# TUNA BE, OR NOT TUNA BE: USING CATCH DATA TO OBSERVE THE ECOLOGICAL IMPACTS OF COMMERCIAL TUNA FISHERIES IN THE PACIFIC OCEAN AT VARYING SPATIAL SCALES

by

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# ABSTRACT

Tuna are arguably the world's most valuable, versatile, yet vulnerable fishes. With current landings over 4 million tonnes annually, all species of tuna from all three major ocean basins are caught, traded, and consumed at various intensities around the globe. Understanding the implications of such an extensive industry is paramount to protecting the long-term health and sustainability of both the tuna fisheries as well as the ecosystems in which they operate.

Given that the Pacific Ocean accounts for roughly two-thirds of the global commercial tuna catch, this thesis assesses the trends and ecological impacts of commercial tuna fishing at both the artisanal and industrial scale in this ocean. To observe the importance of tuna fisheries at a local scale, a case study of the Galápagos Islands is presented. In this context, it was observed that over-fishing and the subsequent depletion of large, low fecund serranids has resulted in a high level of 'fishing down' within the near-shore ecosystem. Consequently, as fishers are forced to expand to regions off-shore, tuna and coastal scombrids are becoming increasingly targeted. With regard to industrial fishing, tuna vessels (especially distant-water longliners) are known to generate a substantial amount of associated bycatch and discards.

The second component of this thesis quantified the amount of bycatch (retained and discarded) generated by Pacific tuna fishing fleets from 1950 to 2010. Unreported retained bycatch amounted to 1.4 million t; the total discarded catch associated with tuna fishing was 3.6 million t of target species and 7.9 million t of non-target species; sharks were the most commonly discarded species. These totals represent about 14% of the reported landings during this time.

Lastly, an analysis of the applicability of the ‘Catch-MSY’ method developed by Martell and Froese (2012) in the context of large pelagic fishes is presented. It was observed that this method produces MSY estimates highly correlated to those produced by complete stock assessments. Collectively, the results of this thesis suggest that the tools to adequately manage tuna exist; however, proper data collection is rare, and the implementation of adequate sustainable fishing measures by fisheries managers is still wanting.

# PREFACE

With the exception of the bookend Chapters 1 and 5, each chapter in this thesis has been prepared as a stand-alone manuscript. All background research, data acquisition and analyses, and writing included in this thesis were completed by myself. However, I received guidance with the conceptualization of these chapters and applicable methodology from my supervisor, Daniel Pauly, as well as other colleagues. These collaborations are discussed below.

A version of Chapter 2 has been published and I am the lead author on this work. As such, I assumed primary responsibility for its design, analysis, and completion. Nonetheless, I received invaluable contributions with regard to the context and historical background of Galápagos fisheries from my co-authors Juan Jose Alava, Jack Grove, Günther Reck, and Daniel Pauly. These authors, as well as the Charles Darwin Foundation, also provided some of the data used for the analyses in this chapter.

Chapter 3 is part of a larger global analysis of the impacts of commercial tuna fisheries that will be incorporated into the *Sea Around Us* Project global fisheries database and future publications. As such, Daniel Pauly provided guidance with regard to some of the methodology and, upon the completion of the data analyses, I worked closely with Frédéric Le Manach and Andrés Cisneros Montemeyor to ensure my results were properly formatted and transferable to the main database.

The overarching concept and methodology used in Chapter 4 was designed by Steve Martell and Rainer Froese and is discussed in detail their 2012 paper, ‘A simple method for estimating MSY from catch and resilience’. Daniel Pauly suggested the application of the Catch-MSY method for tuna, and assisted me in its conceptualization in the context of this thesis.

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Lastly, thank you to all my family and friends who patiently listened whenever I attempted to share my knowledge of fisheries and sustainable seafood. I hope that— on some level—my tuna talk was retained.

For Nana, who first encouraged me to love the creatures of the sea.
And for Mom and Dad, who enabled me to study them.

What caught my eye was a faint chevron bulging ever so slightly from the molten, glassy sea, fifty yards from where I sat adrift. As I rose to my feet to study it, the chevron grew to a distinct wake. A wake without a boat. The wake ran along the surface for a few seconds, accelerated, and exploded like a revelation. A giant bluefin tuna, among the largest and most magnificent of animals, hung suspended for a long, riveting moment, emblazoned and backlit like a saber-fined warrior from another world, until its six-hundred pounds of muscle crashed into the ocean like a boulder falling from the sky.

-Carl Safina, *Song for the Blue Ocean*

# 1 | VALUABLE, VERSATILE, VULNERABLE

A rock pile ceases to be a rock pile the moment a single man contemplates it, bearing within him the image of a cathedral.

-Antoine de Saint-Exupéry, *The Little Prince*

*The rise of seafashion*

At present, Earth is home to an estimated seven billion people— a substantial increase from sixty years ago, when the human population was a modest 2.5 billion (World Bank 2011). In conjunction with this exponential increase in population, has come the emergence of the age of globalization. While many people tend to think that this international assimilation is the byproduct of either technological innovation, improvements in production and transport efficiency, or the onset of free trade, it is actually advancements in *all* of these areas that have contributed to a dramatic psychological shift in the developed world's perception of what constitutes an essential lifestyle requirement.

Fish is the last remaining wild animal protein that can be obtained by most countries. The most recent Status of Fisheries and Aquaculture (SOFIA) Report by the Food and Agricultural Organization of the United Nations (FAO) estimated that, in 2011, 78 million tonnes of seafood was removed from the ocean; nearly half of the world's population depends on marine resources for 25% of their annual protein intake (FAO 2012). While these values may seem to reflect the world's social demographics, perhaps the most disconcerting observation from the same report is that the total global per capita consumption of fish has nearly doubled in the last fifty years: from 9.9 $kg^{-1}$ $person^{-1} \cdot year^{-1}$ in the 1960s to 18.4 $kg^{-1}$ $person^{-1} \cdot year^{-1}$ in 2009.

In developed countries, the distinction of high-end seafood (including sushi) as some of the trendiest cuisine available is due largely to the clever marketing of its putative cardiac health benefits (Jenkins *et al.* 2009), and the emergence of the red-meat conscious consumer. Why eat a 500-calorie sirloin steak when you could eat the same size piece of halibut at only 275 calories with not only *less* fat, but *good* fat? While two servings of fish per week appears sufficient for addressing one's omerga-3 fatty acid requirements (Kris-Etherton *et al.* 2002)—not to mention their availability from other sources, such as nuts—the per capita consumption statistics in developed countries suggest people are eating far more than that. Indeed, for many, even the basic notion of food has ascended through Maslow's hierarchy to a point where it is no longer seen as a fundamental need, but as a status symbol instead. Especially in North America, seafood has become increasingly fashionable as a luxury meal choice. However, largely without public awareness, this increasing demand for fish has impacted the underlying ecological relationships within the marine environment and, unless management improves, it has the potential to affect fish species never before hunted (Sumaila *et al.* 2010a).

It may not seem like long ago, but looking back to the turn of the 20th century, fishing fleets were largely restricted to regions near-shore and their catch was mainly small, fast reproducing forage fish, such as sardines and herring (Roberts 2007). Now, with coastal fish populations collapsing or becoming heavily depleted (Pauly *et al.* 2002), technological advancements resulting in increased catchability (Fridman 2009), and government subsidies allowing fisheries to switch target species and move farther and deeper offshore to acquire their catch (Pauly *et al.* 2002; Sumaila *et al.* 2010b; Swartz *et al.* 2010a), the globalization of the seafood trade enables consumers of the developed world to eat nearly any species desired—regardless of their proximity to the ocean in which it was caught (Swartz *et al.* 2010b). And, instead of looking to cease the fishing pressure and rebuild depleted fisheries, people have instead expanded their horizons and palates, allowing a greater diversity of seafood to grace our plates. In short, we are running out of both places to fish and—much more importantly—out of the fish themselves.

### *Cat food to cult food*

While canned skipjack and albacore tuna have been common, inexpensive staple food items for North Americans and Europeans since the 1930s, fresh tuna was rarely sold or consumed. In fact, less than a century ago, Atlantic bluefin tuna (*Thunnus thynnus)* was not only abundant in the North Sea, but considered a nuisance by mackerel fishers because although it would frequently get caught in their nets, it had no commercial value other than as canned pet food (Pauly 1995). Not until the late 1970s, when trans-continental commercial airlines started to transport these massive fish, did their flesh became a desirable commodity for sushi patrons abroad (Issenberg 2007). Today, flash-freeze capabilities enable fishers to transport their catch around the world without it spoiling: a tuna caught in Kiribati on a Wednesday can reach a dinner table in Tokyo by Thursday. To further promote the prestigious allure of this species, the sale of a bluefin tuna now marks the start of the calendar year at Tokyo's Tsukiji fish market; a tradition that is quickly evolving to be a quest for publicity rather than quality seafood. It might sound surreal but, only thirty years after its introduction to Japanese restaurants, a 222 kg Pacific cousin (*Thunnus orientalis*) of the very same North Sea nuisance tuna sold at Tsukiji for over ¥155 million (US$1.78 million)[1].

A similar status-driven demand exists for shark fins. However, contrary to the world's recent onset of a craving for bluefin tuna, sharkfin soup is a dish that has deep roots in Chinese culture. During the Sung dynasty (968 AD), the Emperor often served sharkfin soup (as well as other marine delicacies) to his guests at banquets and ceremonies as a symbol of respect and wealth[2]; the importance and exclusivity of these foods has been retained to present day. However, unlike sea cucumbers and urchins (species that are also sought for aphrodisiac and ceremonial purposes), only a small part of the shark's body (i.e., the fins) is desired. As such, between 90-99% of the shark is wasted (often discarded at sea), since their meat fetches a significantly lower market price than their fins (Musick 2005; Biery and Pauly 2012). The demand for sharkfin soup is at an all-time high, and although many countries have legislation banning finning practices, illicit shark fishing operations and bureaucratic loopholes allow finning to continue at a global scale (Jacquet *et al.* 2008; Biery and Pauly 2012).

