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The demise of Darwin's fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands

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ABSTRACT

1. The fauna of the Galápagos Island chain is characterized by high biodiversity and endemism. Thus, the conservation of its terrestrial and marine wildlife, including the sustainable management of local fisheries, is of paramount importance.
2. Although the commercial exploitation of fish in the Galápagos did not intensify until the mid-1900s, issues of overexploitation and mismanagement are already of serious concern. However, to date, research on Galápagos fisheries has been largely species or island specific, and no long-term cumulative catch statistics exist.
3. In this study, total landings associated with the industrial and artisanal fisheries of the Galápagos Islands were compiled and analysed in an effort to assess accurately the amount of seafood that has been extracted from this region over the last six decades.
4. The total catch for all sectors from 1950–2010 was 797 000 t, of which industrially caught tuna made up 80%.
5. The results also show a high degree of fishing down within the in-shore ecosystem catch, whereby planktivorous mullets have replaced high trophic level groupers within the past three decades. This shift has coincided with the spatial expansion of the Galápagos fishing fleet to areas further off-shore, where predatory species are not yet depleted.
6. In addition to legally caught and exported seafood, Galápagos waters are also prone to illegal fishing. Of primary concern are shark finning practices that have escalated in intensity since the 1980s. Despite attempts at mitigation, this ecologically destructive and wasteful practice continues to occur in the Galápagos Marine Reserve.

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KEY WORDS: archipelago; biodiversity; marine reserve; fish; invertebrates; fishing

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INTRODUCTION

Island geography and demographics

Located 1000 km west of mainland Ecuador in the eastern Pacific Ocean, the Galápagos Islands (Table 1; Figure 1) have been the subjects of curiosity, mystery, and scientific discovery for nearly 500 years. Charles Darwin's voyage aboard the *H.M.S. Beagle* in 1835 offered him the unique opportunity to take a variety of biological specimens from this region, and although best known for his work on finches, Pauly (2004) demonstrates that Darwin's subsequent research on speciation was largely influenced by the phenotypic variations that he observed in fishes, rather than in birds.

The land area of the Galápagos Islands is only 7880 km^2 (Snell *et al.*, 1996), yet they are rich in biodiversity. Current estimates suggest that this archipelago is home to approximately 3000 terrestrial species (GC, 2012), and over 95% of the mammals and reptiles, 80% of the avian species, and 30% of the plants are endemic (GC, 2012). Another unique characteristic of these islands is the unconventional coexistence of tropical species, temperate species, and typically Southern Ocean species within a small geographic region (Jackson, 2001). Such assemblages are made possible by deep near-shore waters, strong currents, and nutrient-rich upwellings, that provide an excellent habitat for over 2900 species of fish, aquatic invertebrates, and marine mammals, 20% of which are endemic (Grove and Lavenberg, 1997; Bustamante *et al.*, 2002; Okey *et al.*, 2004; Denkinger *et al.*, 2013). In addition, 11 endemic seabirds (as well as 23 migrant species) (Wiedenfeld, 2006) and the world's only marine iguana (*Amblyrhynchus cristatus*) (Jackson, 2001) also rely on these waters for both food and habitat.

Realizing the need to preserve this unique environment, the Government of Ecuador proactively designated the Galápagos as a national park in 1959; in 1979, it was further declared a UNESCO World Heritage Site (Jackson, 2001; Bensted-Smith *et al.*, 2002). In 1998, the foundation of the Galápagos Marine Reserve (GMR) declared a protective boundary around the archipelago, which encompasses 138 000 km^2 around the Islands (Heylings and Bensted-Smith, 2002; Castrejón and Charles, 2013), making it one of the largest marine protected areas in the world.

At present, the Galápagos suffers from many of the same problems that have affected geographically isolated regions throughout history: species invasions (1321 spp. as of 2007), human population growth, and modification of natural habitats for agriculture (Bremner and Perez, 2002; Causton *et al.*, 2006; Watkins and Cruz, 2007; González *et al.*, 2008; Mauchamp and Atkinson, 2010). More recently, marine pollution (i.e. chemical and biological pollution) has emerged as a looming

Table 1. Geography and fisheries demographics of the Galápagos Islands

Island	Location[a]	Land area[a] (km^2)	Inhabited	Number of fishers[b]	Primary fishing port[b]	In-shore fishing area[c] (km^2)
Isabela	0°25′30″, 91°7′W	4588	Y	149	Puerto Villamil	2201
Fernandina	0°22′0″S, 91°31′20″W	642	N	-	-	137
Santa Cruz	0°37′0″S, 90°21′0″W	986	Y	220	Puerto Ayora	1897*
Floreana	1°17′0″S, 90°26′0″W	173	Y	N/A	N/A	708
Pinzón	0°36′30″S, 90°39′57″W	18	N	-	-	60
Santa Fé	0″49′0″S, 90″3′30″W	24	N	-	-	860
Baltra	0″25′30″S, 90″16′30″W	26	Y	N/A	N/A	1897*
San Cristóbal	0″48′30″S, 89″25′0′W	558	Y	290	Baquerizo Moreno	1033
Española	1″22′30″S, 89″40′30′W	60	N	-	-	434
Santiago	0″15′30″S, 90°43′30′W	585	N	-	-	461
Marchena	0″20′20″N, 90′28′25′W	130	N	-	-	95
Genovesa	0″19′40″N, 89″57′20′W	14	N	-	-	44
Pinta	0″35′18″N, 90°45′17′W	59	N	-	-	51

*Combined IFA of Santa Cruz and Baltra.
[a]Snell *et al.* (1996)
[b]Castrejón (2011)
[c]Provided by Melissa Nunes, *Sea Around Us* Project.

