Biodivers Conserv
DOI 10.1007/s10531-014-0679-5

ORIGINAL PAPER

Applying complementary species vulnerability assessments to improve conservation strategies in the Galapagos Marine Reserve

Katherine A. Kaplan · Ignasi Montero-Serra · Ernesto L. Vaca-Pita · Patrick J. Sullivan · Esteban Suárez · Luis Vinueza

Received: 19 October 2013 / Revised: 1 March 2014 / Accepted: 19 March 2014

Abstract Marine biodiversity can be protected by identifying vulnerable species and creating marine protected areas (MPAs) to ensure their survival. A wide variety of methods are employed by environmental managers to determine areas of conservation priority, however which methods should be applied is often a subject of debate for practitioners and scientists. We applied two species vulnerability assessments, the International Union for the Conservation of Nature (IUCN) red list of threatened species and FishBase's intrinsic vulnerability assessment, to fish communities in three coastal habitats (mangrove, rocky and coral) on the island of San Cristobal, Galapagos. When using the IUCN red list of threatened species, rocky reefs hosted the greatest number of vulnerable species, however when applying the FishBase assessment of intrinsic vulnerability mangroves hosted the greatest abundance of 'very-highly' vulnerable species and coral ecosystems hosted the greatest abundance of 'highly' vulnerable species. The two methods showed little overlap

---

Communicated by Angus Jackson.

K. A. Kaplan · E. Suárez · L. Vinueza
Colegio de Ciencias Biológicas y Ambientales, Universidad San Francisco de Quito, Diego de Robles y Vía Interoceánica, Quito, Ecuador

Present Address:
K. A. Kaplan (✉) · P. J. Sullivan
Department of Natural Resources, Cornell University, 310 Fernow Hall, Ithaca, NY 14850, USA
e-mail: kak323@cornell.edu

I. Montero-Serra
Departament d'Ecologia, Facultat de Biologia, Universitat de Barcelona, Avda. Diagonal 645, 08028 Barcelona, Spain

E. L. Vaca-Pita
San Cristobal Technical Office, Galapagos National Park, Vía Perimetral, Puerto Baquerizo Moreno, San Cristóbal, Galapagos Islands, Ecuador

E. L. Vaca-Pita
Galapagos Science Center, Alsacio Northía Av. Vía Playa Mann, Puerto Baquerizo Moreno, San Cristóbal, Galapagos Islands, Ecuador

in determining habitat types that host vulnerable species because they rely on different biological and ecological parameters. Since extensive data is required for IUCN red list assessments, we show that the intrinsic vulnerability assessment from FishBase can be used to complement the IUCN red list especially in data-poor areas. Intrinsic vulnerability assessments are based on less data-intensive methods than the IUCN red list, but nonetheless may bridge information gaps that can arise when using the IUCN red list alone. Vulnerability assessments based on intrinsic factors are not widely applied in marine spatial planning, but their inclusion as a tool for forming conservation strategies can be useful in preventing species loss.

Keywords Conservation planning · Marine fish · IUCN red list of threatened species · FishBase · Fuzzy logic · Galapagos marine reserve

Introduction

The conservation of habitats that host vulnerable species and the establishment of marine protected areas (MPAs) are seen as two of the best approaches to maintaining the biodiversity and ecological integrity of marine ecosystems (Fernandes et al. 2005; Briggs 2011). Protecting biodiversity is the main objective of many successful marine conservation programs (Leslie 2005) and proper implementation of these programs necessitates the identification of species vulnerable to extinction. Species vulnerability is defined as species threatened by extinction or extirpation on local or regional scales (Dulvy et al. 2003; Cheung et al. 2005); however, it is also necessary to include the factors driving a species to extinction in the definition. Extinction drivers may include global climate change, habitat destruction, strong El Niño Southern Oscillation (ENSO) events, pollution, fishing pressure, invasive species or loss of top predators (Myers and Worm 2003; Polidoro et al. 2012). Alternatively, one can conceptualize vulnerable species as possessing biological and ecological characteristics that make them less resilient and resistant to natural and anthropogenic perturbations (Cheung et al. 2005; Dulvy et al. 2004).

The methods used to assess vulnerability vary depending on the conceptual frameworks in which they are founded. For example, some populations, such as many Galapagos species, may be particularly vulnerable to sudden climatic changes such as strong ENSO events (Edgar et al. 2009), which are the primary extinction driver while other species are more intrinsically vulnerable to fishing pressure due to life-history and ecological characteristics that make capture more likely by fishing gear (Cheung et al. 2005; Polidoro et al. 2012). The initial characterization of vulnerability as defined by threats, such as sudden perturbations in extreme climatic events (Edgar et al. 2009), or longer-term pressures such as overfishing (Worm et al. 2009), can significantly impact the efficacy of management strategies used to prevent extinctions, thus we must critically examine the criteria used for vulnerability assessment in the context of the dominant threats present in the MPA being evaluated.

Many marine species are vulnerable to extinction as a result of fishing pressure (Briggs 2011), however we lack data necessary to assess current population trends for many species (Le Quesne and Jennings 2011), and over 80 % of fisheries worldwide remain unassessed (Costello et al. 2012). Since fisheries frequently exploit larger fish, many species of commercial interest are intrinsically vulnerable to extinction due to life-history characteristics such as a large maximum length, a late age of first reproduction and long generation times (Pauly et al. 1998; Cheung et al. 2005; Reynolds et al. 2005). However, even species of little commercial value can come under threat from fishing through by-catch (Walker et al. 2005; Casey and Myers 1998), or disturbances created by fishing activities. Furthermore the loss of species due to fishing can have cascading effects on the ecosystem as a whole (Baum and Worm 2009; Myers and Worm 2003), which threatens biodiversity and the ecological integrity of marine ecosystems (Duffy 2003; Le Quesne and Jennings 2011; Worm et al. 2006). Although species vulnerability assessments do not consider the functional role of species, protecting vulnerable keystone species has the dual benefit of preventing species loss and promoting the ecological integrity of the entire ecosystem (Myers and Worm 2003; Myers et al. 2007; Ferretti et al. 2010). Many species possessing life-history and ecological traits that make them intrinsically vulnerable also play important roles in maintaining trophic structures, which enhances the resilience of the ecosystem (Myers and Worm 2005).

Cheung et al. (2005) created a method that employs a fuzzy logic expert system to determine species intrinsically vulnerable to extinction in the context of fishing pressure relative to ecological and life-history characteristics. This methodology, which is used in a vulnerability assessment on FishBase (Froese and Pauly 2014), allows estimation of intrinsic vulnerability even when uncertainty exists for some life-history traits, and therefore can be useful in assessing vulnerability in data-poor areas. The method applies the ‘precautionary principle’ (Lauck et al. 1998) as it conceptualizes vulnerability by identifying inherent characteristics that make species susceptible to fishing pressure, rather than characteristics used to identify species already on the path to extinction. However, this method has yet to be widely applied to large-scale marine spatial planning for conservation purposes.

