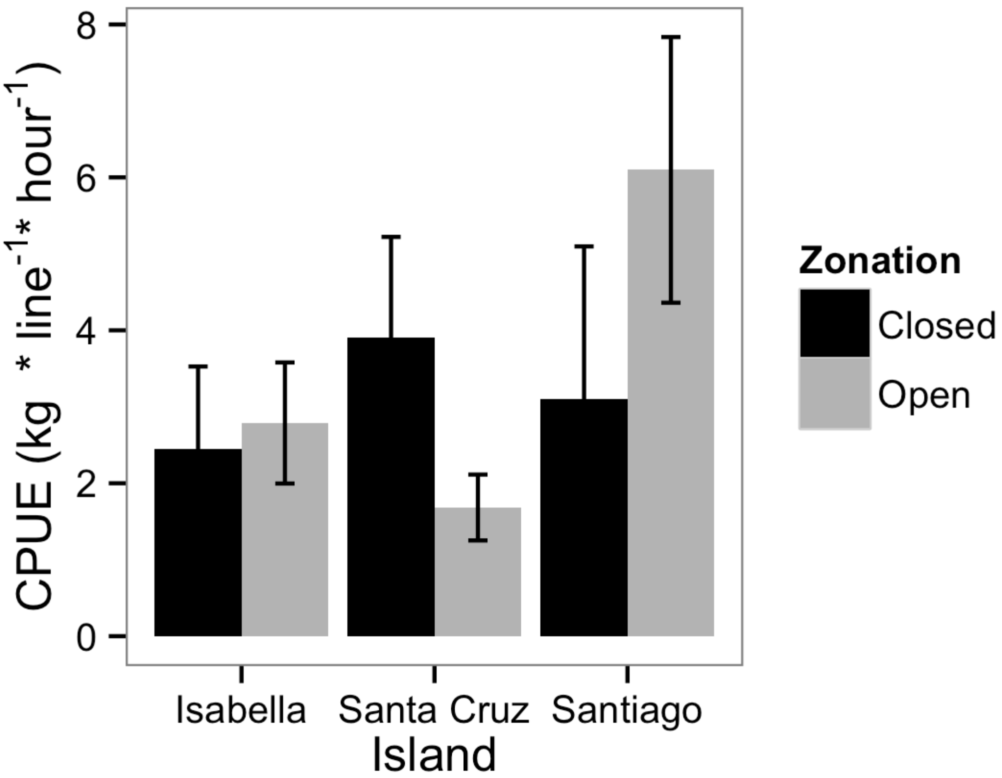


Figure 16 Mean CPUE obtained from fishing trips to the island of Santa Cruz, Isabela, and Santiago.

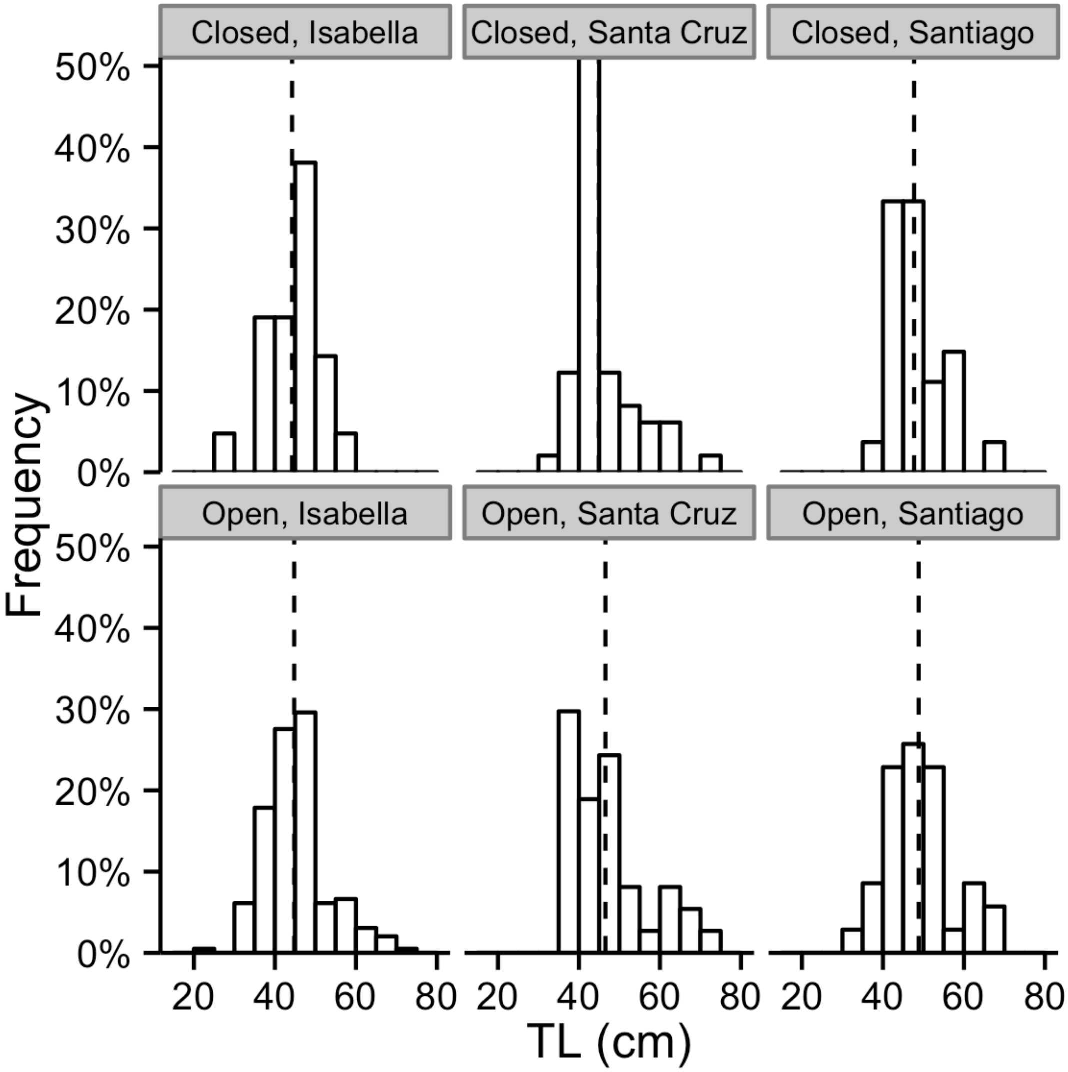


Figure 17 Size class distribution of landings among areas, dashed line represents the mean TL.