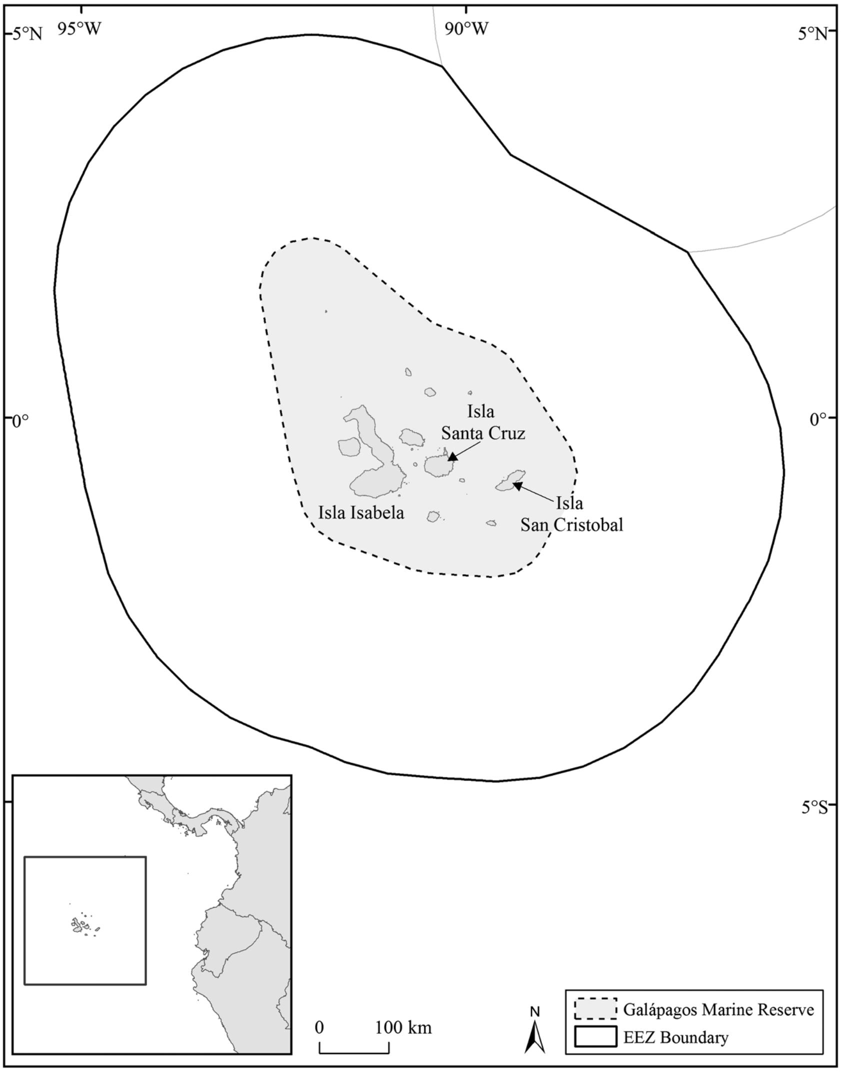

Figure 1. The Galápagos Islands archipelago. The Galápagos Islands span the equator and are located ~1000 km west of mainland Ecuador in the Pacific Ocean (inset). A protective 138 000 km^2 zone, the Galápagos Marine Reserve (GMR), extends around the islands and industrial-scale fishing is prohibited within this area. The Galápagos exclusive economic zone (EEZ; Ecuadorian waters) extends 320 km (200 nmi) off the Islands and serves as the invisible boundary for all catches included in this study.

threat for conservation of the GMR (Alava *et al.*, 2014). Additionally, the ecotourism industry of this archipelago has exploded over the latter half of the 20th century. Approximately 2000 people visited the Galápagos Islands in 1969 (Epler, 2007), a tiny fraction of the 180 000 people who visited them in 2012 (PNG, 2013), and whose activities result in a local annual profit of over $US60 million (Watkins and Cruz, 2007). Despite these direct economic benefits, the negative environmental impacts of this foreign attention remains one of the primary threats facing the Galápagos today.

Fishing in the Galápagos Marine Reserve

Human exploitation of marine life at a large scale in the Galápagos began in the late 18th century, with the onset of hunting of Galápagos fur seals (*Arctocephalus galapagoensis*) for their pelts, and with commercial whaling, the latter subsequently leading to the rapid local depletion of sperm whales (*Physeter macrocephalus*) (Townsend, 1934; Whitehead *et al.*, 1997; Toral-Granda *et al.*, 2000; Denkinger *et al.*, 2013). In addition to hunts for marine mammals, the Galápagos finfish[1] fishery has a long history in the islands and dates back to the time of colonization, when about a dozen species were taken for subsistence (Toral-Granda *et al.*, 2000; Castrejón, 2011). As detailed in Reck (1983), a commercial finfish fishery was permanently established in 1945, and for decades, the primary target of this hand-line operation was the Galápagos grouper (*Mycteroperca olfax*), a species locally referred to as *bacalao*[2] (Reck, 1983; Nicolaides *et al.*, 2002). Despite the finfish fishery's simple origins, catches today are from two distinct spatial groups (in-shore and off-shore), and include 68 different species from 27 families (Castrejón, 2011).

Various invertebrates are also caught in the archipelago. Red (*Panulirus penicillatus*) and green (*Panulirus gracilis*) spiny lobsters have been fished for commercial export since the 1960s (Bustamante *et al.*, 2000), and previous estimates suggest that the Galápagos has always contributed upward of 95% to Ecuador's total spiny lobster export (Reck, 1983; Bustamante *et al.*, 2000). A similar species, the slipper lobster (*Scyllarides astori*), is also harvested at a smaller scale (Hearn, 2006), although it is sold primarily for local consumption (Bustamante *et al.*, 2000; Andrade and Murillo, 2002).

When coastal mainland stocks collapsed in the early 1990s, Ecuador's sea cucumber fishery re-established itself in the Galápagos, where it has had a problematic impact ever since (Shepherd *et al.*, 2004; Castrejón *et al.*, 2005; Hearn *et al.*, 2005; Toral-Granda, 2008). At present, it is legal to harvest only the brown sea cucumber (*Isostichopus fuscus*). However, illegal fishing exists for at least three other species (Toral-Granda, 2008).

Fishing activity within the GMR is currently organized by zones, whereby subsistence and artisanal fishing is allowed in specified locations (PNG, 2009), but all large-scale industrial fishing has been prohibited since 1998 (Jennings *et al.*, 1994; Jacquet *et al.*, 2008). As such, the artisanal fleet of the Galápagos is largely made up of small boats with limited technology. Between 1971 and 2000, the number of fishers increased by 325% (Bustamante, 1998; Toral-Granda *et al.*, 2000); this substantial intensification in fishing effort and vessels was influenced by the economic incentives generated by the lucrative sea cucumber fishery. Conversely, from 2000–2007, there was a 65% decrease in the total number of active fishers in the Galápagos, probably due to the diminishing profitability of the spiny lobster and sea cucumber fisheries, and subsequent shifts in livelihood (Castrejón, 2011).