In contrast, the International Union of the Conservation of Nature (IUCN) red list of threatened species calculates risk for extinction based on data from existing populations, their geographic distributions and external threats (Mace et al. 2008). It provides valuable information on species that are currently under threat by various factors and is the most widely accepted method for identifying species at risk of extinction (Rodrigues et al. 2006; Hayward 2011). The IUCN red list determines vulnerability by examining populations that are declining worldwide as well as endemic species with a limited geographic range under threat by various factors (Mace et al. 2008). Though this assessment approach is comprehensive in that it considers multiple extinction drivers and population attributes, collecting the necessary data for such assessments can be costly and time consuming. Also, some marine species are not assessed on the IUCN red list because data is lacking about the degree to which these populations are threatened and population projection information remains incomplete.

Several studies have attempted to use vulnerability assessments to create conservation priorities in reserve planning; for example (Eken et al. 2004) outline the key-biodiversity area concept, which involves identifying areas of global conservation significance using information on vulnerability and irreplaceability of species. Vulnerable sites include areas that host one or more globally threatened species, while irreplaceable sites are areas that host a significant proportion of the global population of a species. Key-biodiversity areas are created using globally applicable criteria (Margules and Pressey 2000) and use the IUCN red list of threatened species for identifying conservation targets (Eken et al. 2004). A study by Edgar et al. (2009) applied the key-biodiversity area criteria, to sites on several of the islands in the Galapagos Archipelago and recommendations were made for changing the coastline zoning scheme based on their findings. Key-biodiversity area methods are increasingly being employed by marine managers, for example a 45 million dollar conservation project was recently approved in the Philippines with the objective of improving MPAs using key-biodiversity area methodologies, based on the IUCN red list, to identify areas in need of protection (GEF, Global Environment Facility 2012). These strategies are significantly affected by the conceptual frameworks of vulnerability in which their methods are founded and can be expanded by allowing project managers to apply complementary methods based on the specific context of the protected area.

This study applies intrinsic vulnerability data from FishBase and the IUCN red list of threatened species to assess the vulnerability of fish communities at six sites off the island of San Cristobal, Galapagos, Ecuador. The two vulnerability assessments were applied to fish communities in three coastal habitats (rocky, mangrove and coral) to determine whether vulnerability assessments using these methods would draw similar conclusions in terms of locating habitat conservation priorities of vulnerable fish species. Although the two methods use different criteria, it was hypothesized that there would be a high degree of overlap in the number and type of fish species identified as vulnerable and that similar conclusions would be reached as to which ecosystem types host the most vulnerable species. By comparing FishBase and IUCN criteria we demonstrate that dissimilarities in the definition of species vulnerability can significantly affect the identification of areas that should have a high priority for conservation and that these approaches to vulnerability can complement each other providing stronger conservation recommendations.

Materials and methods

Study area

The Galapagos Marine Reserve covers 133,000 km^2 and is the largest MPA in Ecuador and one of the largest in the world. The islands are 1,000 km from the Ecuadorian mainland (between 01°40 N' to 01 °25′ S and 89°15′ W to 92°00′ W). The climate varies between the cool dry season (June to December), and a hot wet season (December to May). The Galapagos is one of the areas of the world most significantly impacted by the ENSO, a periodic extreme warming of oceanic temperatures during which time temperatures up to 5 °C above the long-term average are observed. In the warm season an El Niño event may occur followed sometimes by unusually cold temperatures, a La Niña event, during the cool season. (Barber and Chavez 1986). The warming El Niño event can have devastating consequences for marine species, since it reduces the number of dissolved nutrients thereby decreasing primary production (Barber and Chavez 1986; Edgar et al. 2009).

The study areas are in six different locations on San Cristobal Island (Fig. 1). Only a few coral and mangrove habitats have been found on this island, two of each are included in this study, while the rest of the island, and over 90 % of Galapagos is dominated by rocky reef ecosystems (Bustamante et al. 2002). The six sites and ecosystem types for this study include: Isla Lobos (rocky), Negritas (rocky), Punta Pitt (coral), Rosa Blanca (coral), Rosa Blanca (mangrove), and Tortuga (mangrove, Fig. 1). The Island of San Cristobal also hosts an important fisher community in the Galapagos Marine Reserve and commercially important species populations have declined along its coast (Nicolaides et al. 2002).

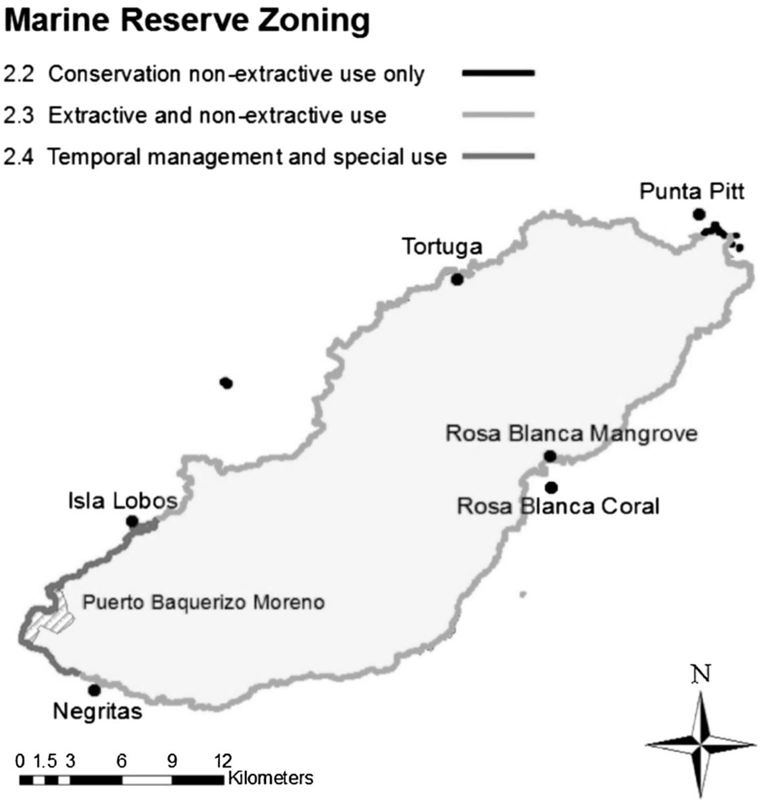


Fig. 1 Map of San Cristóbal island with Galapagos National Park Marine Reserve Zoning and locations of the six sites where the study was conducted: Negritas (Rocky); Isla Lobos (Rocky); Rosa Blanca (Coral and Mangrove); La Tortuga (Mangrove); Punta Pitt (Coral). The island of San Cristobal is under Zone 2, which is designated in the Limited Use category of the Galapagos Marine Reserve Zoning. Zone 2.1 Conservation and Non-extractive activities such as fishing are prohibited in these areas. Zone 2.2 Extractive and Non-extractive activities indicates these areas are open to fishing and tourism. Zone 2.3 Temporal Management and Special Use indicates these areas are subject to change based on local participatory management decisions and may be used as experimental zones, recovery zones for degraded areas or remain open to extractive and non-extractive activities