Despite the fact that all three species of bluefin are overfished (Boustany 2011; CCSBT 2011), and sharks are hunted only for their fins, people continue to demand these products; a quality piece of *otoro*[3] and a bowl of sharkfin soup now linger on the second highest level of necessity, where one searches for ways in which to publicly portray their social esteem and self worth. As such, it is this complex interaction of

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[1] From: http://www.bbc.co.uk/news/world-asia-20919306 [accessed 24 February 2014].

[2] From: http://www.sharktruth.com/learn/history-of-shark-fin-soup [accessed 12 May 2014]; some sources attribute this tradition to the Ming Dynasty (1368-1644) instead.

[3] The fattiest cut of bluefin tuna sashimi available (and typically the most expensive).

consumer preferences and demand, culture, market mechanisms and food availability, in addition to biological factors, that lead to the problem of overfishing illustrated in the case of tuna and sharks.

### *Quantifying the world's appetite*

At present, the FAO estimates that 30% of the world's fish stocks are overexploited (FAO 2012). However, these values likely do not depict the true state of exploitation. Since 1950, the FAO has collected annual fisheries landings from its member countries and these are compiled in their FishStat database (see www.fao.org). These statistics rely on the accuracy of reporting countries and, in many cases, refer primarily to commercial and large-scale operations (Shimada 1958; Castro 2005). Consequently, smaller sector fishing (i.e., subsistence, recreational, artisanal), illegal, and unreported catches (e.g., bycatch and discards) are often overlooked or mis-reported. This discrepancy is largely due to a lack of infrastructure for acquiring these data in developing countries (Caddy *et al.* 1998; Bedoya 2009) or, as is the case in some regions (e.g., the Galápagos Islands), fishers may not even be required to record or report their catches (Hearn *et al.* 2005). On the other end of the spectrum, industrial-scale catches may be falsified in order to satisfy government officials (Watson and Pauly 2001). Thus, the availability and accuracy of FAO catch data is highly varied by country and area, and, in many cases, landings are largely under-reported.

However, since catch statistics are a key component of many management publications and analyses (including both FAO's SOFIA reports and smaller-scale stock assessments), ensuring that the input data are accurate is of paramount importance.

Contrary to the largely accepted (but erroneous) belief that missing catch data for a given fishery or region means there was no catch (Pauly 1998), the *Sea Around Us* Project at the University of British Columbia has attempted to acquire missing information and reconstruct catches for all countries and exclusive economic zones (EEZs) around the world. Using a variety of sources from the primary literature and national management agencies, as well as grey literature, more precise estimates of landings can be obtained and, when necessary, estimated using all available information (Zeller *et al.* 2007). Through this undertaking, the *Sea Around Us* aims to quantify the total biomass of fish extracted from the oceans, and ultimately communicate the impacts of both small-scale and industrial sized fisheries to a variety of stakeholders with the hope of mitigating their effects (Pauly 2007).

### *Research objectives and purpose*

From the polar seas to the tropical islands of the equator, no region of the world is left un-fished (Swartz *et al.* 2010a); at all spatial scales—from local to international—stocks are being overexploited to satisfy the world's demand for seafood. The result is both a shift in the perception of what represents a healthy stock, as well as the actual species composition of the catch (Pauly 1995; Ottolenghi 2008a; Polovina and Woodworth-Jefcoats 2013).

To understand the scale at which under-reporting can occur at the artisanal level, as well as observe any trends in tuna landings at a local level (i.e., within an EEZ), a regional analysis will be conducted through the historical review and subsequent catch reconstruction of the fisheries of the Galápagos Islands. Specifically, this reconstruction will aim to give an accurate representation of the total marine fisheries landings from all sectors by both Galápagos fishers and fleets from mainland Ecuador within the EEZ of the Galápagos Islands between 1950 and 2010. A secondary goal is, in view of the ongoing debate about the validity of the ‘fishing down’ phenomenon (Pauly et *al.* 1998; Caddy et *al.* 1998; Pauly and Palomares 2005; Essington et *al.* 2006; Pauly, 2010, 2011; Branch et *al.* 2011), to observe whether this trend is also occurring in the Galápagos Island artisanal fisheries and, if it is, at what intensity.

Fish of the high seas contribute 12-15% of the total annual global catch by weight, and 25% by value (Worm and Vanderzwaag 2007). However, since these fisheries are far offshore and often out of range for proper observation and policy enforcement, they are also highly vulnerable to overexploitation. Presently, FAO statistics pertaining to high seas fisheries are largely dependent on data obtained from the world’s Regional Fisheries Management Organizations (RFMOs), which were previously supplied by member countries. While Pacific RFMOs are responsible for the management of certain tuna species, their available data pertaining to associated non-target catches are incomplete. As such, this study will attempt to improve upon previous estimates of both bycatch and discards associated with both large-scale and small-scale fleets in the hope of giving a more holistic picture of the impacts of commercial tuna fishing in the Pacific Ocean.

Lastly, to observe the further importance of obtaining adequate catch data, and its application beyond catch reconstructions, a review of the accuracy of the Catch-MSY method developed by Martell and Froese (2012) will be applied in the context of Pacific Ocean tuna stocks.

# 2 | THE DEMISE OF DARWIN'S FISHES[4]

"But what does that mean— 'ephemeral'?" repeated the little prince, who never in his life had let go of a question, once he had asked it.
"It means, 'which is in danger of a speedy disappearance.'"

-Antoine de Saint-Exupéry, *The Little Prince*

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[4] A version of this chapter has been published: Schiller L, Alava JJ, Grove J, Reck G, and Pauly D. 2014. The Demise of Darwin's Fishes: Evidence of fishing down and illegal shark finning in the Galápagos Islands. Aquatic Conservation: Marine and Freshwater Ecosystems. doi: 10.1002/aqc.2458.

## INTRODUCTION

### *Island geography and demographics*

Located 1,000 km west of mainland Ecuador in the eastern Pacific Ocean, the Galápagos Islands (1°40'N–1°36'S, 89°16'–92°01'W) have been a subject of curiosity, mystery, and scientific discovery for nearly five hundred years. Charles Darwin's voyage aboard the *H.M.S. Beagle* in 1835 (Pauly 2004) offered him the unique opportunity to take a variety of biological specimens from this region. And, although best known for his descriptions of finches, Pauly (2004) demonstrates that Darwin's subsequent research on speciation was actually largely influenced by the phenotypic variations that he observed in fish species, rather than in birds.

At present, the Galápagos archipelago encompasses thirteen islands (> 10 km$^2$; Table 2-1) and over 100 islets (Snell *et al.* 1996). Although frequented by sailors and explorers since their initial discovery, permanent human residency in the Galápagos only began in the 1830s (Camhi 1995). The population remained quite low until the 1970s, when political and social issues in Ecuador, combined with increased tourism to the Islands, contributed to substantial emigration from the mainland (Epler 2007). Realizing the need to preserve the unique environment of the archipelago, 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 (Camhi 1995; Bensted-Smith *et al.* 2002). In 1998, the foundation of the Galápagos Marine Reserve (GMR) endowed a protective boundary around the archipelago, which extends 60 km beyond the islands and encompasses 138,000 km$^2$ (Camhi 1995; Heylings and Bensted-Smith 2002), making it one of the largest marine protected areas in the world.

With five inhabited islands, the 2010 population of the Galápagos was estimated at over 25,000—a dramatic increase from the approximately 2,000 individuals who lived there in 1959 (Bremner and Perez 2002; INEC 2011). Unfortunately, as a result of this colonization, the Galápagos suffers from many of the same problems that have affected geographically isolated regions throughout history: species invasions (1,321 spp. as of 2007), increasing human population growth, and the use of natural habitat for

**Table 2-1. Geography and fishing demographics of the Galápagos Islands.**

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

*combined IFA of Santa Cruz and Baltra

[✢] Snell *et al.* (1996)

[u] Castrejón (2011)

agriculture (Causton *et al.* 2006; Watkins and Cruz 2007; Mauchamp and Atkinson 2010).

Additionally, the ecotourism industry of this archipelago has exploded over the latter half of the 20th century. Until the mid-1970s, tourism in the Galápagos Islands was virtually non-existent. Approximately two-thousand people visited the archipelago in 1969 (Epler 2007). This is a tiny fraction of the 180,831 people who visited them in 2012 (PNG 2013), and whose activities result in a direct, local, annual profit of over $60 million (Watkins and Cruz 2007). This exponential gain in foreign attention and the negative impact it is having on the Islands' environment remains one of the primary threats facing the Galápagos today.

### *Overview of Galápagos fisheries*

The biodiversity of the Galápagos Islands is extensive: they are home to a cornucopia of species, and nearly 20% of the sea life is endemic (Bustamante *et al.* 2002). One of the most unique characteristics of these islands is the unconventional co-existence of tropical, temperate, and Southern Ocean species within such a small region (Jackson 2001). Such assemblages are made possible by deep near-shore waters, strong currents, and nutrient-rich upwellings, which provide an excellent habitat for over 2,900 fish, aquatic invertebrates, and marine mammals (Grove and Lavenberg 1997; Bustamante *et al.* 2002; Okey *et al.* 2004; Castrejón 2011). 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). Although these industries lasted less than a few decades each, fishers have exploited the rich marine ecosystem surrounding the Galápagos ever since and, presently, the economic importance of the fishing sector is second only to tourism (Bremner and Perez 2002).