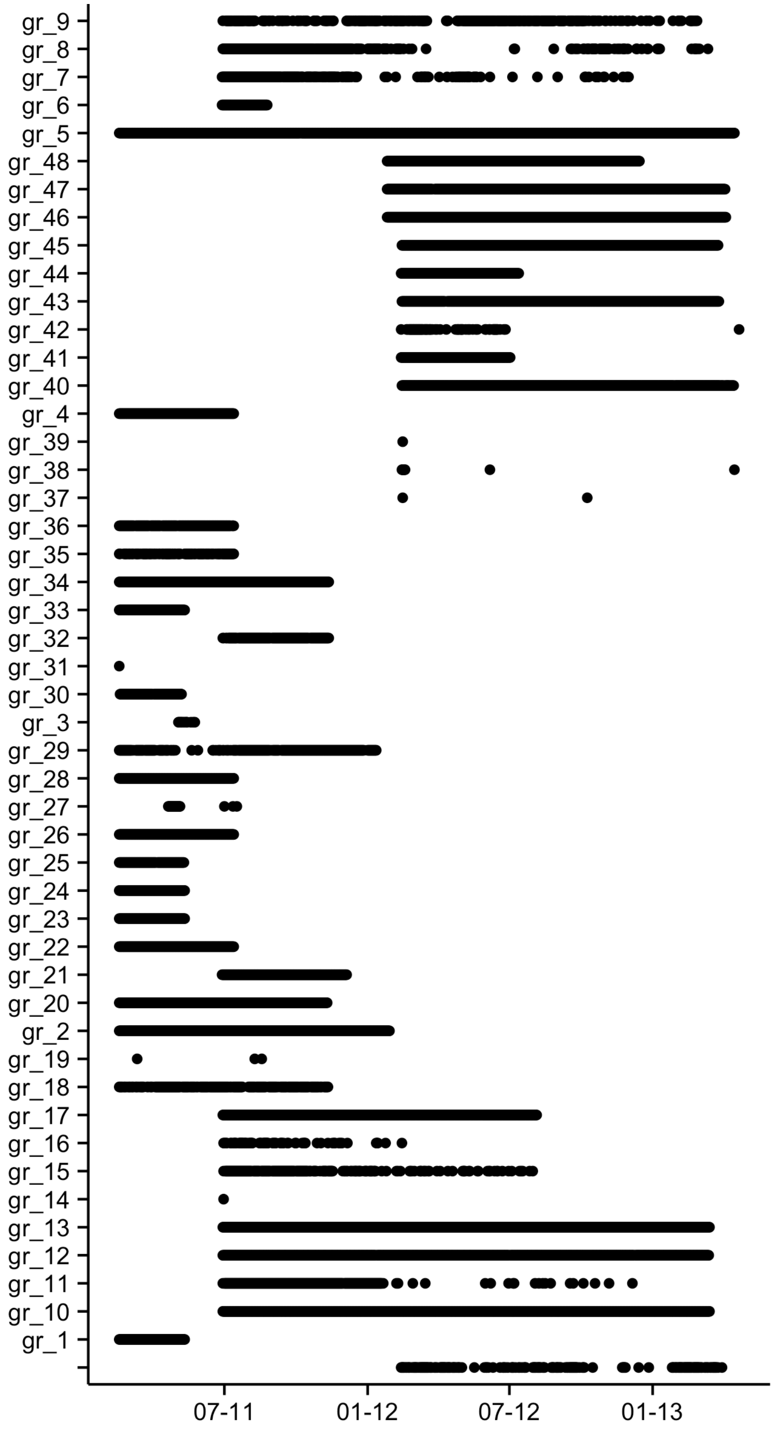


Figure 18 Acoustic detections for tagged bacalao in the island of Santa Cruz.

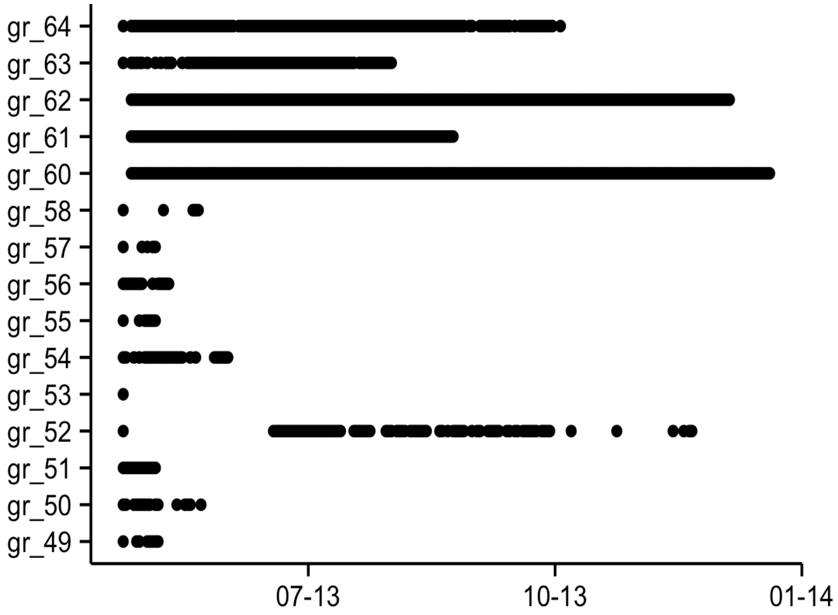


Figure 19 Acoustic detections for tagged bacalao in the island of Bartolome.

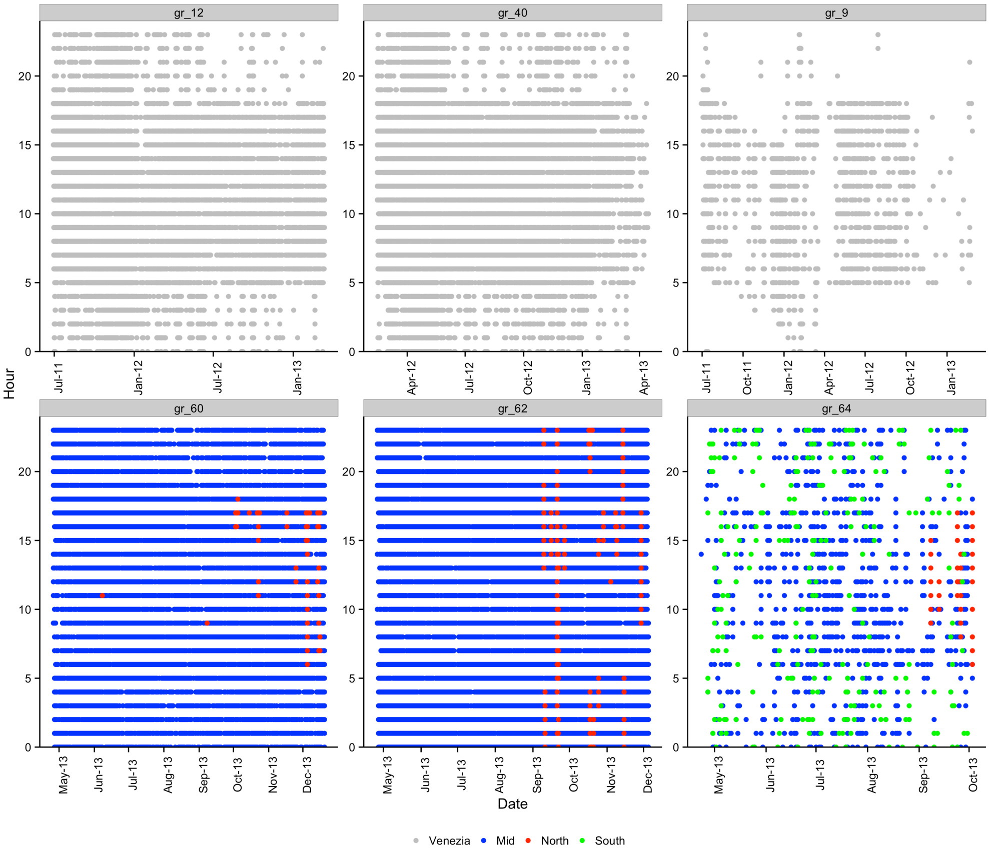


Figure 20 Detections of acoustically tagged bacalao, top three panels fish tagged in Santa Cruz, bottom three panels fish tagged in Bartolome. Dots are color coded by monitoring station.