Fish community survey

Data were collected over an eight-month period from January 2010 to August 2010 with a total of 181 transects allocated across the six study sites. Data on fish abundance and species richness were collected visually using transects two meters wide 50 m long and two meters in height measured from the sea floor toward the surface. The survey method consisted of one researcher holding one end of the transect line while another researcher lay the transect line, both researchers then fastened their end of the transect line in place using rocks. Then one randomly selected researcher would swim toward the other counting species in the water column up to two meters above the benthic habitat. In total, 67 fish species were observed across all ecosystem types during the study period. Data were collected by scuba diving at all sites except the mangrove ecosystems where transects were collected through snorkeling (Tortuga and Rosa Blanca). Between three to six transects were conducted for each scuba-dive (at a depth of 5–12 m) or snorkel (at a depth of 1–3 m) survey. Rarefaction was used to determine the number of transects necessary to provide a representative sample of the fish community in each habitat type (Krebs 1999; Fig. 2). The method calculates the cumulative average diversity of a species and its standard deviation using the Shannon index (H') (Krebs 1999). Diversity curves and standard deviations were generated by MATLAB 2009 (version 7.8, 2009), using a permutation method applied to the original data while maintaining a margin of error at 0.05. This error is obtained from the data's coefficient of variation and is measured when the cumulative average reaches asymptote, thereby determining the minimum sample size necessary for characterizing the fish communities in each ecosystem. Diversity curves reached asymptote (Coefficient of variation = 0.05) at 27 transects for coral, 26 transects for mangroves, and 21 transects for rocky habitats, confirming that the sample size or number of transects obtained for each ecosystem (56 for coral, 67 for mangrove and 58 for rocky) was sufficient to describe the composition of each ecosystem's fish community with a Type I error lower than 0.05 (Fig. 2a–c).

Methods for assessing vulnerability

Intrinsic vulnerability assessment using fuzzy logic expert system

The method created by (Cheung et al. 2005) and applied within the FishBase protocol assumes that the intrinsic vulnerability of a species is a function of the susceptibility of the species to fishing pressure, which is related to the species' maximum rate of population growth and strength of density dependence. FishBase uses fuzzy logic to estimate the degree of membership in certain vulnerability categories. The input variables for the fuzzy expert system are maximum length, age at first maturity, longevity, von Bertalanffy growth parameter K, natural mortality rate, fecundity, strength of spatial behavior and geographic range (Cheung et al. 2005). The minimum requirement for the fuzzy expert system to operate is maximum length (Cheung et al. 2007), since it has been demonstrated that large, late-maturing species show strong density dependence at low abundances and high vulnerability particularly to fishing pressures (Reynolds et al. 2005), which is also evidenced by the 'fishing down marine food webs' effect (Pauly et al. 1998). The outputs are categorized into four levels of intrinsic vulnerability to extinction and placed on a scale from 1 to 100 with 100 being the most vulnerable described as follows: Low (0–30); Moderate (30–50); High (50–70) and Very high (70–100). For this study only species within the 'High' (50–70) and 'Very High' (>70) intrinsic vulnerability categories were included in the identification process, in order to identify the species that are least resilient, even though these species' populations may not be in imminent danger of extinction.

IUCN Criteria for assessing vulnerable species

The IUCN red list of threatened species categorizes species into the following: extinct (EX), extinct in the wild (EW), critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC) and data deficient (DD) (Mace et al. 2008). There are three categories, which indicate that a species is threatened: vulnerable (VU), endangered (EN) or critically endangered (CR) and only these categories were considered

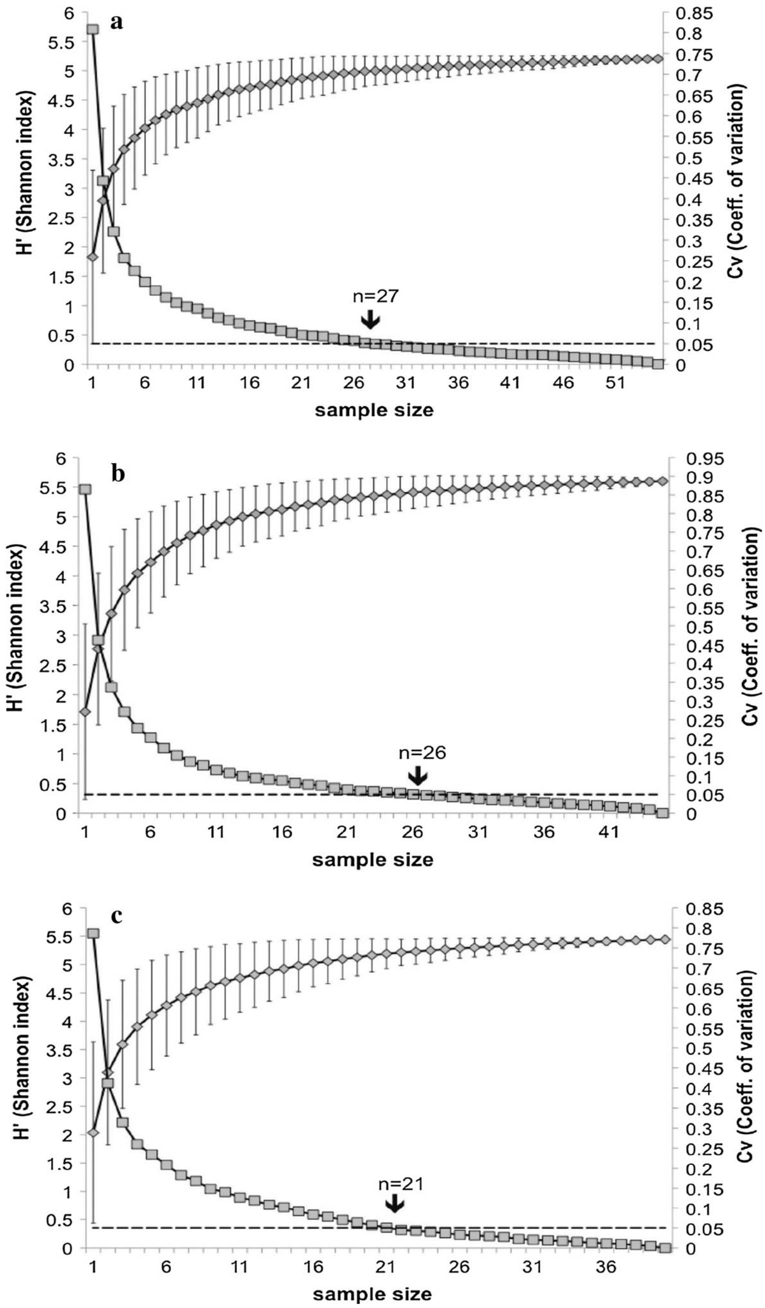


Fig. 2 **a** Coral mean cumulative fish diversity curves (Shannon index, H′) and SD based on sample size (*transects*) collected at two coral habitats, Punta Pitt and Rosa Blanca. **b** Mangrove mean cumulative fish diversity curve and SD conducted at two mangrove habitats, Tortuga and Rosa Blanca Mangrove. **c** Rocky reef mean cumulative fish diversity curve and SD ecosystems based on sample size (*transects*) conducted at two rocky reef habitats, Negritas and Isla Lobos. Cumulative diversity is based on Shannon index (H′). n = optimum sample size

for vulnerable species in this study. A species whose biology is well known, but the global range and known threats are missing will be listed as DD (Mace et al. 2008).