The traditional 'trophy hunting' approach to sport fishing began in the Galápagos in the 1990s. However, these activities were unregulated and operated without the consent of local fishers (Schuhbauer and Koch, 2013). This type of tourism is not currently supported by the GMR and prohibited within its boundaries (PNG, 2009). Since 2005, recreational sport fishing by tourists in the Galápagos has been based on the 'Pesca Artesanal Vivencial' (PVA) approach instead (Schuhbauer and Koch, 2013). This new, experimental initiative aims at giving local fishers an alternative to commercial fishing, and tourists the chance to spend a day with a local licensed fisher. Fish are meant to be caught using traditional gear and methods, and all catch (excluding spiny lobsters caught during the harvest season) is legally required to be released (PNG, 2009). Although very little assessment of PVA has been conducted, initial research suggests that this programme has thus far been unsuccessful (largely due to a lack of organization and clearly defined regulations), and despite efforts to avoid traditional sport fishing, these activities remain prevalent within the archipelago (Schuhbauer and Koch, 2013).

Shark finning in the Galápagos

In addition to the wide range of teleost fishes in the Galápagos Islands, a variety of sharks have also been recorded in this region (Grove and Lavenberg, 1997; Zarate, 2002; Carr *et al.*, 2013). Of the elasmobranchs found around the

[1]More commonly known as 'whitefish' in the Galápagos, despite the fact that both white-fleshed (e.g. serranids) and red-fleshed (e.g. scombrids) fish are landed by this fishery.
[2]The English translation of *bacalao* is 'cod' (Family Gadidae); however *M. olfax* is a grouper (i.e. a member of the family Serranidae).

Galápagos, ~90% meet the IUCN Red List criteria as 'Threatened' or 'Near-Threatened' (Camhi *et al.*, 2009).

Fishing for sharks has occurred in the Galápagos since the 1950s (Watts and Wu, 2005; Jacquet *et al.*, 2008), although sharks caught in the archipelago are typically landed at ports on mainland Ecuador. While shark finning is prohibited within the GMR (Jacquet *et al.*, 2008; Carr *et al.*, 2013), this practice became increasingly prevalent in the 1980s, and its magnitude has increased ever since (Camhi, 1995; Zarate, 2002; Coello, 2005; Watts and Wu, 2005; Jacquet *et al.*, 2008; Carr *et al.*, 2013). Between 1988 and 1991, illegal shark fisheries were discovered to be using sea lion flesh as bait (Camhi and Cook, 1994; Camhi, 1995), and the onset of finning practices with the discard of shark bodies led to the slaughter of tens of thousands of sharks for the Asian market (Merlen, 1995; Zarate, 2002). These operations were conducted largely by Ecuadorian, Colombian, Costa Rican, Japanese, Taiwanese and Korean industrial longline fishing fleets, some of which were licensed only for tuna, but were illegally fishing for sharks (Camhi, 1995; Merlen, 1995; Zarate, 2002).

Purpose of study

If the fisheries of the Galápagos are to be sustainable in the long-term, an understanding of the cumulative catch trends, interactions, and impacts within the region is essential in order to properly implement (or improve upon) marine management objectives and conservation initiatives within the archipelago. Thus, the primary objective of this study is to give an accurate representation of the total marine fisheries landings within the Exclusive Economic Zone (EEZ) of the Galápagos Islands from 1950–2010. Specifically, this will amalgamate industrial-scale landings from Ecuador's commercial tuna fleet (outside the GMR), landings associated with the artisanal fisheries of the Galápagos (within the GMR), and illegal catches in the region as a whole. The second aim of this paper is to determine how this reconstructed total catch compares with the data on Galápagos fisheries reported to the FAO and included in their FishStat database. In view of the continuing debate about the validity of the 'fishing down' phenomenon (Caddy *et al.*, 1998; Pauly *et al.*, 1998; Pauly and Palomares, 2005; Essington *et al.*, 2006; Branch *et al.*, 2010; Freire and Pauly, 2010), a tertiary goal is to analyse the reconstructed catch to observe whether this trend is also occurring in the Galápagos artisanal fisheries and, if it is, at what intensity.

METHODS

This study acquired and analysed fisheries information from over 30 unique sources, including primary and grey literature. The key data anchor points used for this reconstruction are highlighted below, and the associated assumptions of each anchor point and additional data are discussed in further detail in Schiller *et al.* (2013).

Although there are time periods for which catch data do not exist, it would be incorrect to suggest that there were no catches during these years. In this study, attempts were made to use assumptions and interpolations based on the best available data and anecdotal evidence to give a realistic and conservative estimate of the landings associated with this biodiversity hotspot.

To quantify the uncertainty of this catch reconstruction, a method inspired from the 'pedigrees' of Funtowicz and Ravetz (1990) was used. This consisted of attributing to each species subgroup (e.g. finfish, sharks, sea cucumbers) a 'score' expressing an evaluation of the quality of the reconstructed catch time series, i.e. (1) 'very bad', (2) 'bad', (3) 'good', and (4) 'very good'. Each score was assigned an asymmetric triangular confidence interval (1 = –10 to +20%; 2 = –20 to +30%; 3 = –50 to +80%; 4 = –80 to +150%) whose ranges were adapted from Monte-Carlo simulations in Ainsworth and Pitcher (2005) and Tesfamichael and Pitcher (2007). To obtain levels of uncertainty over time, the weighted average of these scores was calculated for three periods (1950–1969, 1970–1989 and 1990–2010).

Local consumption

To calculate the quantity of fish caught for consumption within the islands, residency and tourist data were extracted from Taylor *et al.* (2008), González *et al.* (2008) and Ecuador's Instituto Nacional de Estadística y Censos (INEC)[3] and Galápagos National Park entry records,[4] and linear interpolation was used for missing years. Although an archipelago-wide rate of seafood consumption could not be found, as determined in a study on Santa Cruz Island, 6.75 kg person^{-1} year^{-1} was used as the 2010 *per capita* consumption rate for locals, and 1.1 kg person^{-1} vacation^{-1} was used for tourists (Manuba, 2007). Given decreased accessibility to food from the mainland, it was assumed that locally caught seafood was more prominent in people's diets on the islands for the earlier time period. Thus, a starting *per capita* consumption of 10 kg person^{-1} year^{-1} for locals and 1.4 kg person^{-1} trip^{-1} for tourists was used for 1950. Although these *per capita* seafood consumption rates are very low in comparison with other oceanic islands and countries (Harper and Zeller, 2011), this disparity is probably due to the prominence of agricultural land in the Galápagos, as many residents tend to maintain a diet similar to that of people on the mainland, consuming primarily grains and meat.