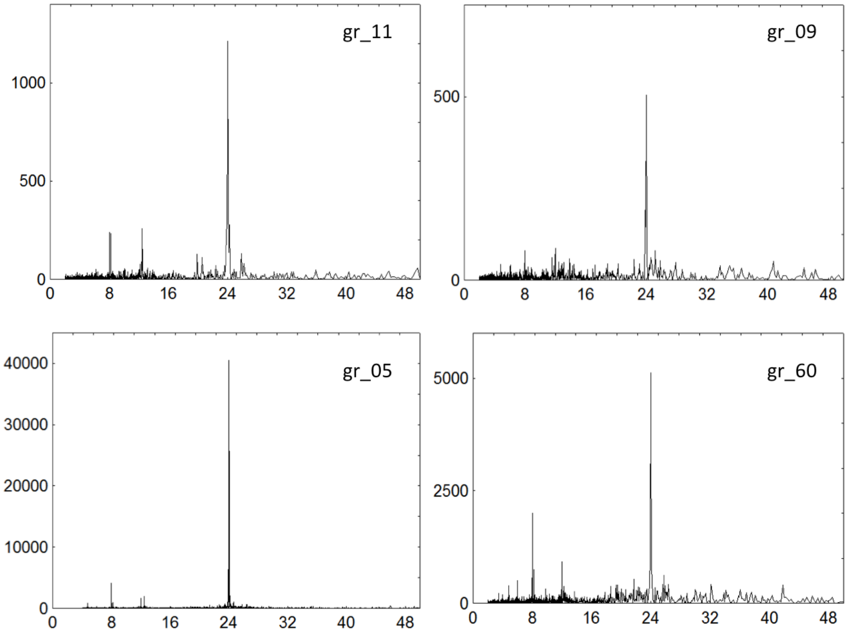


Figure 21 Example of time series analysis (FFT) for four acoustically tagged fish.

Chapter V

Collaborative approach to fisheries management as a way to increase the effectiveness of future regulations in the Galapagos archipelago

Abstract

For coastal fishing communities it is becoming increasingly clear that the key to success is community-based co-management, which incorporates all users and stakeholders in the decision making processes about fisheries management. Established regulations can easily fail due to the lack of enforcement. However, many coastal communities do not have the economic resources for the necessary enforcement and therefore rely on compliance by fishers. There are about 400 local fishers in the Galapagos Marine Reserve (GMR), who depend on the exploitation of coastal resources for their living. Evidence shows that the GMR suffers from the lack of compliance; coastal resources have been overexploited and illegal fishing has been observed. The results of interviewing 26% of Galapagos' active fishers show: no trust in scientific studies; lack of income alternatives provided; no dissemination of results and lack of participation of fishers in the studies. We argue that the above-mentioned problems can be tackled by using a collaborative approach, which includes fishing community members in each step of the research process. This would foster a sense of belonging of the Galapagos fishers, who are currently an underrepresented part of the already established co-management scheme, which has yet to achieve sustainable fisheries in the Galapagos Islands.

Introduction

The overexploitation of coastal resources has become increasingly evident around the world. Globally, around three billion people depend on seafood as their main protein source and sustainable fisheries management is the cornerstone of their livelihoods (FAO 2012). Stakeholder engagement and community-based co-management have been recognized to be essential throughout the development of any fisheries management strategy (Gutiérrez et al. 2011; Wiber et al. 2004). Co-management has many advantages which include: the enhancement of sense of ownership to encourage responsible fishing; improved management through the use of local knowledge, and increased compliance through peer pressure and fishers controlling each other (Dietz et al. 2003; Gutiérrez et al. 2011). The enforcement of fisheries regulations, especially in small-scale fishing communities, can be a huge challenge due to lack of resources and therefore largely depends on the fishers' compliance. Self-compliance can be greatly augmented through stakeholder education, understanding of need for regulations and believing in these regulations, which will ultimately result in a more effective implementation of management systems.

Fisheries management relies on fishery science and research in order to obtain the information necessary to create regulations. Because there is a human component inherent to fisheries, the inclusion of fishers in these activities is necessary. Research efforts can involve fishers in joint activities, which can be seen as ranging from cooperative approaches, where a fisher accompanies scientists, to collaborative approaches where fishers are included in all aspects of the research (NCRS 2003; Yochum et al. 2011). For co-management to function properly, a more collaborative approach to research would be a great advantage in comparison to the less involved cooperative one. This change from minimum involvement in research, toward a full immersion in all research activities leads to more transparent communications between fishers and managers, creating a stronger relationship that will result in members of the fishing community being more likely to trust the scientific results. If fishers are allowed to participate and engage in research, and understand how scientific activities are carried out and the reasons behind them, they will be more likely to comply with the management suggestions derived from the research (Johnson and van Densen 2007).

The Galapagos Islands are presented here as an example where co-management has been established, but has struggled, particularly due to the lack of compliance of fishers to fisheries regulations (Castrejón and Charles 2013; Hearn 2008). The Galapagos Islands marine ecosystem, unique for its endemism, has been subjected to heavy fishing (small-scale and industrial) of invertebrates and reef fishes since the 1960s (Reck 1983). However, lack of regulations and the explosive growth of the sea cucumber and lobster fisheries have led to the collapse of the sea cucumber fishery and severe declines in spiny lobster stocks (Bucaram et al. 2013; Hearn 2008). In order to protect the islands' unique biodiversity and stop the overexploitation of these commercially valuable resources, the Galapagos Marine Reserve (GMR) was created. The GMR, which covers 133,000 km^2 , was established in 1998, and with it a ban on industrial fisheries and a zonation plan of all coastlines enacted. Along the coastline fishing is permitted in 78% of the area, with the remaining 22% made up of several no-take areas and tourist visitor sites (Calvopina and Visaira 2005).

With the creation of the GMR, a fisheries management plan was established based on a co-management regime to promote sustainable marine resource use. The objectives of this plan included the creation of refuge zones where fished species could recover from overexploitation and fishing could be regulated through other management tools such as closed seasons, total allowable catch limits, and minimum landing sizes in order to achieve sustainable fisheries. One of the main goals of developing a co-management scheme, rather than a top-down approach, was to reduce conflicts among the various users (SPNG 1998). However, the major fisheries resources have been overexploited with no signs of recovery and many ensuring challenges, both on institutional as well as socio-economical levels, still have to be overcome (Castrejon and Charles 2012; Hearn 2008; Wolff et al. 2012). Today in the Galapagos Archipelago there are 1035 registered fishers, of which only about 470 are active (GNP Database 2011). This reflects the economic downturn in the Galapagos fishing sector, as fishing has not been profitable for most fishers, who have over the last 10 years left the islands or discontinued fishing commercially. Furthermore, the currently active fishers can still be considered an overcapacity as resources are not recovering and continue to decline. To reduce overexploitation and secure the fishers' livelihoods, alternative income opportunities have already been proposed in Galapagos.