Fishing activity within the GMR is currently organized by zones, whereby subsistence and artisanal fishing is allowed in specified locations and all large-scale industrial fishing has been prohibited since 1998 (Jennings *et al.* 1994; Jacquet *et al.* 2008). The main fishing ports in the Galápagos are located on San Cristóbal (Puerto Baquerizo Moreno), Isabela (Puerto Villamil) and Santa Cruz (Puerto Ayora) (Castrejón 2011); these towns service the three primary artisanal fisheries in the archipelago: finfish[5] (year round), sea cucumber (seasons from March/April to May/June), and lobster (July/September to December/February) (Bustamante 1999; Jácome and Ospina 1999; Toral-Granda *et al.* 2000). The artisanal fleet of the Galápagos is largely made up of small fishing boats with limited technology. Based on size, the vessels are divided into three main types: *botes* (wooden boats, 7-16 m with diesel engines), *pangas* (plywood boats, 3-6 m with 60Hp outboard motor) and *fibras* (fiberglass boats, 5-9m with >60Hp large outboard motor) (Bustamante 1998).

Between 1971 and 2000, the number of fishers increased by 326% from 160 to 682 individuals (Bustamante 1998; Toral-Granda *et al.* 2000). This substantial intensification in fishing effort and vessels (mainly *pangas*) was largely influenced by the

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[5] Commonly referred to as 'whitefish' in the Galapagos, this term refers to all teleost species landed by the artisanal fleet, regardless of the colour of their flesh.

economical incentives generated by the lucrative sea cucumber fishery in the 1990s. Conversely, from 2000-2007, there was a 65% decrease in the total number of active fishers in the Galápagos, likely due to the diminishing profitability of the major export fisheries (spiny lobster and sea cucumber), and subsequent shifts in livelihood (Castrejón 2011).

### *Artisanal fisheries*

From 1998, artisanal fisheries were regulated through a co-management approach and internal consensus process led by the Galápagos Marine Reserve's Participatory Management System Board (PMS), which encompassed several stakeholder groups (Artisanal Fishers Association, Charles Darwin Research Station, Tourism Galápagos Chamber and Galápagos National Park Service) and was approved by the Inter–institutional Management Authority (IMA)[6]. The PMS was legally founded on three fundamental principles: participation, precaution, and adaptive management, with the overall aim of creating a consensus building process that allowed local stakeholders (i.e., fishers, natural guides, tourism operators, and conservationist-environmentalist groups) to participate in decision making for the sustainable use of marine resources (Castrejón *et al.* 2005; Castrejón 2011). Therefore, artisanal fishing was conducted in agreement with negotiations and regulations enacted by the GNPS. The legal framework for fishing was thus focused on permits, including seasonal fishing openings, quotas, and limits on the number of active fishers.

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[6] The IMA is the government entity conformed by the Ministries of Fishery, Tourism, Environment and Defense and is based in continental Ecuador.

However, declines in the abundance of both sea cucumber and spiny lobster, and diminishing economic rent resulted in the realization that the initial co-management model coupled with legal tools for sustainable fisheries management in the GMR had not accomplished its original goals (Castrejón 2011). As such, the Participatory Fisheries Stock Assessment (ParFish) model was developed to assess and improve the co-management system by taking into account the local idiosyncrasies of the Galápagos and the legal framework of fisheries management. The ParFish process ran from February 2006 to January 2009, and the activities and results obtained are described in Castrejón (2011). The outcomes of this exercise were used as inputs by the PMS to formulate a new proposal for the GMR fishery management ("Capítulo Pesca"), which was approved by the IMA in 2009[7].

### i. Bacalao and finfish

The Galápagos finfish fishery has a long history in the Islands and dates back to the time of colonization, when about a dozen species of fish were taken for subsistence (Reck 1983; Toral-Granda *et al.* 2000; Castrejón 2011). Today, fish have four potential destinations: i) local markets where they are sold fresh to Galápagos residents; ii) the tourism sector (e.g., hotels, dive boats) for consumption by tourists; iii) dried and exported to mainland Ecuador for local consumption; or iv) freshly exported to the mainland for further export to the United States (Nicolaides *et al.* 2002). As detailed in Reck (1983), commercial finfish fishing became permanently established in 1945, after

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[7] From: http://www.galapagospark.org/documentos/capitulo_pesca_reserva_marina_galapagos.pdf [accessed 12 December 2012].

failed attempts in the 1920s and 1930s. For decades, the primary target of this hand-line fishery was the Galápagos grouper (*Mycteroperca olfax*), a species locally referred to as *bacalao*[8] (Reck 1983; Nicolaides *et al.* 2002). In the past, this species was fished from October to March, dried, and exported to mainland Ecuador for use in traditional Easter soup (Nicolaides *et al.* 2002).

There has since been a decline in the abundance of *M. olfax* (Ruttenberg 2001; Banks 2008), and 64% of fishers from Puerto Baquerizo Moreno (traditionally the main fishing port for the catch and export of bacalao) have observed declines in their catch rates (Castrejón 2011). However, Galápagos-wide catch rates appear to have remained stable since the 1970s. These two seemingly contradictory observations suggest that the fishery is expanding throughout the Islands. Castrejón (2011) additionally suggests that within the finfish fishery there exist cases of 'shifting baselines syndrome', whereby newer generations of fishers do not perceive declines in abundance to be as dramatic as they are in reality, since the state of the environment for their initial frame of reference (i.e., when they started fishing) is already vastly different from the pristine, pre-fished state (Pauly 1995).

### **ii.** Sea cucumber

Initially established in 1991 after mainland Ecuadorian sea cucumber stocks collapsed, the artisanal sea cucumber fishery has a relatively short, but problematic, history in the Galápagos (Shepherd *et al.* 2004; Castrejón *et al.* 2005; Hearn *et al.* 2005;

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[8] The English translation of *bacalao* is 'cod' (Family Gadidae); however *M. olfax* is a grouper (i.e., a member of the family Serranidae).

Toral-Granda 2008). The primary fishing grounds are located on the west side of Isabela Island, near the Bolivar Channel (Castrejón 2011). While nearly forty species of sea cucumber occur within the archipelago (Maluf 1991, in Toral-Granda 2008), it is only legal to harvest the brown sea cucumber (*Isostichopus fuscus*); illegal fishing operations exist for at least three other species (Toral-Granda 2008).

Although there were initial efforts to ensure the sustainable extraction of this resource, overfishing and illegal catches strongly contributed to the closure of the fishery in 1992 (Bremner and Perez 2002). However, this moratorium lasted only two years before the fishery was again opened for a brief three-month trial period. The total allowable catch (TAC) set for the trial period was 500,000 sea cucumbers, but a lack of enforcement and management resulted in an actual take of between 6-10 million individuals before the fishery was again closed (Camhi 1995). The sea cucumber fishers (*pepineros*) did not take the closure lightly, and violently protested to the Ecuadorian Government by seizing Galápagos National Park Service offices and the Charles Darwin Foundation (CDF), and by threatening Galápagos tortoises (*Geochelone* spp.), an action that has occurred on more than one occasion (Camhi 1995; Stone 1995; Ferber 2000). Despite these demonstrations, the fishery remained closed until 1999.

Recent management efforts, including the implementation of an individual transferable quota (ITQ) system and minimum size restrictions suggest that there are ongoing attempts to manage the sea cucumber fishery more effectively. However, population sizes are still variable and recovery appears to be slow (Toral-Granda 2008; Castrejón 2011). Additional conservation precaution was made in 2003, when *I. fuscus* became the first sea cucumber species listed under Appendix III of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Toral-Granda 2008). However, the following year, 383,000 sea cucumbers (approximately 100 t) were caught without a CITES permit (Toral-Granda 2008). Additionally, although the CDF estimated a maximum sustainable quota of 450,000 sea cucumbers for 2004, the IMA allowed an opening season for two months with a maximum capture of 3 million individuals, and a total moratorium for 2005 and 2006. However, the last resolution was revoked, leading to a judicial trial and claims for an extension of the fishing season, as well as to permit fishing of sea cucumbers in no-take areas, where fisheries or extractive activities are excluded (i.e., Fernandina Island and Bolivar Channel). Ultimately, the fishery was open for 2005, but closed in 2006 in an effort to allow the population to recover. Due to increased concerns over population health, it was again closed between 2009-2010.

iii. Spiny and slipper lobster

The red spiny lobster (*Panulirus penicillatus*) and the green (or blue) spiny lobster (*Panulirus gracilis*) 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 90-95% to Ecuador's total spiny lobster export (Reck 1983; Bustamante *et al.* 2000). Between 1979 and 1980, the average 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, and an all-time low of 4.0 kg of tails · diver$^{-1}$ · day$^{-1}$ was observed in 2005 (Hearn *et al.* 2006, in Castrejón 2011). Given these changes in catch rate, the spiny lobster fishery incurred a brief 18-month closure in 1994. Although declines in abundance have caused the commercial value of these species to increase (US \$28.60· $kg^{-1}$ in 2006 compared to US\$7.92 in 1997), there has been a substantial decrease in the gross income of the fishery (Hearn *et al.* 2006). In addition to the spiny lobsters, a similar species, the slipper lobster (*Scyllarides astori*), is also harvested at a smaller scale (Hearn 2006). Although endemic to the Eastern Pacific, the slipper lobster is not as valuable as the spiny lobsters; thus it is sold primarily for local consumption (Bustamante *et al.* 2000).

### *Industrial fishery for tuna*

Records allude to industrial fleets in Galápagos waters catching approximately 400 t of tuna as far back as 1933, and 2,300 t in 1940 (CDF 2010). Fishing pressure from both foreign fleets and mainland-based Ecuadorian vessels has increased ever since (Shimada 1958; Castro 2005; Bedoya 2009), and the primarily targeted species in the Eastern Pacific Ocean (EPO) are skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*), and yellowfin (*Thunnus albacares*). At present, Ecuador’s EPO tuna fleet consists of 86 vessels (IATTC 2011a), although only a small fraction of these operate within the Galápagos EEZ. Since the GMR prohibits large-scale industrial fishing within its borders, this type of tuna fishing is limited to regions farther offshore. However, it has been observed that foreign vessels operating under fishing access agreements with Ecuador do not respect the rules or the integrity of the GMR (Bustamante 1999), and incidents of illegal fishing within the marine reserve are an ongoing concern (Altamirano and Aguiñaga 2002; Reyes and Murillo 2007). Independent of the industrial endeavors of Ecuador's fleet, artisanal tuna fishing by local Galápagos fishers is allowed within the GMR and these catches are considered as part of the finfish fishery.