Artisanal fisheries

With regard to FAO data, it was assumed that all FishStat lobster data referred exclusively to catches in the Galápagos since the archipelago has contributed roughly 90–95% of Ecuador's total catch since its establishment; these FAO data were accepted as correct for most years, but amounts were adjusted when additional data were available. In most cases, lobster weight was given in terms of tail weight, and a conversion factor of 2.86 (as determined by Reck, 1983) was used to calculate whole animal weight. Most sources provided a species breakdown; when this was unavailable, an approximate species catch composition of 45% *P. penicillatus*, 45% *P. gracilis*, and 10% *S. astori* was used for catches before 2000. An approximate catch composition for the last decade was adjusted based on a species breakdown provided in Hearn and Murillo (2008).

FAO data also included annual landings of sea cucumbers. However, additional catch data for *I. fuscus* were collected from the primary literature (Schiller *et al.*, 2013). An average weight of 271 g (Sonnenholzner, 1997) was used to calculate tonnage in cases where the original data referred to the number of individuals caught rather than total weight. Some data were available for illegal catches of *I. fuscus* (Jacquet *et al.*, 2010) and the warty sea cucumber (*S. horrens*), but very little qualitative information and no quantitative data were found for the other two species (*Holothuria atra* and *H. kefersteini*) fished illegally in the archipelago.

There was no indication that Ecuador's FAO dataset included catches of finfish from the Galápagos; thus it was assumed that these data were not included. The starting year of this fishery was assumed to be 1950, as early anecdotal estimates by Reck (1983) suggest annual finfish landings of approximately 500 t during this time but no data were available until 1977 (Reck, 1983). GraphClick was used to extract data from a time series of catches that served as anchors for further interpolations (Schiller *et al.*, 2013). Export data provided by the Charles Darwin Foundation (CDF) were used to calculate the catch between 2004 and 2010. Up until the 1970s, mullets were not considered part of the finfish catch (Reck, 1983); since later datasets did include them as part of the finfish fishery, the calculated catches of the Galápagos mullet (*Mugil galapagensis*) and Thoburn's mullet (*Xenomugil thoburni*) were added to the earlier finfish catch data. Approximate species breakdowns were available from most primary sources; when these were unavailable, the species composition for known years was calculated and applied to the total catch.

Trophic level analysis

Given reported quantitative and qualitative changes in catch composition, an analysis of the mean

[3]http://www.inec.gob.ec/cpv/
[4]http://www.galapagospark.org/onecol.php?page=turismo_estadisticas

trophic level (TL) of the artisanal catch was also performed to test if 'fishing down'[5] was occurring (i.e. if there were any noticeable ecological shifts in the species landed over time).

Since the fishing down effect can be easily masked by aggregating data from different ecosystems, an 'in-shore' ecosystem that comprised all species typically occurring along the coast, or within the in-shore fishing area (IFA; area up to 50 km off-shore or 200 m deep, whichever comes first) was defined. Given the instability and innate boom-and-bust nature of the sea cucumber fishery, the in-shore analysis was performed with and without sea cucumbers. The separate 'off-shore' species category refers to larger pelagic fishes that would typically be found outside of the IFA (Table 2). An average TL value (3.54) was used for finfish species in this analysis that could not be disaggregated by species and regression analyses were performed to assess the changes in mean trophic level over time.

Industrial tuna fisheries

Although the Inter-American Tropical Tuna Commission (IATTC) has published various reports on tuna caught in the eastern Pacific since the 1950s, a lack of information pertaining to the country fishing made it impossible to deduce how much of this tuna was caught in the Galápagos EEZ by Ecuador's industrial fleet. As such, only two data sets (Jácome and Ospina, 1999; Pacheco-Bedoya, 2010) for three species (skipjack, *Katsuwonus pelamis*; yellowfin, *Thunnus albacares;* and bigeye, *Thunnus obesus*) of Ecuador-caught tuna in the Galápagos could be found. Similar to the spiny lobster and sea cucumber fisheries, it was assumed that industrially caught tuna in the Galápagos were included with Ecuador's FAO data, and these catches were assumed to be accurate. Since it closely matched Bustamante's (1999) suggestion that 24.3% of Ecuador's tuna comes from the Galápagos, the percentage breakdown from Pacheco-Bedoya (2010) was applied to the FAO data to determine the total Galápagos catch and species composition.

Sharks

Based on anecdotal evidence, 1950 was used as the starting year for this fishery. Values for sharks caught in the Galápagos were obtained primarily by calculating the difference between the reconstructed shark catch of mainland Ecuador and Ecuador's shark exports from 1979–2004 as determined by Jacquet *et al.* (2008). There are no numerical or anecdotal indications that shark fishing ever declined or stopped in the Galápagos. Thus, when export data from Jacquet *et al.* (2008) were less than Ecuador's reconstructed catch, it was assumed that shark fishing was still occurring in the archipelago, but that exports during this time were under-reported; interpolation between these years was used instead. Species-specific landings of the sharks in this region were estimated based on the 1997–1998 Galápagos Report (Ospina *et al.*, 1998).

RESULTS

When taking into account all legal and illegal fisheries in the Galápagos, this reconstruction determined that from 1950–2010, 797 000 t of seafood were extracted from the EEZ surrounding this archipelago (Figure 2). Between 1950 and 1969, the catch was 61 450 t (confidence interval (CI) based on assigned uncertainty value and weighted catch composition = –32 to +50%); between 1970 and 1989 it increased to 151 450 t (CI = –17 to 27%), and from 1990–2010, 584 100 t (CI = –12 to 22%) were caught in the Galápagos. It should be recognized that 80% of the total landings are tuna caught by Ecuador's industrial fleet, and shark fishing – much of which is illegal – is the second highest contributing fishery, accounting for 13% of these landings.

Artisanal fisheries

From 1950 to 2010, 26 500 t of finfish (Figure 3), 9200 t of spiny lobster (Figure 4), and 700 t of slipper lobster were caught within the EEZ of the Galápagos Islands. Of these catches, 6700 t of

[5]Here, 'fishing down' is defined as a decline in the mean trophic level of fisheries catches, reflecting a decline of higher-trophic level (predatory) species, relative to species low in food webs, such as planktivores (e.g. mullets) and detritivores (e.g. sea cucumbers).