Tourism in Galapagos is booming and it is the archipelago's main source of income (Epler 2007), with an increase from 40,000 tourists in the 1990s to 185,000 in 2011 (GNP database 2011). Therefore, it is not surprising that fishers are attracted to this lucrative sector while fishing has become less profitable. Linking fishers to the tourism sector has been attempted in the Galapagos by offering two different alternatives: access to an activity called "Pesca Artesanal Vivencial (PAV)" (recreational fishing for tourists) in 2005, and granting them new permits for tourism operations in 2009 (Palacios and Schuhbauer in press).

The implementation of the co-management regime has been a step in the right direction; however, the established objectives have not yet been met mainly due to the lack of enforcement and high rates of non-compliance (Castrejón and Charles 2013). The latter results from the view held by some fishers that fisheries management strategies, especially no fishing zones, are illegitimate (Viteri and Chávez 2007). The root of non-compliance can be traced back to the lack of credibility and legitimacy that fishers have in the co-management of the GMR (Castrejón and Charles 2013). This lack of credibility leads to unhealthy relationships between the fishing communities and management agencies, (Kaplan and McCay 2004; Hartley and Robertson 2006; Johnson and van Densen 2007), which have the ultimate effect of undermining management actions. These injurious relationships can be alleviated by collaborative research, where close participation by all parties involved creates avenues of communication that ultimately build, rebuild, or strengthen communications (Conway and Pomeroy 2006; Hartley and Robertson 2006).

In this study, we evaluated the perceptions that Galapagos' fishers have of scientific research aimed at advising management, their perception towards participation in these studies, and sources of income alternatives to fishing. We propose a collaborative research approach as a way to increase the effectiveness of future management efforts in the Galapagos.

Methods

Study area

The GMR lies 1000 km off the coast of Ecuador, and encompasses a marine area of approximately 133,000 km2. Three major ocean currents are responsible for its unique dynamics and variability of weather, climate, biodiversity, and productivity. The Galapagos is renowned for its high endemism in both marine and terrestrial ecosystems. Commercial fishing started in the 1940s when the Galapagos sailfin grouper (Bacalao, Mycteroperca olfax) represented almost the totality of landings (Reck 1983). In the early 1990s most of the fishing effort switched to sea cucumbers, but by 1994 the fishery had collapsed, resulting in a five year moratorium followed by a strict management plan starting in 1999 (Murillo et al. 2002). As a consequence of this enormous growth in the sea cucumber fishery, the number of fishers in the GMR increased from 392 in 1993, to nearly 1000 in 2001, when the official registration for local fishers was closed (Bremner and Perez 2002; GNP 2011). However, of these 1035 registered fishers only about 400 are currently active. Over the years, levels of conflict between the fishing and management communities have been evident. Some of these conflicts escalated in the past and fishers organized public protests, took over park offices, and even kidnapped giant land tortoises (Finchum 2002). This conflict has origins, according to fishers, in the lack of inclusion of the fishing community in the decision making process, and the lack of communication between the Galapagos National Park (PNG) and the Charles Darwin Foundation and the fisher community (Finchum 2002).

Interviews

In order to test the perceptions of today's fishers towards research aimed at advising management suggestions, we used a questionnaire that was presented to participants. Fishers were approached at the main fishing landing sites on the islands of Santa Cruz, San Cristobal, and Isabela between February and April 2012. Previous conversation with fishers, and other scientists informed us of their aversion towards long interviews; therefore we designed a structured and standardized questionnaire composed of 11 questions that would take about 20 minutes to complete. The questions were designed to explore the perceptions of fishers towards research used to advise management, the way fishers felt about being included in these studies, and preferences for alternative sources of income. Trained personnel administered the questionnaire by approaching fishers at the landing dock and asking permission to conduct an interview. In no case did an approached fisher refuse to participate in the survey. Based on previous work with the fishers and the park rangers, we found that fishers were more easily convinced to participate when approached by personal not directly involved with PNG, since Park personnel are viewed as regulators and enforcers. Furthermore, interviewers who participated in this survey had already gained the fishers' trust by working closely with them and by guaranteeing their anonymous status. We therefore felt that the majority of the answers we were given were truthful. Following each interview, fishers were asked to suggest fellow fishers who could be interviewed; these individuals were sought out and usually found at the fishing dock where they were also asked to participate in the interview. This use of the snowball sampling technique (Goodman 1961) helped ensure an adequate number of responses.

Analysis

Because we used an open questionnaire, fishers were able to broadly express their perceptions in an unstructured way. Open-ended questions were chosen because they can provide details in fishers "own words", and can provide a rich description of the respondent reality (Jackson and Trochim 2002). Answers given by fishers were coded by manually developing a coding scheme based on the frequency of the most common answers. A manual coding scheme was chosen because of the ability of a human reader to detect the subtleties and nuances of the answers given by fishers. Numerical summaries of the coded answers were generated by calculating the percentage of answers within each of the resulting coded categories.

Results

Out of the 400 active registered fishers in the Galapagos Islands we interviewed a total of 104, accounting for 26% of the total fishing population. Fishers were interviewed in San Cristobal (58%), Santa Cruz (40%), and Isabela (2%). No fishers from Floreana were interviewed as only three fishers live there. Overall, age ranged from 19 to 80 years, with a mean age of 42.4 years old and a standard deviation of 11.3 years. The median age was also 42 years old. Regarding place of origin, 42% of interviewed fishers were born in the Galapagos Islands while the remaining 58% were originally from mainland Ecuador. Reported place of origin per island and age classes are reported on Table 7.

Survey results

Perception of fishers towards research aimed at advising management

We explored the perceptions that fishers have towards studies aimed at providing scientific data meant to be used to advise fisheries management and policies within the GMR. 51% of respondents perceived these studies as being bad, 26% perceived them as good, 22% had mixed feelings about them, and the remaining 1% did not answer. The main reasons associated with the negative perception to these studies included: lack of trust in the studies (16.7%), lack of identification of alternative sources of income resulting from fishing closures (13.1%), lack of dissemination of results (11.9%), lack of inclusion of fishers in studies (7.1%), studies aimed at closing fisheries (6.0%), studies resulting in limits to income (6.0%), and others (Table 8).

Among the main reasons associated with the positive perception towards management and scientific studies are: the conservation of species (62.0%), research activities are good (8.0%), education of fishers (6.0%), preventing overfishing (4.0%), and others (Table 9).

Perception of fishers towards participation in studies

Fishers were asked what they thought about the inclusion of the fishing sector in studies aimed at producing management regulations. While the majority of fishers think that they should be included in these studies (89.5%), a few (7.6%) thought that the fishing sector should not be included, and the remaining 2.9% did not have an opinion.

The reasons to include fishers in the investigations aimed at advising management included: the benefit from using fishers' knowledge (52.9%), including the needs fishers have (14.7%), and improving fishers' education (5.9%). The remaining reasons are given in table 10.

The reasons given by fishers as the rationale for why they should not be included in research aimed at producing management regulations included the lack of trust in studies (14.3%), data going to the Galapagos National Park (14.3%), regulations lower the fishers' income (14.3%), fishers make bad decisions (14.3%), national park office makes their own decisions regardless (14.3%), the way things are should not change (14.3%), and authorities, not fishers, should make the regulations (14.3%).

Income alternatives to fishing

When asked whether they would rather work in a field other than fishing, 60.4% of interviewed fishers responded positively while the remaining 39.6% answered that they would not like to stop fishing. The main alternative activities identified by fishers, who would like to work in something different, include no answer (55.7%), tourism (22.6%), public sector (3.3%), mechanic (3.3%), driver (3.3%), biologist (1.6%), commerce (1.6%), boat pilot (1.6%), working on anything on dry land (1.6%) and private sector (1.6%). When asked whether they wanted their children to work in the fishing sector 91% responded that they would like their children to work in a different sector, 4% responded that they would like their children to work in the fishing sector and the remaining 5% did not answer. The career paths/activities that fishers would like to see their children are on Table 11.