### *Shark fishing*

In addition to the plethora of teleost fishes in the Galápagos Islands, a significant diversity of sharks has also been recorded in this region (Grove and Lavenberg 1997; Zarate 2002; Carr *et al.* 2013). Among these species, it is possible to find schools of hammerhead (scalloped, *Sphyrna lewini* and smooth, *S. zygaena*), tiger (*Galeocerdo cuvierii*), mako (*Ixurus oxyrhinchus*), white-tipped reef (*Triaenodon obesus*), blue (*Prionace glauca*), Galápagos (*Carcharhinus galapagoensis*), oceanic whitetip (*Carcharhinus longimanus*), silky (*Carcharhinus falciformis*), three species of thresher (*Alopias vulpinus*; *A. superciliosus;* and *A. pelagicus*), and even whale sharks (*Rhincodon typus*). About 90% of the elasmobranchs found around the Galápagos have been included on the IUCN Red List as 'Threatened' or 'Near-Threatened' (Carr *et al.* 2013). The scalloped hammerhead, one of the most abundant and gregarious sharks in Galápagos marine waters (Stone 1995; Coello 1996), was recently moved up from 'Near Threatened' to 'Endangered' status, and both the whale and great white sharks are categorized as 'Vulnerable'[9].

Shark fishing and finning has been conducted in the Galápagos since the 1950s (Watts and Wu 2005; Jacquet *et al.* 2008). Sharks caught in Galápagos waters are typically landed on the Ecuadorian mainland; the destination and connection ports where illegal operations take place are Guayaquil and Manta, the two major industrial

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[9] From: http://www.iucnredlist.org [accessed 9 August 2012]

and harbor fishery cities. Fishing for sharks in the Galápagos became increasingly prevalent in the 1980s and the magnitude of this endeavor has increased ever since (Camhi 1995; Coello 1996; Watts and Wu 2005). Between 1988 and 1991, illegal shark fisheries were discovered to be using pieces of sea lion flesh as bait, 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 (Camhi 1995; Merlen 1995). These operations were conducted largely by Ecuadorian, Colombian, Costa Rican, Japanese, Taiwan and Korea semi-industrial and industrial longline fishing fleets, some of which were licensed only for tuna fishing, but were illegally fishing for sharks (Camhi 1995; Merlen 1995).

### *Sportfishing*

The traditional 'trophy hunting' approach to sport fishing began in the Galápagos in the 1990s. However, these activities were highly unregulated and operated without the consent of local fishers (Schuhbauer and Koch 2013). As such, this type of tourism is not currently supported by the GMR and is 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, with the exception of spiny lobsters caught during the harvest season, all catch is legally required to be released (PNG 2009). Although very little assessment of PVA has been conducted, initial research suggests that this program has not been successful (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).

## METHODS

Given the lack of catch reporting by Galápagos fishers, it is unknown how much (if any) data from the fisheries of the Galápagos are pooled with the FAO data for Ecuador as a whole. The finfish species associated with the Galápagos (e.g. bacalao, mullet) were not featured independently in Ecuador's data set and it was therefore assumed they were not included. Conversely, the start of Ecuador's recorded catch data of other species, including spiny lobsters and sea cucumbers, did appear to be correlated with the commencement of these fisheries in the Galápagos. Therefore, in an effort to avoid overestimating or double counting, it was assumed that for these fisheries, Galápagos catches were included within the FAO Ecuador data.

### *Local consumption*

In order to calculate the amount of fish consumed at a local level, GraphClick was used to extract permanent residency data from Taylor *et al.* (2010), and Galápagos National Park entry records were used to estimate the amount of tourism from 1979 to present[10]. Additional information was also obtained from González *et al.* (2000) and Ecuador's Instituto Nacional de Estadística y Censos (INEC)[11], and linear interpolations were performed to "fill in" data gaps. Although an archipelago-wide value of seafood consumption could not be found, as determined in a study on consumption on Santa

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[10] From: http://www.galapagospark.org/onecol.php?page=turismo_estadisticas [accessed 2 May 2012].
[11] From: http://www.inec.gob.ec/cpv/ [accessed 4 May 2012].

Cruz Island, 6.75 kg $person^{-1} \cdot year^{-1}$ was used as the 2010 *per capita* consumption rate for locals, and 1.1 kg $person^{-1} \cdot vacation^{-1}$ 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 1.5 times higher than present (i.e., 10.1 kg $person^{-1} \cdot year^{-1}$ for locals and 1.4 kg $person^{-1} \cdot vacation^{-1}$ for tourists) was used for 1950. Linear interpolation between past and present *per capita* consumption rates applied to the population over time was therefore used to determine a subsistence catch component.

*Bacalao and finfish*

Early anecdotal estimates by Reck (1983) suggest annual finfish landings of approximately 500 t in the 1950s. However, this observation is difficult to contextualize, as no other catch statistics for this time exist. Nonetheless, this tonnage was used as the starting point for 1950 and held constant until 1955. No data were available until 1977 (Reck 1983), so linear interpolation was used between these years. GraphClick was used to extract data from a time series of catches in Castrejón (2011) and additional time series (Andrade and Murillo 2002; Anonymous 2009) served as anchors for further interpolations. Export data provided by CDF were again used to calculate the catch between 2004-2010. Up until the 1970s, mullets were not considered part of the finfish catch (Reck 1983); since later data sets did include them with as part of the finfish fishery, the calculated catches of *Mugil galapagensis* and *Xenomogil thornburi* were added to the earlier finfish catch data.

Approximate species breakdowns were available from the aforementioned sources; when these were unavailable, the species composition for known years was calculated and applied it to the total catch. Specifically, the catch composition of Reck (1983) was used for 1977-1981 and applied it to the finfish catch for all years prior. Subsequently, the ratios from the species composition available from the most recent years (i.e., 2004-2010 CDF export data) were applied to the catch since 1981 for years where the composition was unknown.

For each year, the total annual calculated consumption was used to determine an approximate exported catch. Between 1950-1970, it was determined that finfish catches were 95% exported, compared to 49% exported for the last two decades. However, given the way in which total consumption was calculated, this value is a coarse approximation.

### *Sea cucumber*

Sea cucumber catches were obtained from a variety of sources, namely: Bremner and Perez (2002), Shepherd *et al.* (2004), Reyes and Murillo (2007), Toral-Granda (2008) and Wolff *et al.* (2012). When a range was given, the authors' preferred value was used. 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* (Shepherd *et al.* 2004) and linear interpolation was used between these anchor points. Hearn and Pinillos (2006) suggest that illegal fishing for the warty sea cucumber (*S. horrens*) began in 2004, and an illegal catch estimate was determined from this time onward using the annual average of known seizures. Unfortunately, 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.

### *Spiny and slipper lobster*

FAO data show landings for only one species of lobster (*P. gracilis*); however it was assumed that these data were meant to include *P. penicillatus* as well. It was also assumed that all FAO lobster data referred exclusively to Galápagos catches (i.e., no lobsters from mainland Ecuador) since the fishery in the archipelago has contributed roughly 90-95% to Ecuadorian catches since its establishment. These FAO data were largely accepted to be correct. However, additional catches ('ad-ons') for 1973-1976 were obtained from Reck (1983), Hearn and Murillo (2008) for 1995-2003, and export data provided by the Charles Darwin Foundation (CDF) for 2004-2010[12]. In most cases, lobster weight was given in terms of tail weight, thus a conversion factor of 2.86 (as determined by Reck 1983) was used to calculate live 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 prior to 2000, based on the information provided by Bustamante *et al.* (2000). An approximate catch composition for the last decade was adjusted based on information in Hearn and Murillo (2008), which suggests, "*P. penicillatus* makes up over 75% of the yearly spiny lobster catch". Available information was used to estimate export percentages, such that prior to 1982, 95% of spiny lobster was exported (Reck

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[12] From: http://www.galapagospark.org/boletin.php?noticia=354 [accessed 16 July 2012].

1983), 92% was exported in the 1990s (Busamante *et al.* 2000), and between and 2000-2010, 88% was exported (Castrejón 2011).

### *Tuna (industrial)*

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 by Ecuador's industrial fleet. As such, only two data sets (Jácome and Ospina 1999; Bedoya 2009) for three species (skipjack, yellowfin, and bigeye) 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 was included with Ecuador's FAO data. Ecuador's tuna catches were accepted as accurate and two time series were used to estimate what proportion of Ecuador's tuna was from the Galápagos. Since it closely matched Bustamante's (1999) suggestion that 24.3% of Ecuador's tuna comes from the Galápagos, the percentage breakdown from Bedoya (2009) was used to determine the total Galápagos catch and species composition for all years in which data were unavailable.

### *Sharks*

Based on anecdotal evidence, 1950 was used as the starting year for this fishery. Estimates of 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). Information suggests that the extent of shark fishing that occurred in the past was not as substantial as it is presently. However, since no estimates were available, the first available data set (from 1979-1984) was averaged and, to keep early estimates conservative, 15% of this catch was applied to 1970. Subsequently, linear interpolation between 1950 and this anchor point was used to approximate missing catches. There are no quantitative or anecdotal indications that shark finning 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 still assumed shark fishing was occurring in the archipelago, but that exports during this time were under-reported and a linear interpolation between these years was used instead.

A species breakdown was determined from the Fundación Natura-World Wildlife Fund's *Galápagos Report* (WWF 1998) which states that "the main shark species captured in Galápagos in 1994 were the blue (*P. glauca*), accounting for 67.2% of the catch; the thresher (*A. vulpinus* and *A. superciliosus*), at 13.2% of the catch; the Mico[13] at 15.6%; and the hammerhead (*Sphyrna* spp.), at 2.3%." Although these percentages refer to only one year, this breakdown appears consistent with anecdotes in Jacquet *et al.* (2008), which suggest that blue sharks and thresher sharks currently constitute nearly 90% of all shark landings in the 'shark mafia' epicenter of Manta, Ecuador.