Five different criteria (A–E) are used to determine species vulnerability and a species is classified using only one category (Mace et al. 2008). The first criteria, or Criterion A, is a high rate of decline as determined by an estimate of the current population size in comparison of an estimate from the past or a projection for the future and change over a specific time measured in as percentage of loss. A species is classified into Criterion B when the geographical range becomes overly restricted and when other factors suggest that it is at risk. This applies when a species is restricted to small areas or to habitat remnants that are being diminished. Criterion C focuses on small population sizes and decline. The thresholds are selected by the number of mature individuals and are derived by theoretical values for minimum viable populations adjusted to reflect timescales appropriate for the species. Criterion D involves very small population sizes without evidence that there has been or will be a decline because small populations can have high extinction risks from internal processes such as demographic stochasticity meaning the process whereby random variation among individuals in certain demographics such as sex ratios can lead to extinction. Criterion E uses any kind of quantitative analysis for assessing risk of extinction, which is then compared to the extinction-risk thresholds and expressed as the probability of extinction within a given time frame. Essentially it is any case where a robust estimate of extinction risk can be determined, which might be done without detailed information on population dynamics.

While, there is some overlap between the criteria used in the fuzzy logic expert system on FishBase and the IUCN red list (Table 1), the IUCN red list generally requires more extensive data inputs (Mace et al. 2008; IUCN 2014) whereas the fuzzy logic expert system is more flexible in its input requirements (Cheung et al. 2005; 2007).

Table 1 A comparison of criteria analyzed by FishBase and IUCN vulnerability assessments

Criteria:	IUCN red list	FishBase's fuzzy expert system
Declining population from past or future projection	X	
Limited number of mature individuals	X	
Declining number of mature individuals	X	
Extreme population fluctuations	X	
Generation length	X	X
Limited geographic range/distribution	X	X
Small population size	X	
Population viability/habitat degradation projections	X	
Maximum length		X
Age at first maturity	X*	X
Von Bertalanffy growth parameter (K)		X
Natural mortality rate	X*	X
Maximum age		X
Fecundity	X*	X
Spatial behavior strength		X

X* indicates factors are considered only as they relate to population trend analysis and population predictions. The fuzzy expert system can use these categories independently to make an assessment

Data analysis

We calculated the total abundance of vulnerable species per transect (using both IUCN and FishBase assessments) by ecosystem (mangrove, coral and rocky) and by seasons (cool and warm) using negative binomial generalized linear models (NB-GLM) to account for the large numbers of zero vulnerable species along some transects. All statistical analyses were performed using R programming language (v 2.15.3), including NB-GLM from the package MASS (Venables and Ripley 2002).

Additionally, we calculated the mean trophic level per habitat type to see if there are differences in the trophic positions of the species being recommended for protection when using IUCN vulnerable species abundance and FishBase vulnerable species abundance. Mean trophic level (MTL) was calculated by summing the total abundance of vulnerable species using the IUCN red list species and the FishBase species for all transects per ecosystem and weighting species' trophic levels by their abundance to obtain a final weighted average.

$$MTL_j = \frac{\sum_{i=1}^{n} N^\circ Spi \cdot TLSpi}{\sum_{i=1}^{n} N^\circ Spi}$$

MTL = Mean Trophic Level in habitat type (j). N°Spi = Number of individuals from the vulnerable species (i) counted during the surveys. TLSpi = Trophic Level of the vulnerable species (i), obtained from FishBase.

We also determined the richness (number of species) and the total abundance (total number of individuals) to see which ecosystem had the greatest biodiversity and productivity for its fish assemblage. A two-way analysis of variance (ANOVA) was used to test differences in richness between habitat types (mangrove, coral and rocky) and between seasons (cool and warm) since normality and homogeneity of variances were proven after a square root transformation. A generalized linear model under a Poisson likelihood was used to test for differences in abundance between ecosystems and season.

Results

Distribution of IUCN vulnerable species across ecosystems

A total of nine species out of the 67 species encountered in the study were found to be vulnerable according to the IUCN red list criteria (Table 2, Appendix). The NB-GLM demonstrated that rocky reef habitats hosted the greatest total abundance of IUCN vulnerable species compared to mangroves and corals ($p < 0.001$, Fig. 3a), with no significant difference between seasons ($p = 0.374$, Fig. 3a). The majority of species from the IUCN red list qualify because they are endemic and threatened by El Niño events, as are all Galapagos species (Table 2, Appendix).

The Galapagos ring-tail damsel fish, *Stegastes beebei,* was the most abundant of the IUCN vulnerable species (making up 65 % of the abundance in rocky habitats, 90 % in corals and 34 % in mangroves), and the black-striped salema (*Xenocys jessiae)* was the second most abundant (33 % in rocky, 3 % in corals and 54 % in mangroves). The black striped salema is endemic to Galapagos, and the Galapagos ring-tail damsel fish is found in Galapagos, Malpelo Island, Pearl Islands and Cocos Islands, though Galapagos is considered the only self-sustaining population since its adult population

Table 2 FishBase and IUCN red list vulnerable species with corresponding population trends, threats and endemism (IUCN 2013) and trophic level information (FishBase 2013)

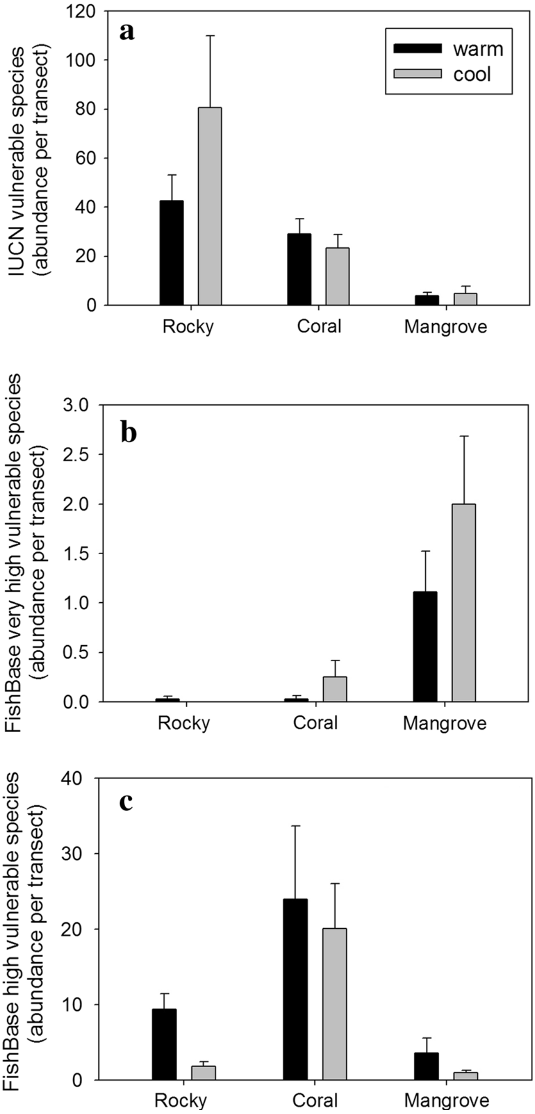
FishBase very highly vulnerable species	FishBase vulnerability score	IUCN status	Population trends	Endemism	Trophic level
Dasyatis brevis	76	DD	Unknown	Native	3.85
Lutjanus novemfasciatus	76	LC	Unknown	Native	4.10
Aetobatus narinari	74	NT	Decreasing	Native	3.24
Triaenodon obesus	83	NT	Unknown	Native	4.19
Taeniura meyeni	77	VU	Unknown	Native	4.20
FishBase highly vulnerable species					
Kyphosus elegans	50	LC	Stable	Endemic	2.94
Muraena argus	52	LC	Unknown	Endemic	4.02
Scarus rubroviolaceus	52	LC	Unknown	Native	2
Balistes polylepis	54	LC	Unknown	Endemic	3.34
Carcharhinus limbatus	55	NT	Unknown	Native	4.24
Lutjanus argentiventris	56	LC	Unknown	Endemic	4.04
Mycteroperca olfax	56	VU	Unknown	Endemic	4.5
Anisotremus interruptus	58	LC	Unknown	Endemic	3.5
Bodianus diplotaenia	63	LC	Stable	Endemic	3.44
Fistularia commersonii	68	LC	Not available	Native	4.26
IUCN vulnerable species					
Acanthemblemaria castroi	10	VU	Unknown	Galapagos	3.43
Archosargus pourtalesii	37	VU	NA	Galapagos	2.90
Hippocampus ingens	27	VU	Decreasing	Native	3.26
Labrisomus dendriticus	10	VU	Unknown	Galapagos and Malpelo islands	3.98
Mycteroperca olfax	56	VU	Unknown	Galapagos and Cocos islands	4.50
Stegastes beebei	32	VU	Unknown	Galapagos, Malpelo, Cocos and Pearl islands	2.95
Taeniura meyeni	77	VU	Unknown	Native	4.20
Xenichthys agassizi	25	VU	Unknown	Galapagos	3.36
Xenocys jessiae	32	VU	Unknown	Galapagos	3.4