Discussion

The few management regulations that exist in the GMR suffer from non-compliance and although a comprehensive management plan was established in 2005 (Castrejon and Charles 2013), it could be argued that current management regulations are not adequate; however, in this study we only discuss the problems attached to non-compliance by fishers to current regulations as well as how this can be improved.

Perceptions towards scientific studies

Our results indicated that only 26% of the fishers in the GMR are in favor of scientific studies aimed at advising management. Nearly half of the opinions associated with the negative perception of these studies were: lack of trust in studies, lack of alternative sources of income provided by these studies, no dissemination of results, and lack of participation by fishers. These reasons represent a common thread, which can be interpreted as the lack of participation of the fishing sector in research carried out to assist in fisheries management in the Galapagos. This lack of participation results in a lack of buy-in to management regulations, which ultimately leads to lack of compliance (Viteri and Chávez 2007). Participation of fishers in research activities can be achieved by means of cooperative or collaborative approaches. In a cooperative approach, fishers join research activities by helping in data collection, or guiding scientists during fishing trips. Although these practices are common procedures in Galapagos, the involvement of fishers in developing the objectives and implementing the research is minimal. A collaborative approach, on the other hand, includes fishers in all aspects of the research. Collaborating with fishers in this sense means including them in formulating research questions, choosing a methodology, generating hypothesis, field work (data collection), data analysis, and dissemination of results (NRC 2003). However, for collaborative research to function, both the scientists and the fishers need to be willing to openly participate. The following section explores the willingness of fishers in the GMR to participate in collaborative projects.

Perceptions towards participation in scientific studies

The dominant perception among the majority of fishers is that they should be included in research activities (89.5%). This shows great promise in helping enhance future participatory research efforts in the GMR. Use of local ecological knowledge (LEK) has been shown to be a supplementary source to scientific studies in identifying nursery areas, fish diets, or when economic resources are limited, as is often the case (Poepoe et al. 2007; Le Fur et al. 2011). Resource-limited scientific endeavors can benefit greatly by using LEK and having the community participate to reduce costs of sampling (Harms and Sylvia 2008; Johnson and van Densen 2007; Hart et al. 2008), increase the sampling frequency (Conway and Pomeroy 2006), and thanks to the increase in the numbers of personnel available to collect data, the ability to generate fine-scale data (Hams and Sylva 2008).

Cooperative projects, involving the fishing community, have several benefits such as increasing the level of participation of fishers to create a sense of belonging, which results in greater compliance with regulations (Viteri and Chávez 2007). Furthermore, these projects often increase communication between the fishing and scientific community, resulting in building or strengthening trust, and fostering mutual education and knowledge exchange (Johnson and van Densen 2007). This strengthening of trust is clearly necessary in Galapagos since our results indicated that a majority of fishers had a negative perception of scientific studies and that lack of trust was specifically identified as a major reason. Of course strengthening of trust will not happen overnight, a successful collaborative project will lead to greater trust for successive projects.

Options for alternative income

The lack of providing income alternatives to fishers was one of the top reasons why fishers did not agree with current management strategies. Worldwide, alternative income sources for fishers have had mixed results due to the predilection of fishers to continue fishing (Pollnac et al. 2001; Pollnac and Poggie 2006; Cinner et al. 2009). Our results, however, suggest that in the GMR this might not be the case, as 60% of interviewed fishers responded that they would be willing to change professions, choosing the tourism sector as the main alternative. Furthermore, 91% responded that they would not like their children to work in the fishing sector.

Alternative livelihood programs have been offered to the Galapagos fishing sector, but unfortunately not been successful. The main reasons why offering recreational fishing and boat operated tourism to the Galapagos fishers have not achieved their objectives to date are: the lack of consensus among stakeholders; the lack of guidance to the fishers during the conversion process; no monitoring; no follow up, and the lack of compliance to the established regulations (Schuhbauer and Koch 2013, Palacios and Schuhbauer in press).

The problems faced by both programs, however, can be mitigated by developing long term management plans based on consensus reached by all stakeholders that would reflect the current situation realistically (Schuhbauer and Koch 2013, Palacios and Schuhbauer in press). Using a collaborative approach in the design of these plans could greatly enhance the compliance and effectiveness of these programs.

Fishers' willingness to change occupation is encouraging, and it suggests that given a stronger role in future consultation processes, they could consider alternative options that will not necessarily be related to fishing.

Drawbacks of collaborative approaches

The previous sections discuss the usefulness of collaborative projects, which would alleviate the issues expressed by fishers in the GMR. However, it is important to note that this approach is not without drawbacks that could impede the projects' effectiveness. These drawbacks include the fear by fishing communities that the data they help produce will be used against them (Conway and Potteroy 2006; Schuhbauer and Koch 2013). Our results agree with this notion, showing that some fishers perceived that scientific studies would result in regulations that would lower their income (Table 2).

The fishing sector and scientists might have different goals, and the tendency of different groups to work independently towards different goals can impair the overall effectiveness of the cooperation (Conway and Pomeroy 2006). These different goals are epitomized by fishers aiming to produce fishing regulations that would result in fewer restrictions, even if these regulations do not agree with the current state of a resource but reflect a need for income; whereas scientists might only focus on publication opportunities, or preconceived notions that conservation is the ultimate goal. Our survey found that these were indeed valid concerns, as some fishers listed "scientist interested only in their career" and "maximum allowed catch is too low" as reasons why they had negative perceptions of scientific studies (Table 2).

There could be misunderstanding about the impact that management decisions could have on the people who are being managed. Fishers' concerns with diminishing income need to be addressed and quantified. Kaplan and McCay (2004) suggest that regulators and managers should be held accountable for the social, cultural, and economic costs that result from management regulations. A collaborative approach requires the inclusion of all stakeholders from the beginning. However, groups or individuals could be unintentionally left out of this process (e.g. minorities or women), while other groups could be included after the initial stages of the process. This could lead to the exclusion of specific needs or interests by parties or individuals, which could directly result in lack of interest and ultimately non-compliance with the regulations.

Disparate technical awareness by participants can limit the efficient communication amongst all parties involved. This communication should recognize cultural differences (Gilden and Conway 2002), and ensure that all parties are "speaking the same language". A highly technical description of the parameters that go into a fisheries model might not be the best way to transmit to fishers the state of a given resource. Collaborative research projects may also suffer from lack of administrative and infrastructure support. Lastly, lack of organization within the fishing community and divergent interests among fishers make any participatory process extremely difficult (Schuhbauer and Koch 2013).

Despite these limitations, ensuring that collaborative projects are founded on a transparent process that ensures adequate communication between all parts involved can improve the effectiveness of the already established co-management, and greatly benefit future projects in the GMR.