*Trophic level analysis*

Given reported quantitative and qualitative changes in catch composition, the

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[13] Silky shark (*Carcharhinus falciformes*)

mean trophic level (TL) of the artisanal catch was also analysed to see if 'fishing down'[14] was occurring (i.e., if there were any noticeable ecological shifts in the species landed

**Table 2-2. Trophic level (TL) of commonly caught finfish and invertebrates of the Galápagos Islands.**

| 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 |

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[14] 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).

over time). Although still caught by Ecuadorian vessels in the Galápagos EEZ (i.e. Ecuadorian waters), we chose to omit industrially and illegally caught tuna and sharks from this analysis since these species are not directly related to the fisheries and fishers of the Galápagos.

We used the average of the TL values provided by Okey *et al.* (2004) and FishBase (www.fishbase.org) for fishes, and SeaLifeBase (www.sealifebase.org) for invertebrates (Table 2-2). However, since the fishing down effect can be easily masked by aggregating data from different ecosystems, we defined an 'in-shore' ecosystem that comprised all species typically occurring along the coast, or within the in-shore fishing area (i.e., to 50 km from the coast or 200 m deep). Given the instability and innate boom-and-bust nature of the sea cucumber fishery, we also chose to perform the in-shore analysis 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 2-2). We used the average TL value (3.54) of all species in this analysis for finfish landings that could not be disaggregated by species (i.e., the 'others'), and kept these fish in both spatial categories. Regression analyses were performed to assess the changes in mean trophic level over time.

## RESULTS AND DISCUSSION

Although primarily established within the last sixty years, this catch reconstruction demonstrates a relatively high level of overexploitation within the commercial fisheries of the Galápagos, particularly with regard to sea cucumber and spiny lobster. Of additional concern is the decline in abundance of large apex-level fish, such as the groupers, and the subsequent changes in catch composition that followed.

Given that no cumulative baseline data set from either the FAO or Government of Ecuador was available for the Galápagos, we are unable to give a total comparison between landings reported to the FAO and those presented in this reconstruction. Nonetheless, when taking into account all legal and illegal fisheries in the Galápagos, we determined that from 1950-2010, a total of 797,000 t of seafood was extracted from the EEZ surrounding this archipelago. It should be recognized that 80% of these landings are tuna caught by Ecuador's industrial fleet, and shark fishing—which is currently illegal—is the second highest contributing fishery, accounting for 13% of these landings. These and additional sector breakdowns are discussed below.

### *Local consumption*

Since spiny sea cucumbers are entirely exported, locally consumed seafood is composed of finfish species (including tuna), slipper lobster and a small amount of spiny lobster. Given the increased residency and tourism on the Galápagos, it is understandable that there has also been an increase in the amount of seafood consumed on the Islands. From 1950 to 2010, we estimate that 6,700 t of finfish, 700 t of slipper lobster, and 600 t of spiny lobster were consumed by locals on the Islands. The aforementioned *per capita* seafood consumption rates are very low in comparison to other oceanic islands and countries (see Jones 2013). However, this disparity is likely due to the prominence of agricultural and farmland on the islands; many Galápagos residents maintain a diet similar to that of people on the mainland, consuming primarily grains and meat.

*Bacalao and finfish*

Between 1950 and 2010, artisanal fishers in the Galápagos landed 26,500 t of finfish, of which approximately 75% has been exported. Most significant to this finding is not the tonnage, but rather the changes in species composition that have occurred over the years (Figure 2-1). Between 1977-1981, *M. olfax* constituted 36% of the annual finfish catch and, in general, serranids made up 89% (Reck 1983). 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). Between 1997 and 2001, the finfish fishery was primarily composed (41%) of two mullets: *X. thoburni* and *M. galapagensis* (Andrade and Murillo 2002), species, which, during the

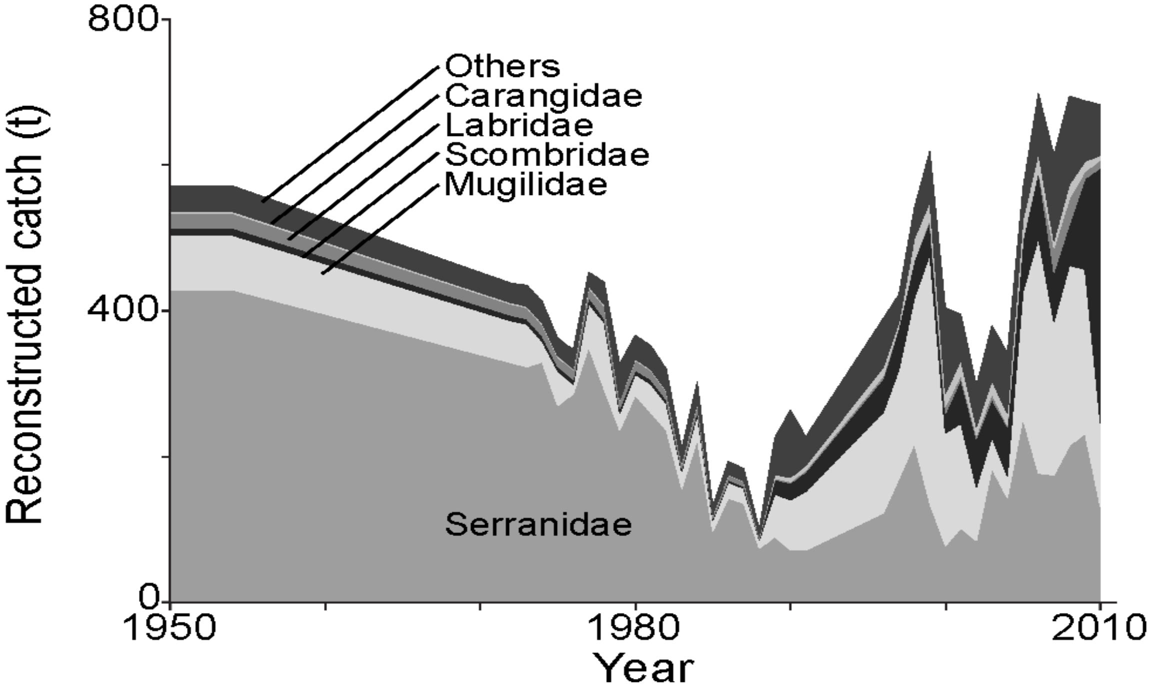

**Figure 2-1. Reconstructed Galápagos artisanal finfish catch (1950-2010), by family.** Prior to the 1980s, the bulk of landings were composed of large, predatory in-shore serranids (e.g., groupers; in particular *Mycteroperca olfax*). Over the last two decades, the species composition has changed such that off-shore species (e.g., tuna) and smaller in-shore forage fish (e.g., mullets) are now much more prevalent in the catch.

1970s, were only fished occasionally. During this time, mullets were not exported and were consumed locally as subsistence, or used as bait for larger fish (Reck 1983). Between 2000 and 2010, *M. olfax* constituted only 17% of the total catch, and another endemic serranid, *Paralabrax albomaculatus*, which made up 32% of the catch between 1977-1981 (Reck 1983), made up only 3% between 2000-2010. It is also particularly troublesome 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' under 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 (Reck 1983), which is reflected by an increasing prominence in current catches. With a total landing of 840 t over sixty years, artisanal-caught tuna in the Galápagos contributes a very small fraction (0.1%) to the total tuna caught in this EEZ. However, given the observed decline in the abundance of *M. olfax* within the GMR, the importance of tuna in the finfish fishery will likely continue to increase.

### *Sea cucumber*

Taiwan and Hong Kong are the primary importers of sea cucumber, and between 2005-2006, they accounted for 83% of exported dried sea cucumber from the Galápagos (Toral-Granda 2008). Given that a kilogram of dried sea cucumber can fetch as much as US$170 in Asia (Castrejón 2011), lucrative financial incentives promoted by global demand have generated both a substantial legal and illegal take of this resource. This reconstruction determined that 16,100 t of sea cucumber was caught in the Galápagos between 1950 and 2010. Of this, 13,000 t was legally caught *I. fuscus* and the rest illegal catch of both *I. fuscus* (3,060 t) and *S. horrens* (40 t). This reconstructed catch is 36 times as much as Ecuador's reported landings of sea cucumber to FAO for the same period (Figure 2-2). The largest annual catch of *I. fuscus* (2,800 t) occurred in 1994, just prior to the four-year closure of this fishery (when it was still largely unregulated).