IUCN status: Least Concern (LC), Vulnerable (VU), Near Threatened (NT) and Data Deficient (DD) (IUCN 2013)

FishBase 'very highly' vulnerable species received a vulnerability score above 70 and FishBase 'highly' vulnerable species received a score between 50 and 70 using the fuzzy logic expert system for determining intrinsic vulnerability

appears to be restricted to Galapagos (Allen et al. 2010). Only one of the species, the marbled ray (*Taeniura meyeni*), overlaps as vulnerable on the IUCN red list and as very highly vulnerable using FishBase's fuzzy logic expert system (Table 2). Mean

Fig. 3 **a** Average abundance per transect of IUCN vulnerable species between habitat types ($p < 0.001$) and season ($p = 0.29$) ± 1 SEM. **b** Abundance per transect of FishBase's very-high intrinsically vulnerable species across habitat types ($p < 0.001$) and season ($p = 0.109$) ± 1 SEM. **c** Abundance per transect of FishBase's high vulnerable species across habitat types ($p < 0.001$) and season ($p = 0.001$) ± 1 SEM



trophic levels (MTL) of the aggregated abundance of FishBase vulnerable species were higher than IUCN vulnerable species across all habitat types with mangroves, corals and rocky reefs having a MTL of 4.10, 4.02, and 4.20 respectively for 'very-high' vulnerable species and FishBase high vulnerable species had a MTL of 4.04, 3.48 and 3.45 for mangroves, corals and rocky reefs respectively. For IUCN vulnerable species mangroves, corals and rocky reefs had MTLs of 3.25, 3.02, and 3.11 respectively. Furthermore, three species were listed as DD and population trends were unknown for 37 of the 67 species found in this study, although all species had a vulnerability score on FishBase (Appendix).

Distribution of FishBase's intrinsically vulnerable species across ecosystems

Using FishBase's vulnerability assessment, five species across all three habitat types had life history and ecological characteristics that placed them in the 'very-high' intrinsic vulnerability category with a score greater than 70 in the fuzzy logic expert system (Table 2). In addition to being very highly vulnerable, two of the five species are high trophic level predators with a trophic level above 3.8 (*Triaenodon obesus* and *Lutjanus novemfasciatus)* and the other three are predatory rays (*Dasyatis brevis, Aetobatus narinari, Taeniura meyeri*; Table 2). Mangroves had the greatest abundance of very-highly vulnerable species per transect as indicated by the NB-GLM when compared to rocky and coral habitats ($p < 0.001$, Fig. 3b), and there was no significant effect of season ($p = 0.109$, Fig. 3b).

When we lowered the FishBase intrinsic vulnerability threshold to represent species with 'high' vulnerability scoring between 50–70 on the FishBase fuzzy logic expert system, ten species encountered in this study were found in this category (Table 2). Coral ecosystems hosted the highest density of species with 'high' intrinsic vulnerability followed by rocky reefs and mangroves ($p < 0.001$) and more highly vulnerable species were present in the warm season ($p = 0.0001$, Fig. 3c) as indicated by the NB-GLM.

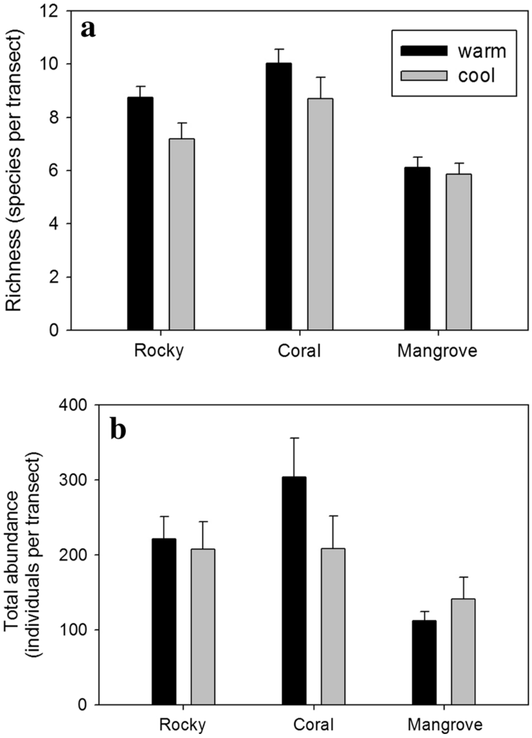
Abundance and richness for determining biodiversity

Although mangroves were shown to host the most vulnerable species, a two-way ANOVA indicated that mangroves hosted the lowest richness ($F_{2,173} = 22.311$, $p < 0.001$, Fig. 4a) with corals and rocky ecosystems having greater richness, though no significant difference was observed between rocky and coral ecosystems (Tukey HSD, $p = 0.167$, Fig. 4a) and the warm season had significantly greater richness across all ecosystems ($F_{1,173} = 7.116$, $p < 0.01$, Fig. 4a), however, no interaction effect between season and ecosystem was observed ($F_{2,173} = 1.044$, $p = 0.354$, Fig. 4a). A generalized linear model (GLM) with a Poisson likelihood was used to test the effect of habitat type and season on abundance, and indicated that coral habitats had the greatest abundance followed by rocky reefs and lastly mangroves ($p < 0.001$, Fig. 4b), and there was a significant difference detected between seasons ($p < 0.001$, Fig. 4b), with greater abundance in the warm season in rocky reef and coral habitats however, mangroves had greater abundance in the cool season ($p < 0.001$, Fig. 4b).