Applying collaborative research in the Galapagos Islands

Our study suggests that fishers still do not trust the science used to establish management regulations, and note lack of dissemination of results and lack of inclusion of the fishing sector in the decision making process as reasons for this lack of trust. However, the majority of fishers are inclined to be a part of this decision making process. While cooperative projects are currently being carried out, it appears necessary that future projects should move along the cooperation-collaboration continuum towards a complete inclusion of the fishing sector in all aspects of research. While this has clearly been tried in the past with the zonation of the GMR and the establishment of fishing regulations, evidence suggests that these approached have not been completely successful (Castrejón and Charles 2013). Yochum et al. 2011 suggests a framework with eight steps that are key to the success of collaborative research projects, and we expand on these steps with suggestions from this study in Table 12.

Conclusions

The current perceptions of fishers in the GMR of scientific studies aimed at advising management regulations for fisheries are extremely negative. This can be traced back to a historical lack of involvement and trust that the fishing community has had in these studies. Cooperative research projects have been shown to increase communication between fishing communities and management entities, resulting in an increase in a sense of belonging and ultimately greater compliance. While it is recognized that this approach is not a panacea, it is definitively a step towards successfully managed fisheries in the GMR, and an improvement to the existing co-management regime.

References

Bremner MPH and Jaime P (2002) A case study of human migration and the sea cucumber crisis in the Galapagos islands. Ambio 31(4) 306-310

Bucaram SJ, White JW, Sanchirico JN, Wilen JE, (2013) Behavior of the Galapagos fishing fleet and its consequences for the design of spatial management alternatives for the red spiny lobster fishery. Ocean & Coastal Management. doi: 10.1016/j.ocecoaman.2013.03.001

Calvopina M, Visaira R (2005) Proceso de demarcación física de la zonificación consensuada de la Reserva Marina de Galapagos. In: Pasos hacia la sustentabilidad de la RMG. Proyecto conservación de la RMG. WWF/USAID. Puerto Ayora, Galápagos

Castrejón M, Charles A (2013) Improving fisheries co-management through ecosystem-based spatial management: The Galapagos Marine Reserve. Marine Policy 38:235–245. doi: 10.1016/j.marpol.2012.05.040

Cinner JE, Daw T, McClanahan TR (2009) Socioeconomic factors that affect artisanal fishers' readiness to exit a declining fishery. Conservat. Biol. 23, 124–130.

Conway FDL, Pomeroy C (2006) Evaluating the human - as well as the biological - objectives of cooperative fisheries research. Fisheries 31:447-454

Dietz, T, Ostrom, E, Stern, PC, (2003) The Struggle to Govern the Commons. Science 302:1907–1912.

Epler B (2007) Tourism, the economy, population growth, and conservation in Galapagos. Puerto Ayora. Fundación Charles Darwin.

FAO (2012) Fisheries and Aquaculture topics. The State of World Fisheries and Aquaculture (SOFIA). Topics Fact Sheets. **Text by Jean- Francois Pulvenis.** In: *FAO Fisheries and Aquaculture Department* [online]. Rome. Updated 9 July 2012. [Cited 21 March 2013].

Finchum R (2002) The beliefs & perceptions of fishermen regarding management actions, regulations, and the protection of the Galapagos marine reserve. Master's thesis, Colorado State University.

GNP Database (2001) Galapagos National Park, Puerto Ayora, Galapagos, Ecuador.

Goodman LA (1961) Snowball sampling. The Annals of Mathematical Statistics 32:148-170

Gutiérrez NL, Hilborn R, Defeo O, (2011) Leadership, social capital and incentives promote successful fisheries. Nature 470:386–389.

Harms J, Sylvia G (2000) The economics of cooperative fishery research: a survey of U.S. West Coast groundfish industry and scientists. 10 pages. In: Microbehavior and Macroresults: Proceedings of the Tenth Biennial Conference of the International Institute of Fisheries Economics and Trade, July 10-14, 2000, Corvallis, Oregon, USA. Edited by Richard S. Johnston and compiled by Ann L. Shriver. International Institute of Fisheries Economics and Trade (IIFET), Corvallis, OR, 2001. http://www.st.nmfs.noaa.gov/st5/documents/The_economics_of_cooperative_fishery_research.pdf

Hart AM, Fabris FP, Brown J, Murphy D (2008) Digital video surveys of abalone (*Haliotis sp.*) stocks by commercial fishers in western Australia. Fisheries Research 93:305–314.

Hartley TW, Robertson RA (2006) Emergence of multi-stakeholder- driven cooperative research in the northwest Atlantic: the case of the Northeast Consortium. Marine Policy 30:580–592.

Hearn A (2008) The rocky path to sustainable fisheries management and conservation in the Galapagos Marine Reserve. Ocean & Coastal Management 51:567–574

Jackson KM, Trochim WMK (2002) Concept Mapping as an Alternative Approach for the Analysis of Open-Ended Survey Responses. Organizational Research Methods 5:307–336. doi: 10.1177/109442802237114

Johnson TR, van Densen WLT (2007) Benefits and organization of cooperative research for fisheries management. ICES Journal of Marine Science 64:834–840.

Kaplan IM, McCay BJ (2004) Cooperative research, co-management and the social dimension of fisheries science and management. Mar Pol 28:257-258

Le Fur J, Guilavogui A, Teitelbaum A (2011) Contribution of local fishermen to improving knowledge of the marine ecosystem and resources in the republic of guinea, west africa. Can J Fish Aquat Sci 68:1454-1469

NRC (National Research Council). 2003. Cooperative research in the National Marine Fisheries Service. National Academies Press, Washington, D.C.

Murillo JC, Martinez P, Toral V, Hearn A (2002) Pepino de mar. In: Danulat E, Edgar GJ (eds) Reserva marina de Galapagos: Linea base de la biodiversidad. Fundacion Charles Darwin/Servicio Parque Nacional Galapagos, Galapagos, pp 176–196

Schuhbauer A, Palacios P. (in press) Turismo como una alternativa económica para los pescadores de Galápagos: Lecciones aprendidas y oportunidades. Galapagos Annual report 2011-2012. Puerto Ayora, Galapagos Islands, Ecuador.

Poepoe K, Bartram P, Friedlander AM (2007) The use of traditional hawaiian knowledge in the contemporary management of marine resources. In: Haggan N, Neis B, Baird I (eds) Fishers' knowledge in fisheries science and management. UNESCO, Paris, pp 117–141

Pollnac RB, Poggie JJ (2008) Happiness, well-being and psychocultural adaptation to the stresses associated with marine fishing. Special section on vulnerability and resilience in fisheries. Hum. Ecol. Rev. 15:194-200

Pollnac RB, Pomeroy RS, Harkes IHT (2001) Fishery policy and job satisfaction in three southeast Asian fisheries. Ocean Coastal Manage. 44: 531–544.

Reck GK (1983) The coastal fisheries in the Galapagos Islands, Ecuador. Descriptions and consequences for management in the context of marine environmental protection and regional development. Dissertation, Christian-Albrechts Univ.

Schuhbauer A, Koch V (2013) Assessment of recreational fishery in the Galapagos marine reserve: Failures and opportunities. Fisheries Research. in press

SPNG (1998) Management plan for conservation and sustainable use of the Galapagos Marine Reserve. Puerto Ayora.

Viteri C, Chávez C (2007) Legitimacy, local participation, and compliance in the galápagos marine reserve. Ocean Coastal Manage 50:253-274

Wiber M, Berkes F, Charles A, Kearney J (2004) Participatory research supporting community-based fishery management. Marine Policy 28:459–468.