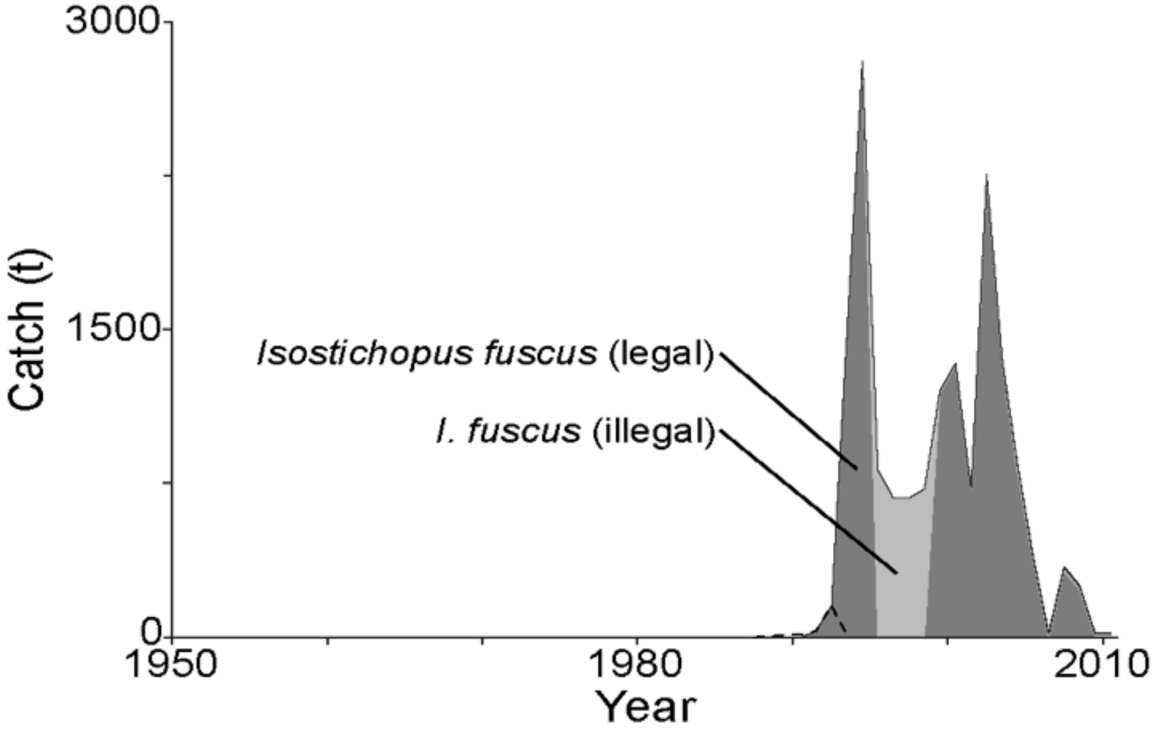

**Figure 2-2. Total reconstructed sea cucumber catch for the Galápagos archipelago, 1950-2010.** An estimated 13,000 t of the brown sea cucumber (*Isostichopus fuscus*) were legally gathered for export since the establishment of the fishery; 30 times as much as reported by the FAO (dashed line) for the same time period. An additional 3,000 t of this species has been illegally taken, primarily between 1994 and 1999. The reconstructed illegal catch of the warty sea cucumber (*Stichopus horrens*) is an estimated 40 t.

When the brown sea cucumber fishery was closed following the initial and unsustainable boom in 1991, extensive illegal fishing was undertaken to continue exporting this species to the Asian seafood and aphrodisiac market (Deborah Chiriboga[15], pers. comm.). Although both *H. atra* and *H. kefersteini* are also fished illegally in the Galápagos (Toral-Granda 2008), no annual catch estimations could be found and therefore these species are excluded from this reconstruction. Therefore, and given that the illegal catch estimates are based only on known seizures, the total tonnage for illegal sea cucumber landings is likely highly conservative.

Given substantial declines in *I. fuscus* (Toral-Granda 2008), there have been suggestions for legalizing the fishery for *S. horrens*, as well as for the white sea urchin (*Tripneustes depresus*) (Castrejón 2011). Although these initiatives have the potential to provide short-term economic benefits, this shift in targeted species is not unlike the mainland to Galápagos sea cucumber boom-and-bust scenario of the 1990s. As such, if management and enforcement were the same as with *I. fuscus,* similar stock depletion of these other two invertebrates should be anticipated.

*Spiny and slipper lobster*

This reconstruction determined that since 1950, 9,200 t of spiny lobster has been extracted from the EEZ of the Galápagos. While the FAO spiny lobster data for the past appear to be accurate, the reconstructed catch of *P. penicillatus* and *P. gracilis* was 400% higher than the FAO data from 1995-2010; this underreporting may be

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[15] Former Executive Director of Fundación Natura in Ecuador, a Latin American non-governmental organization working to bridge the gap between communities, organizations, and businesses in an environmentally sustainable way.

attributable to changes in reporting structure in the region.

The notable decrease in the total catch of spiny lobsters since 2000 (Figure 3-3) is likely a result of the aforementioned changes in their abundance. Declines in spiny lobster have additionally been linked to an increased presence of sea urchins in the sub-tidal 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.

At present, only 5% of the original macroalgae beds remain and, in combination with the impact of the urchins, these threatened environments are under additional stress due to the effects of climate change (Banks 2007). 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"[16].

Given the current state of the spiny lobster fishery, there has been increased pressure to allow the export of slipper lobster (*S. astori*) as well (Hearn 2006). However, Hearn (2006) recommends a cautious approach, as the life history characteristics of *S. astori*, combined with the past overexploitation of many Galápagos fisheries suggest that this species could be at a heightened risk of overexploitation.

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[16] Translated from Spanish.

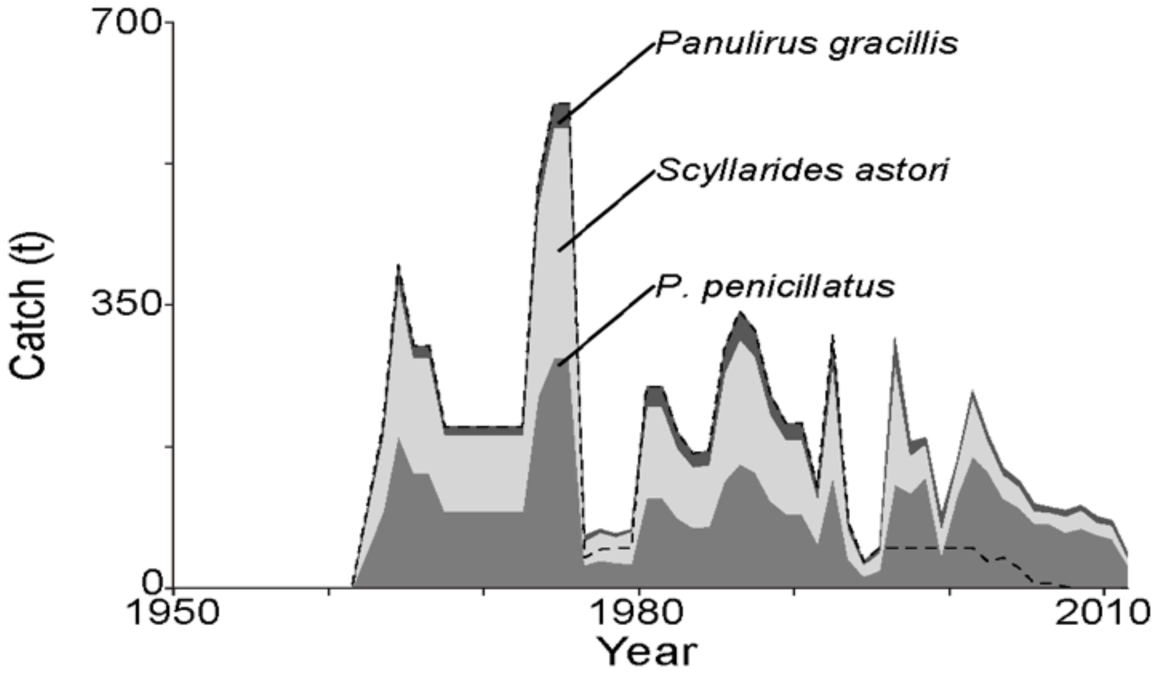

**Figure 2-3. Reconstructed catch of spiny and slipper lobsters for the Galápagos, 1950-2010.** Approximately 9,200 t of spiny lobster (*Panulirus penicillatus* and *P. gracilis*) and 700 t of slipper lobster (*Scyllarides astori*) were caught within the EEZ of the Galápagos from 1950 to 2010. The reconstructed catch of *P. penicillatus* and *P. gracilis* was 400% higher than reported by the FAO (dashed line) between 1995 and 2010.

### *Tuna (industrial)*

This reconstruction estimated that within the Galápagos EEZ, Ecuador's industrial fishery caught 639,000 t of tuna between 1950 and 2010, with skipjack constituting 68% of this catch, followed by yellowfin (23%) and bigeye (9%). Tuna fisheries in the Pacific Ocean contribute over two-thirds of the world's annual tuna catch (Sibert *et al.* 2006) and Ecuador is the primary tuna fishing country in the EPO (IATTC 2011). Given this heavy fishing pressure, it is not surprising that in 2006, the IATTC listed the yellowfin stock as fully exploited and bigeye as overexploited (Castrejón 2011). In response to these concerns, the IATTC imposed a range of fishing restrictions on its member countries, including a closure of the Ecuadorian purse seine fishery in August and

September 2007 and setting a recent total allowable catch (TAC) of 500 t for their industrial longline fleet (Castrejón 2011). While these efforts should not be overlooked, continued management will be required for the long-term health of these stocks and their associated fisheries.

Although no catch estimates were available for illegal industrial tuna fishing, these illicit activities are 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). These vessels are primarily purse-seiners. However, some also use longlines, a largely non-selective technique that catches both targeted marine life, and untargeted species (e.g. other fishes, sea turtles, seabirds) as well. Gales (2007) 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'[17] Waved albatross (*Phoebastria irrorata*) breeds almost exclusively on Española Island (Merlen 1998).

### *Sharks*

As suggested by Jacquet *et al.* (2008), the underreporting of shark catches in Ecuador is substantial. It was determined that, since 1950, approximately 105,600 t of shark has been caught in the Galápagos Islands by the Ecuadorian fleet; the highest catch (7,050 t) was in 2000. If it is assumed that the sharks are caught at half the

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[17] From: http://www.iucnredlist.org/details/106003955/0 [accessed 8 August 2012].

maximum weight reached in their species, the tonnage converts to a very conservative estimate of 112,000 individual sharks caught by Ecuador alone in that year[18]. Therefore, despite attempts to mitigate the amount of shark fishing occurring in these waters, government and policy failures, and the imperfections of open access markets encouraged by millions of dollars, have allowed this unacceptable traffic to continue, thus violating and ignoring both the Special Law of Galápagos and the conservation goals of the GMR. In addition to fishing by Ecuador, foreign boats from Costa Rica, Columbia, and Japan are also known to fish for sharks in Galápagos waters (Watts and Wu 2005; Reyes and Murillo 2007). As such, this reconstruction likely shows only a fraction of the total illegal shark fishing (and finning) occurring in the archipelago.