Table 2. Commonly caught finfish and invertebrate species of the Galápagos

Habitat	Family	English name	Spanish name	Latin name	TL*
In-shore	Serranidae	**Galápagos grouper**	Bacalao	*Mycteroperca olfax*	4.4
		Misty grouper	Mero	*Epinephelus mystacinus*	4.4
		-	Camotillo	*Paralabrax albomaculatus*	4.4
		Starry grouper	Cabrilla	*Epinephelus labriformis*	4.0
		Leather bass	Cagaleche	*Dermatolepis dermatolepis*	4.4
		Olive grouper	Norteño	*Epinephelus cifuentesi*	4.0
	Mugilidae	**Galápagos mullet**	Lisa rabo amarillo	*Mugil galapagensis*	3.0
		Thoburn's mullet	Lisa rabo negro	*Xenomugil thoburni*	2.9
	Labridae	**Galápagos sheephead wrasse**	Vieja mancha dorada	*Semicossyphus darwini*	3.6
	Hemilutjanidae	**Grape-eye seabass**	Ojón/Ojo de uva	*Hemilutjanus macrophthalmos*	3.8
	Scorpaenidae	-	Brujo	*Scorpaena* spp.	3.5
	Malacanthidae	**Ocean finfish**	Blanquillo	*Caulolatilus princeps*	3.9
	Lutjanidae	**Pacific cubera snapper**	Pargo mulato/ pargo rojo	*Lutjanus novemfasciatus*	3.7
	Palinuridae	**Red spiny lobster**	Langosta roja	*Panulirus penicillatus*	2.8
		Blue spiny lobster	Langosta verde	*Panulirus gracilis*	2.8
	Scyllaridae	**Slipper lobster**	Langostino	*Scyllarides astori*	2.7
	Stichopodidae	**Brown sea cucumber**	Pepino de mar	*Isostichopus fuscus*	2.1
Off-shore	Scombridae	**Wahoo**	Guajo	*Acanthocybium solandri*	4.2
		Bigeye tuna	Atún patudo/ atún ojo grande	*Thunnus obesus*	4.2
		Yellowfin tuna	Atún aleta amarilla	*Thunnus albacares*	4.2
		Pacific sierra	Sierra	*Scomberomorus sierra*	4.2
		Albacore tuna	Albacora	*Thunnus alalunga*	4.2
	Carangidae	**Longfin yellowtail**	Palometa	*Seriola rivoliana*	4.2
		Steel pompano	Pampano acerado	*Trachinotus stilbe*	3.8
	Xiphiidae	**Swordfish**	Pez espada	*Xiphias gladius*	4.5

*Trophic levels based on Okey *et al.* (2004), FishBase (www.fishbase.org), and SeaLifeBase (www.sealifebase.org).

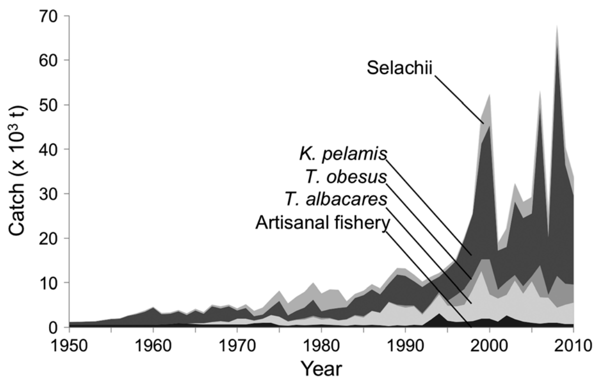

Figure 2. Total reconstructed catch of the Galápagos Islands, 1950–2010. In total, 797 000 t of seafood was extracted from the Galápagos EEZ surrounding this archipelago, with industrially caught tuna (skipjack, *K. pelamis*; bigeye, *T. obesus*; yellowfin, *T. albacares*) comprising 80% of the total landings. Sharks (Selachii) were the second highest contributors to the fishery, accounting for 13% of the landings. The artisanal fleet (including sea cucumbers, lobsters, and finfish) accounted for only 52 500 t over the 61-year period.

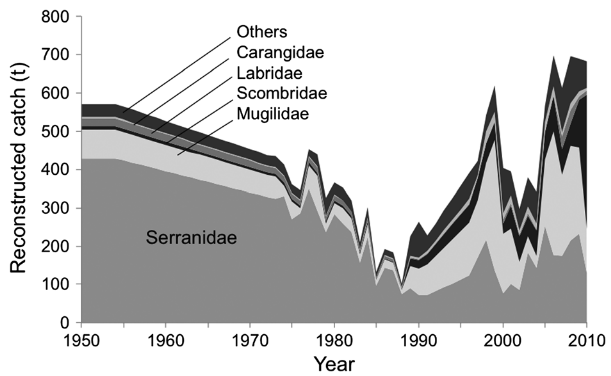

Figure 3. Reconstructed Galapagos artisanal finfish catch (1950–2010), classified by family. Before the 1980s, the bulk of landings were composed of large, predatory in-shore groupers (in particular *Mycteroperca olfax*). Over the last two decades, the species composition has changed such that off-shore species (e.g. tuna) and smaller in-shore forage fish (e.g. mullets) are now much more prevalent in the catch.

finfish, 600 t of spiny lobster, and 700 t of slipper lobster were taken for consumption within the Islands while the remainder was exported. Collectively, 16 100 t of sea cucumber were caught in (and exported from) the Galápagos between 1950 and 2010 (Figure 5). The composition of this catch was predominantly legally caught *I. fuscus* (81%) but also included illegal catches of both *I. fuscus* (19%) and *S. horrens* (<1%).

Trophic level analysis

Figure 6(A) illustrates the changing composition of artisanal fisheries catches around the Galápagos

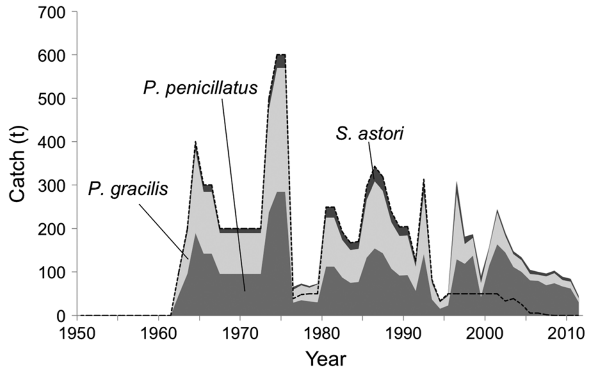

Figure 4. Reconstructed catch of spiny and slipper lobsters for the Galápagos, 1950–2010. Approximately 9200 t of spiny lobster (*Panulirus penicillatus* and *P. gracilis*) and 700 t of slipper lobster (*Scyllarides astori*) were caught within the Exclusive Economic Zone (EEZ) of the Galápagos from 1950 to 2010. The reconstructed catch of *P. penicillatus* and *P. gracilis* was 4 times the amount reported by the FAO (dashed line) between 1995 and 2010.