Wolff M, Schuhbauer A, Castrejón M (2012) A revised strategy for the monitoring and management of the Galapagos sea cucumber *Isostichopus fuscus* (Aspidochirotida: Stichopodidae). Rev. Biol. Trop. 60:539–551.

Yochum N, Starr RM, Wendt DE (2011) Utilizing Fishermen Knowledge and Expertise: Keys to Success for Collaborative Fisheries Research. Fisheries 36:593–605.

Tables

Table 7 Reported place of origin, age group and island of residence of fishers interviewed. Results are based on structured and standardized questionnaire of 104 fishers, one interview did not have any metadata, hence the total of 103.

		Age class			
Island	**Place of origin**	**Less than 30**	**31-50**	**Older than 51**	**Grand Total**
Isabela	Manabi			1	1
San Cristobal	Balzar			1	1
	Cotopeal		1		1
	Ensenada		1		1
	Esmeraldas	1			1
	Galapagos	3	21	9	33
	Guayaquil	1	5	4	10
	Loja			1	1
	Los Rios		2	1	3
	Machala			1	1
	Mainland		1		1
	Manabi		2	1	3
	Quito			1	1
	Tangurrahua		1		1
	Valencia			1	1
	Unknown		1		1
Santa Cruz	Ecuador		1	2	3
	Esmeraldas		1		1
	Galapagos	4	7		11
	Guayaquil		3	1	4
	Guayas		1		1
	Loja		1		1
	Manabi	3	5	2	10

		Age class			
Island	**Place of origin**	**Less than 30**	**31-50**	**Older than 51**	**Grand Total**
	Manta		4		4
	Naranjito			1	1
	Puerto Lopez	1			1
	Quito			1	1
	San Borondon	1			1
	Santo Domingo		1		1
	Unknown		1	1	2
	Total	14	60	29	103

Table 8 Negative perceptions of management and scientific studies in the Galapagos Marine Reserve. Results are based on structured and standardized questionnaire of 104 fishers.

Reason	**Percent response**
No trust in studies	16.7
Studies provide no alternatives	13.1
No dissemination of results	11.9
No participation of fishers	7.1
Aimed to close fisheries	6.0
Limit income	6.0
Studies used to place regulations	4.8
Scientist work for their careers	3.6
Studies are bad	3.6
Bad choice of seasons	2.4
No need for management	2.4
National Park does not enforce	2.4
Conservation interested in money	1.2
Fishers know more	1.2
Studies result in less fishing zones	1.2
Low maximum allowed catch	1.2
Migratory species do not require studies	1.2
No need to close fisheries	1.2
Park makes the wrong decision	1.2
Park oppresses fishers	1.2
Regulations are bad	1.2
Regulations don't respect traditional fishing	1.2
Sea is inexhaustible	1.2
Some regulations are bad	1.2

Reason	Percent response
Things will not get better	1.2
Too late for regulations	1.2
Too many limits imposed on fishers	1.2
Studies used to create closed seasons	1.2
Studies are useless	1.2

Table 9 Reasons associated with positive perceptions towards management and scientific studies in the Galapagos Marine Reserve.

Reason	Percent response
Conservation of species	62.0
Good	8.0
Educate fishers	6.0
Prevent overfishing	4.0
Some regulations are good	2.0
Some studies are good	2.0
Good for socio-economic development	2.0
Being able to see changes in time	2.0
Research is good	2.0
Information about fished species	2.0
Noticeable increase in populations after closed seasons	2.0
Inclusion of fishers	2.0
Ensure sustainability for future generations	2.0
Based on population needs	2.0

Table 10 Reasons given by fishers as to why they should be included in research aimed at producing management regulations.

Reason	**Percentage**
Include fisher knowledge	52.9
Include needs from fishers	14.7
Increase fisher education	5.9
Increase information gathering	2.9
Understand fishers way of life	1.5
Fishers are interested	1.5
Studies affect fishers source of income	4.4
Fishers can help in the search for better solutions	1.5
Prevent management actions from closing all fishing sites	1.5
Fishers can help increase monitoring zones	1.5
Dissemination of results to fishers	1.5
Should also include tourism sector	1.5
Fishers can help make things right	1.5
Fishers should lead conservation efforts	1.5
Fishers can show locations to scientist to ensure captures	1.5
Fishers can prevent species declines	1.5
Find solutions for all	1.5
Fishers can help in creating lax regulations	1.5

Table 11 Occupations/activities, alternative to fishing, which fishers reported as the preferred choice for their children.

Occupation	Percentage
Tourism	30.8
College	25.3
No answer	14.3
Office work	5.5
Biology	4.4
Public service	3.3
Sailor	2.2
Medicine	2.2
Tour guide	2.2
Anything with good salary	2.2
Science	1.1
Private or public sector	1.1
Fishing entrepreneur	1.1
Conservation	1.1
CDF	1.1
Business	1.1
Anything they want	1.1

Table 12 Framework with steps that are key to the success to collaborative research projects (Yochum et al 2011), and suggestions from this study.

Success to collaborative research, from (Yochum et al. 2011)	Suggestions from our study
Create solid foundations	Fishers in Galapagos identified their desire to be included in decision making projects. This clearly is the most important step to ensure the success of these projects.
Define success	Conservation goals differ from fishers views. Only through fishers' perception of fairness can compliance be assured. All stakeholders need to be open to compromise.
Define roles	Individual constraints need to be addressed. Disparate technical awareness requires extra efforts in education.
Define the scope	Goals need to be realistic and each individual needs to understand them. Project objectives should be aligned with available resources.
Develop a sampling plan	Building upon the strengths identified by each participant, the research design should incorporate the expertise of all collaborators.
Implement project	Identify leaders from each sector who ensure that protocols are followed in a standardized manner and do not represent their personal interest.
Evaluate the project	Analyze the collected data in a rigorous manner. Sharing the results, and their interpretation, with all collaborators will require extra effort and education.
Communicate the results	This has been identified by fishers as one of the key points leading to their negative perception of scientific studies. Ensuring effective communication through all the steps of collaborative research will undoubtedly result in increases in sense of belonging and added compliance to regulations.

Chapter VI

Summary and management suggestions

Summary

This dissertation presents the results from a joint effort between the Fisheries Ecology Research Lab, University of Hawai'i, the Charles Darwin Foundation (CDF), and the Galapagos National Park(GNP), aimed at producing management regulations for bacalao in the Galapagos.

Longevity for bacalao is greater than previously reported, with a maximum recorded age of 21 years, which is two to three times higher that previously reported. This current estimate comes from a fish 100 cm TL, as bacalao has been historically reported to reach 120 cm TL (Walford, 1937), it is very likely that longevity for this species is closer to 30 years. Similarly, growth estimates show bacalao to grow larger and slower than previously thought.

Even though it was not possible to collect any transitional individuals that would resolve the sexual pattern for the species, the large proportion of immature individuals in the samples, the low number of larger individuals, and the highly biased sex ratio suggests that the reproductive pattern for the species is hermaphroditic through monandry. At this time the reproductive pattern for bacalao cannot be fully resolved until accurate histological evidence is provided, and the irony lies in that the observed pattern of very low abundance of larger size individuals will make obtaining this samples difficult, and will place these individuals at greater fishing pressure.

Size at maturity was estimated to be larger than the previous accepted estimate of 47 cm TL (Coello, 1989). This estimate is a crucial parameter for establishing management regulations such as minimum size and slot limits (Heppell et al., 2005). While logistic difficulties precluded validation of reproductive periodicity, previous estimates are considered accurate and would therefore provide the basis for seasonal closures during the reproductive season which runs from October to January.