Carr *et al*. (2013) recently documented that of 379 sharks taken by an illegal Ecuadorian longlining vessel in 2011, 80% were bigeye thresher (*A. superciliosus*), 11% were silky (*C. falciformes*), and only 6% were blue (*P. glauca*). Although these numbers refer to one isolated seizure, there is a notable difference in the catch composition when compared to 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 blue sharks.

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 (Clarke *et al.* 2007). Although tasteless, cartilaginous shark fins can cost upward of $400/ kg (Jacquet *et al.* 2008) and are the principal ingredient in fashionable sharkfin soup. With an

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[18] This estimate is conservative because the mean weight of individuals in an exploited population of sharks is likely to be less than half the species' maximum weights.

estimated minimum worth of $400-550 million annually (Clarke *et al.* 2007), the trade of shark products is a very lucrative global industry and one that needs immediate and focused attention in Ecuador, and the Galápagos in particular.

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 (Official Register, No. 194; 19 May 1989) and 2004 (Executive Decree 2130; Official Register, No. 437) respectively (PNG 2009). While these efforts initially made Ecuador a world-leader in protective shark legislation, in July 2007, the Ecuadorian Government officially enacted Executive Decree 486 (Official Record 137), an amendment to the previous laws. This amendment still prohibits shark finning and the dumping of sharks at sea. However, 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 *et al.* 2007), with 100% mortality of by-caught sharks (Coello *et al.* 2010), and this loophole has allowed fishers to continue to trade shark fins without legal consequences (Carr *et al.* 2013). All activities associated with shark fishing were completely forbidden in Galápagos by the GNPS in 2000 (Jacquet *et al.* 2008). However, given that between 2001-2007, there were 29 reported seizures of boats illegally shark fishing in the GMR (Carr *et al.* 2013), and based on the total shark catch determined by this reconstruction, the effect these efforts have had on actually protecting sharks in the archipelago appears to be negligible.

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.* (2011a) 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.

### *Trophic level analysis*

Figure 4A illustrates the changing composition of artisanal fisheries catches around the Galápagos through trends of the mean trophic levels 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 1950-2010. While this may demonstrate a very strong example of fishing down at a cumulative level (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 lobster and tuna), the 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). As is observed in the Galápagos, the mean TL of the catch steadily declined until the early 2000s, at which point it began to increase (see Figure 4A). Although this positive trend could initially be interpreted as the fishery in the process of rebuilding, in reality it is due to the collapse of the sea

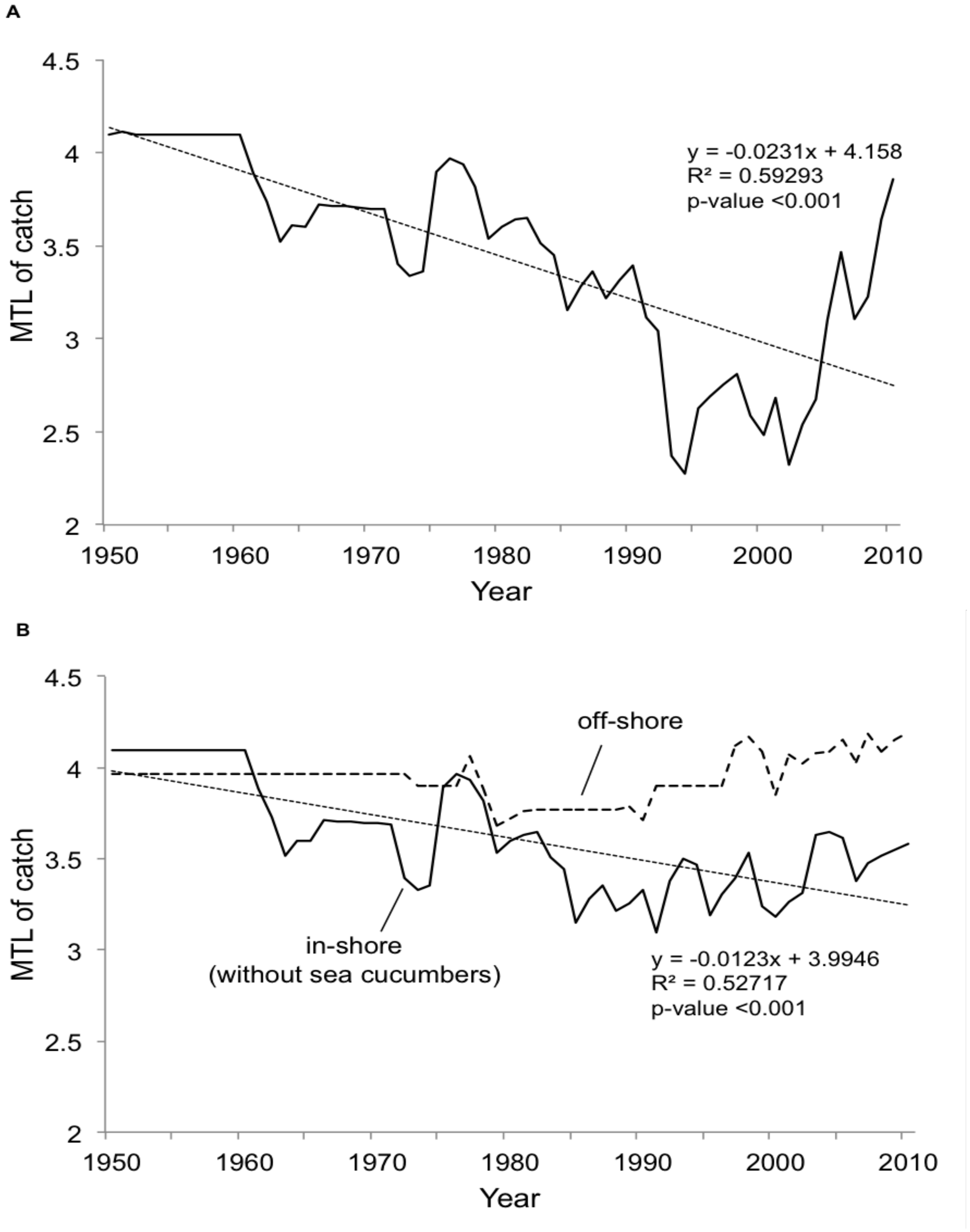

**Figure 2-4. Changes in mean trophic level (TL) of the artisanal catch in the Galápagos Islands.** (**A**) With all species and spatial scales, there has been a significant decline (0.23 TL decade$^{-1}$) in the mean TL of the catch from 1950 to 2010, much of which is attributable to the influence and 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.

cucumber fishery, 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.

When separating the artisanal catch by specific in-shore and off-shore regions (see Figure 4B), it was found 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 offshore catch has increased slightly over the last sixty years. However, this change was not statistically significant ($r^2$= 0.05; F(1, 60)= 3.4; p= 0.67). As depicted in Figure 2-1, the fish species that nowadays contribute most to the finfish catch were all being exploited in the 1950s; it is their relative proportions that have changed. This transition thus 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 max, without the high-trophic level species being depleted (Essington *et al.* 2006). Given the rate of the decline in mean TL (0.12 decade-$^1$), the degree of fishing down observed in the in-shore Galápagos finfish fishery is consistent with global trends (Pauly *et al.* 1998).

## 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 here 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 impacts the size and health of targeted populations, but also triggers cascading effects, resulting in decreased natural diversity in community fish 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 feeback from monitoring to account for uncertainties and shortcomings could help improve the ecosystem-based approach in the long term. Since the socioeconomic state of the Islands directly impacts 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 unified manner.

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 whitetip (*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, based on 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.

# 3 | LOST GIANTS OF THE PACIFIC

"What makes the desert beautiful," said the little prince, "is that somewhere it hides a well."

-Antoine de Saint-Exupéry, *The Little Prince*

## INTRODUCTION

### *Large pelagic fishes of the Pacific Ocean*

Covering 162 million $km^2$ and containing 660 million $km^3$ of seawater, the Pacific Ocean is the largest marine basin in the world; it occupies 32% of Earth's total surface area and roughly half of all its ocean space[1]. Although relatively low nutrient availability (when compared to coastal regions) makes the open ocean an undesirable place for most marine life, this environment is the optimal habitat for the world's largest teleosts: the tunas and billfishes.

As part of the scombrid[2] family, the tribe *Thunnini* includes fifteen fishes, which are collectively known as the 'tunas'. Within this taxon, these species can be further classified into five genera: slender tunas (*Allothunnus*), frigate tunas (*Auxis*), little tunas (*Euthynnus*), skipjack tuna (*Katsuwonus pelamis*), and the albacores or 'true' tunas (*Thunnus*) (Collette *et al.* 2001). While all tunas spend at least some part of their life cycle in coastal areas, most slender, frigate, and little tunas primarily remain in this environment throughout their lives. However, although they return to continental shelves to breed, skipjack tuna and the eight species of *Thunnus* are primarily found in open waters.

Given that their genus name originates from the Greek verb *thynō*, meaning 'to rush' or 'to dart' (Ellis 2008), it is not surprising that the *Thunnus* species are among the fastest predators in the ocean. The Pacific is home to six tunas from this taxon: bigeye

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[1] Ocean volumes calculated by Eakins BW and Sharman GF (2010) from ETOPO1 online database data: http://www.ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html [accessed 10 March 2013].

[2] 54 species of mackerels, tunas and bonitos (Nelson 1994).

(*T. obesus*; BET), yellowfin (*T. albacares*; YFT), albacore (*T. alalunga*; ALB), longtail (*T. tonggol*; LTT), Pacific bluefin (*T. orientalis*; PBT), and southern bluefin (*T. maccoyii*; SBT)[3] (IATTC 1980). With the exception of Pacific bluefin, which is found exclusively in the Pacific Ocean, different populations of all these tunas are distributed globally in tropical and temperate regions.