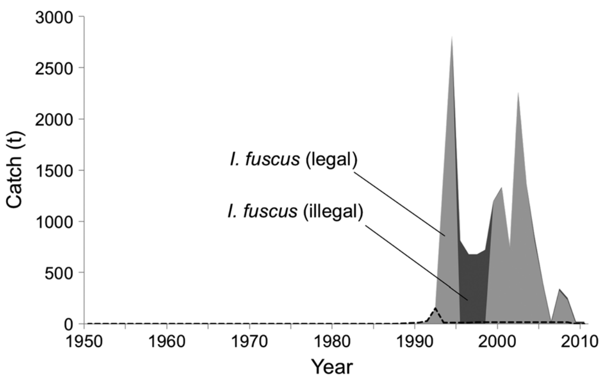

Figure 5. Total reconstructed sea cucumber catch for the Galápagos archipelago, 1950–2010. An estimated 13 000 t of brown sea cucumber (*Isostichopus fuscus*) were legally gathered for export since the establishment of the fishery, which is 30 times as much as reported by the FAO (dashed line) for the same time period. An additional 3000 t of this species has been taken illegally, primarily between 1994 and 1999. The reconstructed illegal catch of the warty sea cucumber (*Stichopus horrens*) is an estimated 40 t.

through trends of the mean trophic levels (TL) of the organisms landed (fish and invertebrates); regression analysis showed a significant change ($r^2 = 0.59$; $F_{1,\ 60} = 85.9$; $P < 0.001$) in the mean TL between 1950 and 2010.

When separating the artisanal catch by region (Figure 6(B)), it was determined that (even when excluding sea cucumbers) the in-shore mean TL has declined significantly from 4.1 in 1950 to 3.6 in 2010 ($r^2 = 0.53$; $F_{1,\ 60} = 65.7$; $P < 0.001$). Conversely, the mean TL of the off-shore catch increased slightly over the last 60 years; however, this change was not statistically significant ($r^2 = 0.05$; $F_{1,\ 60} = 3.4$; $P = 0.67$).

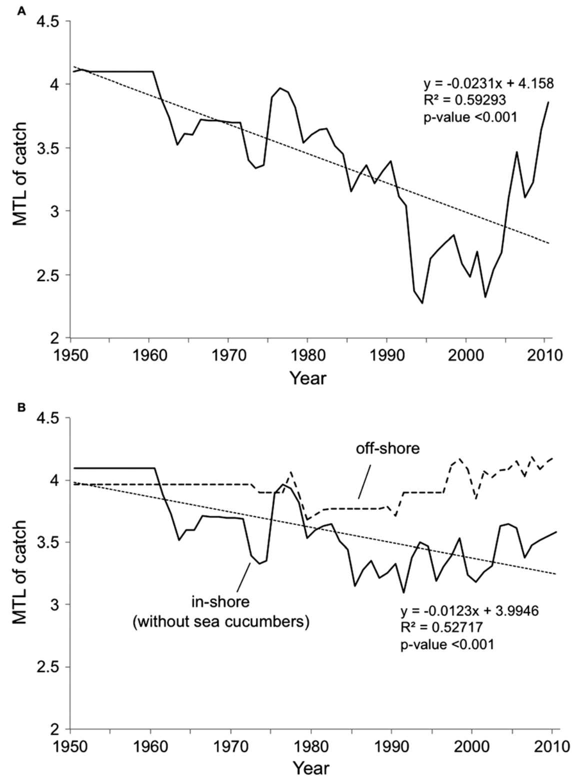

Figure 6. Changes in mean trophic level (TL) of the artisanal catch in the Galápagos Islands. (A) At a cumulative level (i.e., all species and spatial scales), there has been a significant decline (0.23 TL decade^{-1}) in the mean TL of the catch from 1950 to 2010, much of which is attributable to the influence and fluctuations of sea cucumber fishing from 1990 onward; the increase in the late 2000s is not due to stock recovery (see text). (B) When species are spatially disaggregated, the mean TL of the in-shore catch (not including sea cucumbers) also shows a significant decline of 0.12 TL decade^{-1}. The mean TL of the off-shore catch increases, although not significantly over time.

Industrial tuna fisheries

Outside of the GMR within the Galápagos EEZ, Ecuador's industrial fishery caught 639 000 t of tuna between 1950 and 2010, with skipjack comprising 68% of landings, followed by yellowfin (23%) and bigeye (9%).

Sharks

Since 1950, 105 500 t of shark have been taken from the Galápagos Islands EEZ by the Ecuadorian fleet. Foreign boats from Costa Rica, Columbia, and Japan are also known to fish for sharks in Galápagos waters (Camhi, 1995; Watts and Wu, 2005; Reyes and Murillo, 2007). As such, this reconstruction probably gives only a minimum estimate of the total unreported shark fishing (and finning) occurring in the archipelago. Although these catches were all assumed to be unreported, it was not possible to determine how much of this activity occurred within the 60 km boundary of the GMR.

DISCUSSION

Artisanal fisheries

Although the commercial fisheries of the Galápagos were primarily established within the last 60 years, this catch reconstruction demonstrates a high level of over-exploitation within the region.

The reconstructed catch of *I. fuscus* is 36 times as much as Ecuador's reported landings of sea cucumber to FAO for the same period (Figure 5). While FAO spiny lobster data for the past appear to be consistent with the primary literature, the reconstructed catch of *P. penicillatus* and *P. gracilis* is 4 times the reported values between 1995 and 2010 (Figure 4). These inconsistencies may suggest a lack of communication between island and mainland fisheries management bodies, or changes in reporting methodology during these time periods, or both. They also suggest a need for better monitoring of the fisheries in this region, which cannot be managed if the basic metric of fishing activity – the catch – is not known accurately. As red spiny lobster (*P. penicillatus*) and brown sea cucumber (*I. fuscus*) are likely to be the two most profitable fisheries in decline in the Galapagos Islands, an assessment of the fishing fleet behaviour and spatial management options has been advocated to look for potential solutions (Bucaram *et al.*, 2013).