Discussion

Rocky reef habitats hosted the greatest abundance of IUCN vulnerable species due to the presence of two abundant endemic species (Fig. 3a, Appendix), though mangroves hosted the greatest number of FishBase's very highly vulnerable species (>70 on the FishBase fuzzy logic expert system) and corals hosted the greatest number of FishBase's highly vulnerable species (50–70 on the FishBase fuzzy logic expert system). Currently, the only study area in a no-take zone is the coral habitat, Punta Pitt (Fig. 1) and the majority of the island is open to fishing including mangrove habitat, though temporal restrictions exist in some zones. However, this study demonstrates that mangroves and corals are habitats of intrinsically vulnerable species and therefore merit consideration when forming conservation strategies designed to protect vulnerable species (Fig. 3b, c). The species identified as vulnerable by the IUCN red list have the most extensive habitat available, since rocky

Fig. 4 **a** Richness per transect in habitat types ($p < 0.001$) and season ($p < 0.01$). **b** Average total abundance per transect in habitat types ($p < 0.001$) and season ($p < 0.001$) ± 1 SEM



reefs make up over 90 % percent of Galapagos subtidal habitats (Bustamante et al. 2002). Only one of the 67 species found in this study, the marbled ray (*Taeniura meyeni)* overlaps as vulnerable on both the IUCN red list and as FishBase's 'very high' vulnerable species (Table 2) and one species overlaps on the IUCN red list and FishBase's 'high' vulnerable species, the Galapagos grouper (*Mycteroperca olfax)*; indicating that the ecological and life history characteristics that make a species intrinsically vulnerable, are not necessarily the species with declining populations, small population numbers in a restricted range or under threat from various extinction drivers evaluated by the IUCN red list (Mace et al. 2008).

The Galapagos grouper is a species that traditionally has been heavily fished in Galapagos for the past 30 years and was encountered in all three habitat types in this study (Appendix), however fishing efforts shifted to focus more heavily on invertebrates such as the sea cucumber (*Isostichopus fuscus*) and spiny lobster (*Panulirus penicillatus* and *Panulirus gracilis*) in the 1990s and 2000s (Reck 1983; Hearn 2008). San Cristobal Island hosts a large fisher community and as a result lower abundances of some species in certain habitat types may have been observed in this study. For example, *Lutjanus novemfasciatus*, the pacific dog snapper was observed mainly in the juvenile phase in mangroves in this study, however this species has been found in rocky reefs and coral habitats in other areas of the Eastern Tropical Pacific (FishBase 2014). Additionally, some studies indicate that the Galapagos grouper was present in higher densities in the past in the Galapagos Marine Reserve, but overfishing has led to a decline in this population, however data gaps still remain to fully assess population trends for this species on the IUCN red list (Reck 1983; Hearn 2008, IUCN 2014). Since large fishing communities exist in this area, approaches to species vulnerability that incorporate susceptibility to fishing pressure may also help bridge gaps in vulnerability assessment methods and provide a more nuanced recommendation of species in need of protection. Since sustainable management of living marine resources is essential to maintaining marine biodiversity, the tools applied to evaluating areas of conservation priority should consider human influence through fishing pressure and species susceptibility to marine resource use.

A key objective of MPAs is conservation of species by restricting harvest and usage of marine resources, thus when deciding conservation tools to apply in marine spatial planning a vulnerability assessment that is based on likelihood of extinction due to harvesting pressure, such as the FishBase fuzzy logic expert system, can be useful as one technique among several used in marine spatial planning. However, this technique has yet to be applied to large-scale marine spatial planning efforts, whereas the IUCN red list is frequently applied in contexts where population trends are unknown and some species of concern may lack the information needed to include them in conservation priorities. Additionally, our calculation of mean trophic levels for FishBase's intrinsically vulnerable species and IUCN vulnerable species across habitat types highlights the differences in the functional roles of species identified as vulnerable by the two assessment methods. The mean trophic level of FishBase vulnerable species is higher than that of the IUCN red list, and the necessity of protecting high trophic level predators to maintain ecological integrity has been well documented (Myers et al. 2007). Since intrinsically vulnerable species also tend to occupy higher trophic levels, protecting these species has the dual function of promoting ecological integrity while maintaining trophic structures. Additionally the widespread evidence for 'fishing down marine food webs' globally (Pauly et al. 1998) should necessitate a proactive approach toward maintaining species most vulnerable to fishing pressure. Furthermore, the characteristics of species determined intrinsically vulnerable by the FishBase criteria such as large maximum length and slow growth rate, also make a species less likely to recover from other extinction drivers since these populations recover slowly after a decline. Therefore, the FishBase vulnerability assessment can help inform marine managers within the context of the precautionary principle, since intrinsically vulnerable species are susceptible to slow recovery rates they merit special consideration when considering their habitat requirements.

Relying on the IUCN red list of vulnerable species as the only basis for identifying vulnerable species and basing conservation strategies around those designations can be problematic due to the lack of data for many marine species. For only three of the 15 species identified as intrinsically vulnerable using FishBase's vulnerability criteria, is the population trend known on the IUCN database (Table 2, Appendix) and one other species (the diamond ray) is too DD (data deficient) to make an assessment (Table 2); this suggests that many species that exist without sufficient data to make assessments may be in need of special conservation efforts. In the Eastern Tropical Pacific, half of the bony fishes listed as DD on the IUCN red list are threatened by heavy overfishing, but lack demographic and catch statistics to determine their threat status (Polidoro et al. 2012). Furthermore, approximately 45 % of marine mammals and cartilaginous fishes in the Eastern Tropical Pacific are classified as DD (Polidoro et al. 2012). In this study, population trends were identified on the IUCN red list for only 20 of the 67 species encountered (Appendix). Poor information about declining marine populations may result in an improper prioritization of areas for conservation action given information provided in IUCN red list alone and therefore the FishBase vulnerability assessment might be considered to complement the IUCN red list when data is lacking. A regional IUCN red list specific to Galapagos as a highly endemic area would be useful in this context since the high level of data inputs required would yield high accuracy, however data for regional IUCN red lists are even more lacking than the global list and a regional IUCN red list specific to Galapagos does not exist, therefore the problem of data deficiency remains for managers that need to make decisions in the present. Since the FishBase approach requires less data it may be more broadly applicable to areas that are high in biodiversity, but have relatively low investment and resources for research and monitoring programs.

The IUCN red list is useful in assessing extinction risk from multiple drivers including ENSO events, which are a major extinction driver on the islands. The comprehensive approach used by IUCN ensures that species with declining populations are identified and incorporated into conservation planning when data is available. For fish communities on San Cristobal Island our study identified rocky reefs as hosting species at greatest risk of extinction using the IUCN red list. Since the majority of the species qualify as vulnerable because of ENSO events it is necessary protect rocky reefs as habitats of these species in order to minimize the risk of extinction in endemic species. At the same time our study identified that mangroves host the extreme intrinsically vulnerable species and corals host species with a high level of intrinsic vulnerability. The FishBase intrinsic vulnerability assessment therefore complements the IUCN red list providing a more nuanced recommendation by expanding the criteria for ecosystems to be included as vulnerable species habitat, since it employs an alternative definition of vulnerability. Marine spatial planning efforts could benefit from this expansion of the tool set used to form conservation priorities, especially in data poor contexts since the minimum data requirements for FishBase's intrinsic vulnerability assessment are relatively low in comparison to the IUCN red list. If the precautionary principle is applied to marine management, FishBase can provide a useful benchmark for protecting species in that it can identify vulnerable populations before they begin to decline or come under threat (Lauck et al. 1998). Environmental managers should be cognizant of the unique features their protected area may possess as well as the scope of their conservation objective and then apply a suite of conservation tools that can complement each other to prevent key species from being overlooked when forming conservation recommendations.