The current status of the bacalao fishery is worrisome as it is undergoing both recruitment and growth overfishing. The percentage of fish above size at maturity in the catch has dropped to an all-time low, and the Spawning Potential Ratio (SPR) suggests that bacalao is facing imminent reproductive failure. Furthermore, over a 20-year period there have been declines in all of the stock health indicators, with 2012 being the lowest year on record for all of these metrics. Results from this chapter strongly suggested that the bacalao fishery in the Galapagos Marine Reserve (GMR) is in critical condition, highlighting the need for stringent management regulations that will ensure the resilience of this important resource.

In lieu of management regulations specifically aimed at bacalao, the GMR relies on no-take zones to provide protection from fishing, however there was no identifiable protection effect for bacalao in terms of size or composition of the landings. Likewise, Catch Per Unit Effort (CPUE), and the metrics used to assess the status of the fishery among areas open and closed to fishing failed to provide support for effect of protection. Bacalao showed high site fidelity, with relatively small movement patterns on the order of 1 km. Since the scale of no-fishing zones in the GMR is larger than the movement patterns observed, it is likely that lack of effect of these areas does not stem from fish movement, but rather that fish inside the no-fishing zones still experience fishing pressure. An evaluation of the knowledge of fishers of the current GMR zonation suggests that this pattern might result from lack of compliance due to unwitting poaching since many fishers were unable to locate no fishing zones on a map.

Lastly, it was found that 26% of active fishers in the Galapagos show no trust in scientific studies, mostly because they lack proposals for alternative incomes, the results are not disseminated to fishers, and because there is a lack of perceived participation of fishers in the studies.

Implications for management

My results create a template that can be used in the establishment of successful management regulations for bacalao. This research has shown that the current state of the bacalao fishery is worrisome, and that effective, and probably stringent, management regulations are necessary to ensure the resilience of this species. The caveat is that fishers do not trust the current research being carried out in the Galapagos, and would therefore be less likely to adhere to any regulations arising from this research. While this research attempted to engage fishers in all of the field activities, it was clear that these efforts need to be fully supported by the major decision players in the region, such as the CDF and the GNP. Future fisheries research activities need to move beyond a single presentation at the end of the project, to a more cohesive research effort where fishers are fully included.

The findings from this research provide needed inputs upon which management regulation can be formulated. While the sexual pattern of bacalao remains unresolved, it is likely that the species is hermaphroditic (Sadovy & Shapiro, 1987; Sadovy de Mitcheson & Liu, 2008). Therefore heeding the precautionary approach, conservative management approaches for the species should include a mix of controls over catch and fishing effort such as slot limits (Heppell et al., 2005), increasing minimum landing size to reflect size of maturity, seasonal closures during reproductive season, and well enforced no-take spatial closures (Beets & Friedlander, 1999; Sadovy, 2001; Sadovy & Domeier, 2005; Heppell et al., 2006; Sadovy de Mitcheson et al., 2008). With this in mind, the recommended regulations for bacalao should include as a minimum:

- Minimum landing size equal to the size at which 50% of the population matures (65 cm TL)
- Maximum landing size of bacalao ≤ to size of megaspawners (78 cm TL)
- Closed season from October to January during peak spawning
- Active enforcement of the zonation scheme

It is recognized that creating management regulations is often easier than implementing them. This is especially true in developing countries (McClanahan, Maina & Davies, 2005; King, 2013), where using collaborative approaches is necessary to ensure compliance to management regulations (Yochum, Starr &

Wendt, 2011; Usseglio, Schuhbauer & Friedlander, 2014). Enacting these regulations will have negative impacts on the livelihoods of fishers from the GMR, emphasizing the need of working with fishers to develop alternative sources of income in parallel to the development of fishing regulations. This approach is plausible as over 60% of fishers interviewed in the GMR responded that they would be willing to adopt alternative income other than fishing (Usseglio, Schuhbauer & Friedlander, 2014).

The GMR is no stranger to fisheries collapses, as exemplified by the sea cucumber and lobster fisheries, and the typical reaction to implementation of management regulations has included riots and violence (Finchum, 2002). It is essential that the conservation, fishing, and community-at-large of the Galapagos Archipelago recognize that they are facing a choice between managing their resources wisely or maintaining the *status quo* and avoiding political and social conflict. The results from these choices is clear, the former will ensure resilience of an important cultural, economic, and biological resource, while the latter would result in maintaining the *status quo* and not deviating from what Pauly aptly named "Malthusian overfishing" (Pauly, 1990).

References

Beets J., Friedlander A. 1999. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, Epinephelus guttatus, in the US Virgin Islands. *Environmental Biology of Fishes* 55:91–98.

Coello S. 1989. Consideration on the management of the Galapagos Bacalao fishery *Myceroperca olfax* (Jenys) (Pisces:Serranidae). *Revista Pacifico Sur*:705–709.

Finchum R. 2002. The beliefs & perceptions of fishermen regarding management actions, regulations, and the protection of the Galapagos marine reserve. Master's thesis Thesis. USA: Colorado State University.

Heppell SS., Heppell SA., Read AJ., Crowder LB. 2005. Effects of fishing on long-lived marine organisms. *Marine conservation biology: the science of maintaining the sea's biodiversity. Island Press, Washington, DC*:211–231.

Heppell SS., Heppell SA., Coleman FC., Koenig CC. 2006. Models to compare management options for a protogynous fish. *Ecological Applications* 16:238–249.

King M. 2013. *Fisheries biology, assessment and management*. Oxford: John Wiley & Sons.

McClanahan TR., Maina J., Davies J. 2005. Perceptions of resource users and managers towards fisheries management options in Kenyan coral reefs. *Fisheries Management and Ecology* 12:105–112.

Pauly D. 1990. On Malthusian overfishing. *NAGA, The ICLARM quarterly* 13:2–4.

Sadovy Y. 2001. The threat of fishing to highly fecund fishes. *Journal of Fish Biology* 59:90–108.

Sadovy de Mitcheson YS., Cornish A., Domeier M., Colin PL., Russell M., Lindeman KC. 2008. A Global Baseline for Spawning Aggregations of Reef Fishes. *Conservation Biology* 22:1233–1244.

Sadovy de Mitcheson YS., Liu M. 2008. Functional hermaphroditism in teleosts. *Fish and Fisheries* 9:1–43.

Sadovy Y., Domeier M. 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. *Coral Reefs* 24:254–262.

Sadovy Y., Shapiro DY. 1987. Criteria for the diagnosis of hermaphroditism in fishes. *Copeia*:136–156.

Usseglio P., Schuhbauer A., Friedlander A. 2014. Collaborative Approach to Fisheries Management as a Way to Increase the Effectiveness of Future Regulations in the Galapagos Archipelago. In: Denkinger J, Vinueza L eds. *The Galapagos Marine Reserve*. Cham: Springer International Publishing, 187–202.

Walford LA. 1937. *Marine game fishes of the Pacific coast from Alaska to the equator. Contrib. Santa Barbara Mus*. Berkley, California: University of California Press.

Yochum N., Starr RM., Wendt DE. 2011. Utilizing Fishermen Knowledge and Expertise: Keys to Success for Collaborative Fisheries Research. *Fisheries* 36:593–605.