Between 1979 and 1980, the average catch per unit effort (CPUE) for spiny lobsters was 10.7 kg of tails diver^{-1} day^{-1} (peaking at 12.4 kg of tails diver^{-1} day^{-1} in 1978). However, from 1994–2006, the average CPUE was only 6.6 kg of tails diver^{-1} day^{-1}, and an all-time low of 4.0 kg of tails diver^{-1} day^{-1} was observed in 2005 (Castrejón, 2011). Recent information suggests that lobster CPUE is increasing again (i.e. 8.7 kg of tails diver^{-1} day^{-1} in 2011). Nonetheless, it is possible that this may reflect a decline in local fishing capacity or a decrease in market value, rather than an increase in spiny lobster abundance (Ramírez *et al.*, 2013). Declines in spiny lobsters have also been linked to an increased presence of sea urchins in the subtidal zone. As a result of this competitive release, sea urchin cover has dramatically increased (Banks, 2007), contributing to reduced growth and coverage of macroalgae and corals – habitats that were once prevalent in the waters surrounding the Galápagos. These habitats play a key role in the archipelago and, as Castrejón (2011) explains, 'their disappearance is worrying because of their direct effect on the distribution and abundance of many other species that depend on them as sources of food, shelter, and reproduction'.[6]

Given the sessile nature of many invertebrates, serial stock depletion and subsequent spatial expansion is a common characteristic of many of the world's invertebrate fisheries (Anderson *et al.*, 2011a, b; Johnson *et al.*, 2012). Thus, while large populations of sea cucumbers and urchins can yield large catches in the short term, rapid local stock depletion often occurs and the fishery is forced to move elsewhere. As a result of the substantial declines in *I. fuscus* (Hearn and Murillo, 2008), there have been suggestions to legalize the fishery for *S. horrens*, as well as for the white sea urchin (*Tripneustes depresus*) (Castrejón, 2011). Although these initiatives may have the potential to provide short-term economic and environmental benefits (i.e. curtailing sea urchin expansion), this shift in target species could result in further destabilization of the coastal environment.

Of additional concern to the artisanal fisheries is the decline in abundance of large apex-level fish, such as groupers. Here, what is important is not necessarily the total landed tonnage of this fishery, but rather the changes in species composition that have occurred over the years (Figure 3). Between 1977 and 1981, *M. olfax* comprised 36% of the annual finfish catch and, in general, serranids made up 89% (Reck, 1983). Three decades later, *M. olfax* comprised only 17% of the total catch, and another endemic serranid, *Paralabrax albomaculatus*, which made up 32% of the catch

[6]Translated from Spanish by authors.

between 1977 and 1981 (Reck, 1983), made up only 3% between 2000 and 2010. Between 1997 and 2001 the finfish fishery was primarily composed (41%) of two mullets: *X. thoburni* and *M. galapagensis* (Andrade and Murillo, 2002), species that were only fished occasionally during the 1970s. At the time, mullets were not exported and were consumed locally for subsistence, or used as bait for larger fish (Reck, 1983). It is also particularly troubling to note that, although only scientifically described in 1993 (Lavenberg and Grove, 1993), *Epinephelus cifuentesi* was fished so heavily that the average annual catch fell by 80% between 1998 and 2003 (Nicolaides *et al.*, 2002). As such, the Galápagos population of this grouper is currently listed as 'Vulnerable' by the IUCN (Rocha *et al.*, 2008). In addition to the mullets, coastal pelagics such as wahoo (*Acanthocybium solandri*) and pomfret (*Seriola rivoliana*) have taken on increased economic importance (Castrejón, 2011), which is reflected by their increasing prominence in recent catches.

Trophic level analysis

While the results from the trophic level analysis represent a strong example of fishing down (0.23 TL decade^{-1}), it is important to note that if the ecosystem is ill-defined, and combines species that do not interact with each other (such as sea cucumbers and tuna), observed levels of fishing down could potentially be masked or enhanced. Thus, the overall strength of this trend will be a function of the extent of the spatial/ecological over-aggregation error that is committed, and the relative catches involved. Specifically worrisome is that if only an aggregate mean TL is observed, one can get the impression that mean trophic levels in the catch from the exploited 'ecosystem' can actually increase, as suggested by Branch *et al.* (2010). In the Galápagos, the mean TL of the catch steadily declined until the early 2000s, at which point it began to increase (Figure 6(A)). Although this positive trend could initially be interpreted as the fishery in the process of rebuilding, in reality it is due to the influence of the sea cucumber fishery (i.e. a low TL species with a high catch), combined with a change in the directed efforts of the artisanal fleet to off-shore fish species, rather than a result of in-shore stock recovery.

This reconstruction shows that although the fish species that nowadays contribute most to the finfish catch were all being exploited in the 1950s (Figure 3), their relative proportions have dramatically changed over time. This transition represents a strong case of fishing down marine food webs, and not of 'fishing through marine food webs', which pertain to cases where low trophic level taxa are added to the exploited species, without the high-trophic level species being depleted (Essington *et al.*, 2006). When the in-shore and off-shore ecosystems are separated and sea cucumbers are removed from the analysis, the degree of fishing down observed in the in-shore Galápagos finfish fishery (0.12 TL decade^{-1}) is consistent with global trends (Pauly *et al.*, 1998).

Industrial tuna fisheries

Although no catch estimates were available for illegal industrial tuna fishing, this is an ongoing problem within the waters of the GMR. Between 1989 and 1996, 48 vessels (both Ecuadorian and foreign) were caught illegally fishing for tuna (Altamirano and Aguiñaga, 2002). Subsequently, from 1996–1998, 119 tuna boats were either caught or observed, although this decreased to a total of 61 boats in the following six years (Reyes and Murillo, 2007). Most of these vessels were purse-seiners, but some also use longlines, a largely non-selective technique that catches both targeted marine life, and untargeted species (e.g. sea turtles, dolphins, seabirds) as well. Gales (1998) suggests that 'the best available evidence indicates that longline fishing is the most serious threat facing albatrosses today' – a statement that is even more applicable in the Galápagos since the 'Critically Endangered' waved albatross (*Phoebastria irrorata*) breeds almost exclusively on Española Island (Merlen, 1998; Anderson *et al.*, 2008; BirdLife International, 2013).