Acknowledgments We would like to thank the Galapagos National Park and J. C. Murillo for making this project possible. We would also like to thank J. Denkinger, and Universidad San Francisco de Quito-Galapagos Academic Institute for the Arts and Sciences for providing resources and support for data collection.

Appendix

See Table 3.

Table 3. List of the 67 fish species encountered in this study with FishBase vulnerability scores, IUCN status, IUCN population trends, Galapagos Endemism (FishBase 2013, IUCN 2013), and abundance per transect observed across three habitat types

Species	FishBase	IUCN status	Population trends	Coral abundance	Mangrove abundance	Rocky abundance	Endemism
Abudefduf troschelii	30	LC	Unknown	2.34E+00	9.10E+00	1.07E+00	Endemic
Acanthemblemaria castroi	10	VU	Unknown			3.45E−02	Endemic
Acanthurus xanthopterus	37	LC	Stable	9.11E−01			
Aetobatus narinari	74	NT	Decreasing		1.49E−02		
Anisotremus interruptus	58	LC	Unknown	1.06E+01	1.49E−02	7.07E−01	Endemic
Apogon atradorsatus	11	LC	Unknown	2.98E+01		3.78E+00	Endemic
Archosargus pourtalesii	37	VU	Not available		2.54E−01		Endemic
Arothron meleagris	38	LC	Not available	3.57E−02			
Aulostomus chinensis	34	LC	Not available	7.14E−02		3.45E−02	
Balistes polylepis	54	LC	Unknown	3.57E−02			Endemic
Bodianus diplotaenia	63	LC	Stable	1.13E+01	1.79E−01	6.31E+00	Endemic
Canthigaster punctatissima	12	LC	Unknown	3.57E−02			Endemic
Caranx sexfasciatus	45	LC	Decreasing		2.99E−01		
Carcharhinus limbatus	55	NT	Unknown		2.99E−02		
Cephalopholis panamensis	38	LC	Stable	2.32E−01	1.49E−02	5.17E−02	Endemic
Chaetodon humeralis	20	LC	Stable	8.04E−01	1.34E−01		Endemic
Chromis atrilobata	29	LC	Unknown	8.93E−02		5.41E+00	Endemic
Cirrhitus rivulatus	28	LC	Stable	1.25E−01	1.49E-02	1.21E−01	Endemic
Dasyatis brevis	76	DD	Unknown	5.36E−02	8.96E-02		
Diodon holocanthus	28	LC	Not available	3.57E−02			
Diodon hystrix	48	LC	Not available		2.99E-02		
Echidna nocturna	31	LC	Unknown	1.79E−02			Endemic
Epinephelus labriformis	40	LC	Decreasing	3.04E−01	2.99E−02	3.28E−01	Endemic
Eucinostomus dowii	16	LC	Unknown	1.79E−02	7.81E+00		Endemic
Fistularia commersonii	68	LC	Not available	1.25E−01	1.04E−01	3.45E−02	

Table 3. continued

Species	FishBase	IUCN status	Population trends	Coral abundance	Mangrove abundance	Rocky abundance	Endemism
Girella freminvillei	42	LC	Not available	8.93E−02			Endemic
Haemulon scudderi	34	LC	Unknown	1.30E+00	1.18E+00	3.45E−02	Endemic
Halichoeres dispilus	33	LC	Stable	3.90E+01	1.27E+00	4.57E+01	Endemic
Halichoeres nicholsi	39	LC	Stable	1.77E+00	2.09E−01	9.83E−01	Endemic
Hippocampus ingens	27	VU	Decreasing		1.49E−02		Endemic
Holacanthus passer	35	LC	Stable	1.14E+00	5.97E−02	2.74E+00	Endemic
Johnrandallia nigrirostris	15	LC	Stable	1.50E+00	1.49E−02	3.45E−01	Endemic
Kyphosus elegans	50	LC	Stable	7.14E−02		1.72E−02	Endemic
Labrisomus dendriticus	10	VU	Unknown	2.32E−01	4.93E−01	5.69E−01	Endemic
Lutjanus argentiventris	56	LC	Unknown	8.93E−02	2.00E+00		Endemic
Lutjanus novemfasciatus	76	LC	Unknown		8.66E−01		Endemic
Lutjanus viridis	27	LC	Unknown	3.75E−01	9.40E−01	3.45E−02	Endemic
Microspathodon bairdii	42	LC	Unknown			6.21E−01	Endemic
Microspathodon dorsalis	46	LC	Unknown	5.36E−02	1.49E−02	5.86E−01	Endemic
Mulloidichthys dentatus	28	LC	Stable	8.93E−01			Endemic
Muraena argus	52	LC	Unknown	1.79E−02			Endemic
Muraena lentiginosa	29	LC	Unknown	5.36E−02			Endemic
Mycteroperca olfax	56	VU	Unknown	2.32E−01	1.64E−01	1.38E−01	Endemic
Nicholsina denticulata	25	LC	Unknown	5.36E−02	1.49E−02	1.72E−02	Endemic
Ophioblennius steindachneri	35	LC	Stable	5.36E−02	1.34E−01	1.72E−02	Endemic
Orthopristis forbesi	41	DD	Unknown	1.79E−01	2.99E−02		Endemic
Paranthias colonus	34	LC	Stable	9.66E+00	5.97E−02	1.54E+01	Endemic
Pareques perissa	25	DD	Unknown			1.72E−02	Endemic
Plagiotremus azaleus	21	LC	Stable	1.43E+00	3.13E−01	2.22E+00	Endemic
Prionurus laticlavius	41	LC	Stable	7.71E+01	1.79E−01	3.59E+01	Endemic
Scarus compressus	38	LC	Stable	1.61E−01		1.72E−02	Endemic

Table 3. continued

Species	FishBase	IUCN status	Population trends	Coral abundance	Mangrove abundance	Rocky abundance	Endemism
Scarus ghobban	37	LC	Unknown	4.11E+00	2.20E+01	1.21E−01	
Scarus perrico	42	LC	Stable	3.75E−01		2.24E−01	Endemic
Scarus rubroviolaceus	52	LC	Unknown	3.57E−02		1.03E−01	
Serranus psittacinus	24	LC	Unknown	1.79E−02	4.48E−02		Endemic
Sphoeroides annulatus	37	LC	Unknown	5.00E−01	1.55E+00	1.03E−01	Endemic
Stegastes arcifrons	29	LC	Unknown	3.93E+00	4.70E+01	6.00E+00	Endemic
Stegastes beebei	32	VU	Unknown	2.27E+01	1.37E+00	3.76E+01	Endemic
Sufflamen verres	34	LC	Unknown	5.00E−01		6.90E−02	Endemic
Synodus lacertinus	12	LC	Unknown	5.36E−02	1.19E−01	5.17E−02	Endemic
Taeniura meyeni	77	VU	Unknown	5.36E−02	4.48E−02	1.72E−02	
Thalassoma lucasanum	25	LC	Stable	3.41E+01	2.21E+01	2.27E+01	Endemic
Triaenodon obesus	83	NT	Unknown		4.63E−01		Endemic
Xenichthys agassizi	25	VU	Unknown	8.93E−01	2.99E−01		Endemic
Xenocys jessiae	32	VU	Unknown	2.50E+00	2.10E+00	1.86E+01	Endemic
Xenomugil thoburni	32	LC	Unknown		2.52E+00		
Zanclus cornutus	12	LC	Not available	1.07E−01			