Sharks

As suggested by Jacquet *et al.* (2008), there is substantial under-reporting of shark catches in

Ecuador. Carr *et al.* (2013) recently documented that of 379 sharks taken by an illegal Ecuadorian longlining vessel within the GMR in 2011, 80% were bigeye thresher (*Alopias superciliosus*), 11% were silky (*Carcharhinus falciformes*), and only 6% were blue (*Prionace glauca*). Although these numbers refer to one isolated seizure, there is a notable difference in the catch composition when compared with the species breakdown used in this study. At an ecosystem level, these findings may therefore reflect a change in abundance of certain species, specifically a decline in *P. glauca*.

The main incentive for shark fishing and finning in the last decade has been the demand from mainly East Asian markets, and Hong Kong in particular (Camhi, 1995; Clarke *et al.*, 2007). Although tasteless, cartilaginous shark fins typically cost between $US400–1000 kg^{-1} (WildAid, 2007), and are the principal ingredient in fashionable sharkfin soup. As a result of growing concerns over the sustainability and health of shark populations, large-scale shark fishing and shark fin export were banned in Ecuador in 1989 and 2004 respectively (Jacquet *et al.*, 2008). While these efforts initially made Ecuador a world-leader in protective shark legislation, in July 2007, the Ecuadorian Government officially enacted an amendment to the previous laws. Although this amendment still prohibits shark finning and the dumping of sharks at sea, fishers are now allowed to trade fins extracted from sharks incidentally caught during fishery activities under a special permit (Jacquet *et al.*, 2008). Unfortunately, in Ecuador, ‘incidental catch’ can be as high as 70% (Aguilar, 2006), with 100% mortality of by-caught sharks (Coello *et al.*, 2010). This loophole has allowed fishers to continue to trade shark fins without legal consequences (Carr *et al.*, 2013).

Along with other pelagic fish, sharks play a vital role as apex predators in top-down regulated marine ecosystems (Stevens *et al.*, 2000; Myers *et al.*, 2007). Using an ecosystem model, Okey *et al.* (2004) predicted that the complete removal of sharks in the Galápagos would result in increases in toothed cetaceans, sea lions, and non-commercial reef predators, and subsequently lead to a decrease in bacalao and other commercially valuable fish species.

CONCLUSIONS

As of 2006, 57 marine species (including 17 sharks) from the Galápagos were on the IUCN Red List, and the principal threat to 32% of marine species ranked ‘Vulnerable’ or higher was fisheries related (Banks, 2007). Since many of the serranids described in this study are endemic to the Galápagos, they are very susceptible to extinction, and therefore require immediate conservation attention. The removal of predators can be detrimental to the ecosystem as a whole, and Ruttenberg (2001) suggests that fishing for *M. olfax* not only directly affects the size and health of targeted populations, but also triggers cascading effects, resulting in decreased natural diversity in fish community structure in areas experiencing high levels of fishing. Banks *et al.* (2012) have demonstrated that at locations where fishing is prohibited in the GMR, there is a higher biomass of top predators (including *M. olfax*). As such, a potential remedy against ‘fishing down’ could be the insertion of ‘nursery zones’, as well as the addition and strengthening of restricted zones within the GMR (Edgar *et al.*, 2008; Banks *et al.*, 2012). These measures should enable fished-down populations to rebuild, allow high trophic level species to regain their ascendancy, and provide spillover into the surrounding marine environment.

Based on the past history of sea cucumber fishing in the Galápagos and the current state of the in-shore finfish fishery in this region, if additional invertebrate fisheries for other sea cucumbers and urchins were initiated here, it is likely that these species would face a similar overexploitation. As discussed above, trophic interactions between the fish and invertebrate species in the Galápagos appear to be fragile and highly susceptible to the impacts of fishing. Although an ecosystem-based, co-management approach (including the adoption of marine zoning), was implemented in the GMR at the end of the 1990s, the proposed management objectives faced several institutional challenges and were not fully accomplished in practice (Castrejón and Charles, 2013). In this context, the inclusion of an adaptive fisheries management component to provide feedback from monitoring to account for uncertainties and shortcomings could help improve the ecosystem-based approach in the long term. Given that the socio-economic state of the islands directly affects the marine environment, Villalta-Gómez (2013) also suggests an integration of marine and terrestrial management plans. Such merging would not only improve current conservation initiatives and scientific monitoring, but also allow for new challenges (e.g. impacts of climate change) to be addressed in a more coherent manner.

We fear that both the quantity of sharks and the rate at which they are being extracted from the Galápagos archipelago are among the highest of any EEZ in the world, and urgent and immediate attention to the shark fishing problem in the GMR is required (Carr *et al.*, 2013). Given that between 2001 and 2007, there were 29 reported seizures of boats illegally shark fishing in the GMR (Carr *et al.*, 2013), and based on the shark catch determined by this reconstruction, the development of proactive, targeted shark conservation measures within the archipelago should be of paramount importance.

In 2002, the whale shark (*Rhincodon typus*) was listed under Appendix II of the Convention on International Trade in Endangered Species (CITES, 2002), and the recent inclusion of three hammerhead species (i.e. scalloped, *Sphyrna lewini*; smooth, *S. zygaena*; and great hammerhead shark, *S. mokarran*) and the oceanic white tip (*Carcharhinus longimanus*) on this list (CITES, 2013) will hopefully result in increased export monitoring and thus a decreased incentive to catch and fin these species. Nonetheless, given the current scope of these illegal activities, it is not unrealistic to imagine several shark species being locally extirpated from the Galápagos within the next few decades. Despite the monetary cost, increased on-water enforcement and monitoring within the GMR may be the most effective measure, as this would provide a visible deterrent to illegal fishing practices.

As discussed by Villalta-Gómez (2013), the conservation status of the GMR is currently 'unfavourable' and its management plan should be restructured. Nonetheless, it is encouraging to note the recent attention given to obtaining and integrating data on the marine species and environment, interactions with human activities, and the biophysical properties of the archipelago (Banks *et al.*, 2012; Luna *et al.*, 2013). Given both its intrinsic value as a highly biodiverse and endemic region, and its economic value in terms of tourism and fisheries, a continuing focus on rebuilding sustainable fisheries will be essential for the long-term health of the marine resources, and people, of the Galápagos Islands.

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