IUCN status: Least Concern (LC), Vulnerable (VU), Near Threatened (NT) and Data Deficient (DD) (IUCN 2013). Population trends were not available for some species assessed by Polidoro et al. (2012), since these species have not been updated on the IUCN red list (IUCN 2013)

References

Allen G, Robertson R, Rivera R, Edgar G, Merlen G, Zapata F, Barraza E (2010) *Stegastes beebei*. In: IUCN 2013. IUCN Red list of threatened species. Version 2013.1

Barber RT, Chavez FP (1986) Ocean variability in relation to living resources during the 1982–83 El Niño. Nature 319:279–285

Baum JK, Worm B (2009) Cascading top-down effects of changing oceanic predator abundances. J Anim Ecol 78:699–714

Briggs JC (2011) Marine extinctions and conservation. Mar Biol 158:485–488

Bustamante RH, Wellington GM, Branch GM, Edgar GJ, Martínez P et al (2002) Outstanding marine features of Galápagos. In: Bensted-Smith R, Dinnerstein E (eds) A biodiversity vision for the Galapagos Islands: an exercise for ecoregional planning. WWF, Washington DC, pp 60–71

Casey JM, Myers RA (1998) Near extinction of a large, widely distributed fish. Science 281:690–692

Cheung WWL, Pitcher TJ, Pauly D (2005) A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. Biol Conserv 124:97–111

Cheung WWL, Watson R, Morato T, Pitcher TJ, Pauly D (2007) Intrinsic vulnerability in the global fish catch. Mar Ecol Prog Ser 333:1–12

Costello C, Ovando D, Hilborn R, Gaines SD, Deschenes O, Lester SE (2012) Status and Solutions for the World's Unassessed Fisheries. Science 338:517–520

Duffy JE (2003) Biodiversity loss, trophic skew, and ecosystem functioning. Ecol Lett 6:680–687

Dulvy NK, Sadovy Y, Reynolds JD (2003) Extinction vulnerability in marine populations. Fisheries 4:25–64

Dulvy NK, Ellis JR, Goodwin NB, Grant A, Reynolds JD, Jennings S (2004) Methods of assessing extinction risk in marine fishes. Fisheries 5:255–276

Edgar GJ, Banks S, Bensted-Smith R, Calvopiña M, Chiriboga A, Garske LE, Henderson S, Miller KA, Salazar S (2008) Conservation of threatened species in the Galapagos Marine Reserve through identification and protection of marine key biodiversity areas. Aquatic Conserv: Marine Fresh Eco 18:955–968

Edgar GJ et al (2009) El Niño, grazers and fisheries interact to greatly elevate extinction risk for Galapagos marine species. Glob Change Biol 16:2876–2890

Eken G et al (2004) Key biodiversity areas as site conservation targets. Bioscience 54(1110–461):1118

Fernandes L et al (2005) Establishing representative no-take areas in the Great Barrier Reef: large-scale implementation of theory on marine protected areas. Conserv Biol 19:1733–1744

Ferretti F, Worm B, Britten GL, Heithaus MR, Lotze HK (2010) Patterns and ecosystem consequences of shark declines in the ocean. Ecol Lett 13:1055–1071

Froese R, Pauly D (eds) (2014) FishBase, version 02/2014 www.FishBase.org. Accessed February 2014

Global Environment Facility (GEF)-United Nations Development Program project # 4810:473 (2012) Strengthening the marine protected area system to conserve marine key biodiversity areas. http://www.thegef.org/gef/project_detail?projID=4810. Accessed July 2013

Hayward MW (2011) Using the IUCN Red List to determine effective conservation strategies. Biodivers Conserv 20:2563–2573

Hearn A (2008) The rocky path to sustainable fisheries management and conservation in the Galápagos Marine Reserve. Ocean Coast Manag 51:567–574

IUCN (2014) IUCN Red list of threatened species. Version 2013.2. http://www.iucnredlist.org/. Accessed February 2014

Krebs CJ (1999) Ecological Methodology, 2nd edn. Addison Wesley Longman, Inc., Menlo Park

Lauck T, Clark CW, Mangel M, Munro GR (1998) Implementing the precautionary principle in fisheries management through marine reserves. Ecol App 8(1):72–78

Le Quesne W, Jennings S (2011) Predicting species vulnerability with minimal data to support rapid risk assessment of fishing impacts on biodiversity. Appl Ecol 49:20–28

Leslie HM (2005) A synthesis of marine conservation planning approaches. Conserv Biol 19(6):1701–1713

Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C, Akcakaya HR, Leader-Williams N, Milner-Gulland EJ, Stuart SN (2008) Quantification of extinction risk: the background to IUCN's system for classifying threatened species. Conserv Biol 22:1424–1442

Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405:243–253

MATLAB (2009) MATLAB Version 7.8.0. The Math Works Inc., Massachusetts

Myers RA, Worm B (2003) Rapid worldwide depletion of predatory fish communities. Nature 423:280–283

Myers RA, Worm B (2005) Extinction, survival or recovery of large predatory fishes. Philos Trans Roy Soc B 360:13–20

Myers RA, Baum JK, Shepherd TD, Powers SP, Peterson CH (2007) Cascading effects of the loss apex predatory sharks from a coastal ocean. Science 315:1846

Nicolaides F, Murillo JC, Toral Ve, Reck G (2002) Bacalao. In: Danulat E, Edgar GJ (eds) Reserva Marina de Galápagos. Línea Base de la Biodiversidad. Fundación Charles Darwin/Servicio Parque Nacional Galápagos, Galápagos, p 146–161

Pauly D, Christensen V, Dalsgaard V, Froese R, Torres F Jr (1998) Fishing down marine food webs. Science 279:860–863

Polidoro BA, Brooks T, Carpenter KE, Edgar GJ, Henderson S, Sanciangco J, Robertson DR (2012) Patterns of extinction risk and threat for marine vertebrates and habitat-forming species in the Tropical Eastern Pacific. Mar Ecol Prog Ser 448:93–104

Reck GK (1983) The coastal fisheries in the Galapagos Islands, Ecuador. In: Description and consequences for management in the context of marine environmental protection and regional development. Dissertation zur Erlangung des Doktorgrades, Christian-Albrechts-Universität zu Kiel, Kiel, p 231

Reynolds JD, Webb TJ, Hawkins LA (2005) Life history and ecological correlates of extinction risk in European fresh water fishes. Can J Fish Aquat Sci 62:854–862

Rodrigues ASL, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM (2006) The value of the IUCN Red List for conservation. Trends Ecol Evol 21:71–76

Venables, W. N. and Ripley, B. D. (2002) Modern Applied Statistics with S. Fourth edition. Springer

Walker TI, Hudson RJ, Gason AS (2005) Catch Evaluation of Target, By-product and By-catch Species Taken by Gillnets and Longlines in the Shark Fishery of South-eastern Australia. J Northw Atl Fish Sci 35:505–530

Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS et al (2006) Impacts of biodiversity loss on ocean ecosystem services. Science 314:787–790

Worm B et al (2009) Rebuilding Global Fisheries. Science 325:578–585