The only fish faster than the tunas are the billfishes; some members of this family are believed to be capable of reaching swimming speeds upward of 130 km · hour$^{-1}$ (Block and Booth 1992). These large teleosts are categorized based on the presence of an elongated rostrum, either flat or rounded, which is an extension of their upper jaw (Izumi 1983). Swordfish (*Xiphias gladius*), which has a global distribution, is the only member in the billfish family Xiphiidae. Of the eleven species in the family Istiphoridae, six live in the Pacific Ocean: Indo-Pacific sailfish (*Istiophorus platypterus*), black marlin (*Istiompax indica*), Indo-Pacific blue marlin (*Makaira mazara*), striped marlin (*Tetrapturus audax*)[4], and longbill spearfish (*T. pfluegeri*) (IATTC 1980).

Often travelling thousands of kilometers to find food at upwellings or reach specific mating grounds (Squire 1974; Block *et al.* 2001; Dagorn *et al.* 2001; Shadwick *et al.* 2013), tuna and billfish are the world's endurance specialists. In the Pacific, the northern stock of albacore and Pacific bluefin undertake extensive regular migrations across the ocean basin, from the coast of Asia to North America (Allen 2010). All bigeye tuna are believed to be part of a continuous stock throughout the Pacific, however

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[3] The other two *Thunnus* species, blacktail (*T. atlanticus*) and Atlantic bluefin (*T. thynnus*) are native only to the Atlantic Ocean.

[4] Striped marlin is also known by the species name *Kajikia audax*. However, for the purpose of this work, it will always be referred to as *T. audax.*

individual fish exhibit less east to west movement compared to other species (Davies *et al.* 2011; Aires-da-Silva and Maunder 2012b).

The long distance and fast swimming characteristic of all tunas and billfish are made possible by both anatomical and physiological adaptations, including hydrodynamic body forms, specialized fins, and ram ventilation (Brill and Bushnell 2001; Graham and Dickson 2001; Korsmeyer and Dewar 2001; Shadwick *et al.* 2013). Having evolved regional endothermic capabilities (i.e., the ability to self-regulate and heat their brain, muscles, viscera and other organs to a temperature above that of the surrounding water) has further enabled these pelagic fishes to move and hunt across both horizontal and vertical thermoclines and acquire adequate sustenance as they travel throughout the marine environment (Block 1986; Brill 1987, 1994; Graham and Dickson 2001). As such, tunas are opportunistic predators, capable of spending much of their adult lives in open water and the High Seas[5], hundreds of kilometres from the coast in the epipelagic layer (i.e., 0-200 m below the surface) of the ocean.

However, the remote nature of this environment is hardly a deterrent to the world's commercial fishing fleets; tuna caught from the High Seas constitute to a multi-billion dollar annual component of the global seafood industry.

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[5] The term 'High Seas' is international territory, and denotes all bodies of water outside of the 200 nautical mile (370 km) EEZs of the world's coastal and island nations.

### *Industrial tuna fisheries of the Pacific Ocean*

Tuna fishing by pole-and-line began around the Pacific Islands in the 1920s, however it was not until after World War II that industrial[6] efforts began to intensify (Gillett 2007). Landings in the early 1950s ranged from 259,000-348,000 t per year; initially, smaller species (e.g., skipjack and albacore) were sought for canning purposes and dried export by foreign (locally-based) fleets from the United States and Japan. However, improvements in fishing vessel technology and shipping methods—as well as the development of flash freezing capabilities—precipitated a rapid expansion in the industry, in both species targeted and gears employed (Gillett 2007; Majkowski 2007). Within a relatively short period of time, these technical advancements resulted in increased fishing effort in previously unexploited off-shore waters, and the subsequent spatial distribution of the world's industrial fisheries—which primarily targeted tuna—into the High Seas (Swartz *et al.* 2010a).

Today, with annual landings exceeding 3 million t (i.e., about 70% of the current total global tuna catch) and an annual value of more than $US 7 billion (Xiaojie *et al.* 2006; Williams and Terawasi 2013), the tuna fisheries of the Pacific Ocean are among the most economically important seafood providers in the world. The main targets of these fisheries are four species of tuna: skipjack, yellowfin, bigeye, and albacore; note that only two species—yellowfin and skipjack—contribute 86% of the target catch by weight (Williams and Terawasi 2011). However, at the individual level, the most

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[6] There is no universal definition of 'industrial fishing'. However, here it is defined as commercial fishing activity off-shore with large engine-powered vessels (> 15 m in length). This type of fishing typically includes the use of extensive technological assistance (e.g., satellite-based navigation, sonar, hydraulics, automatic rail rollers, etc.) to locate and/or catch the targeted fish.

valuable species caught in the Pacific are bigeye and bluefin (Majkowski 2007; Williams and Terawasi 2011).

i. Western Pacific Ocean (WPO)

Locally-based and foreign vessels operate in the WPO High Seas and within the EEZs of Pacific Island countries and territories, with the latter contributing about 48% of the total regional catch (Lehodey *et al.* 2011). Presently, target tuna landings in the WPO amount to about 2.5 million t annually, and the majority of this catch is acquired through the use of surface gears targeting yellowfin and skipjack for canning (Lehodey *et al.* 2011; Sumaila *et al.* 2014). Specifically, purse seiners are responsible for three quarters of the tuna caught in the WPO, whereas landings by pole-and-line vessels only constitute 7% (Harley *et al.* 2011).

Historically, distant-water fleets (DWFs) from Japan, Korea, Taiwan and the USA were the main purse seining operations in the WPO, with DWFs from China, Ecuador, El Salvador, New Zealand and Spain becoming more prevalent in the region since 2000; a total of 202 foreign purse seiners fished here in 2010 (Williams and Terawasi 2011). In addition, since the late 1980s, Pacific Island-based purse seine fleets have steadily increased in number, and in 2010 there were 78 locally-based purse seine vessels in the WPO (Williams and Terawasi 2011).

Longlines are the second most common gear in the WPO (contributing about 10% of the catch). Approximately 3,500 longliners in the WPO fall into one of two main fishing categories: i) large (>350 GRT) DWF vessels with freeze capabilities that partake in extensive trips (i.e., longer than a month) throughout large areas of the region; and ii) small (< 150 GRT), domestically-based offshore vessels that undertake shorter trips (less than one month) (Williams and Terawasi 2011). Although differences in fishing area and target species exist on a country basis (Williams and Terawasi 2011), all longline fleets target primarily mature bigeye and yellowfin (which are flash frozen, then thawed for sale as fresh for sashimi), as well as some albacore for canning (WCPFC 2011; Sumaila *et al.* 2014).

The prevalence of pole and lining has decreased significantly over the last three decades (from approximately 800 vessels in the 1970s to 150 vessels in 2010), largely as a result of the expansion of purse seining (Williams and Terawasi 2011). Nonetheless, this type of surface fishing remains a seasonal venture for Australia, Fiji, and Hawaii (domestic fleets), as well as Japan (both DWF and domestic fleets), and a year-round fishery for domestic vessels from Indonesia, the Solomon Islands, and French Polynesia (Amoe 2005; Langley *et al.* 2010; WPRFMC 2013). Although variation exists within these fleets (especially at the domestic level), skipjack is the primary species landed by pole-and-line vessels (about 75% of the catch), followed by albacore (about 15%), yellowfin (5-10%), and bigeye (1-5%) (WCPFC 2011).

Large-mesh driftnets were briefly employed by Japanese and Taiwanese DWFs in the WPO during the 1980s to catch albacore and skipjack. However, as a result of concerns over the bycatch of marine mammals and birds, this ecologically damaging practice was banned worldwide by the United Nations in 1991 (Bailey *et al.* 1996). Currently, a small industrial troll fishery, composed primarily of American and New Zealand vessels, targets albacore in the coastal waters of New Zealand (Williams and

Terawasi 2011). Although landings from this fishery were upward of 8,000 t in the 1990s, present day efforts result in approximately 2,500 t annually (WCPFC 2011).

### ii. Eastern Pacific Ocean (EPO)

With an annual landed catch of approximately 650,000 t, commercial tuna fishing in the EPO is substantially less than in the WPO. However, as in the WPO, purse seine fleets are responsible for the majority of the tuna landed in the EPO, with 82% of the catch (Hall and Roman 2013).

The onset of this dominance by purse seine vessels began in the 1950s, when technological innovations in gear efficiency enabled a switch from pole-and-line tuna fishing; today, 201 purse seiners are actively fishing tuna in the EPO, compared to only three pole-and-line vessels (Hall and Roman 2013; IATTC 2013b). The majority of purse seine fishing—targeting yellowfin, skipjack, and bigeye—is carried out by fleets from Ecuador and Mexico (26% and 22% respectively), as well as from other South American countries including Venezuela (10%), Panama (8%), Columbia (7%) and Nicaragua (4%) (IATTC 2013b). Purse seining with the use of fish aggregating devices (FADs) has tripled in less than three decades in the EPO: from approximately 2,000 FAD sets in the early 1990s, to more than 6,000 between 2006 and 2009; 95% of all floating object sets are now associated with this method (Hall and Roman 2013; IATTC 2013b).

Distant-water fleets from Japan, Korea, and Taiwan are the primary longlining countries in the EPO, and these countries target bigeye and yellowfin. Although catches were upward of ~110,000 t in the early 2000s, concern over stock health resulted in an imposed tuna conservation resolution of 20% reduction in effort by each fleet between 2004 to 2009 (IATTC 2004). As a result, in 2010, the total longline catch was 52,113 (IATTC 2013b). In addition to tuna longlining, DWFs from Asia, South America, and Spain have targeted swordfish in the EPO since the 1950s; between 2000-2010, the total annual catch of this species averaged 13,500 t (IATTC 2013b).

Coastal (i.e., within EEZ) driftnetting for swordfish and thresher sharks still occurs in the east Pacific, and these operations are conducted by the USA and Mexico (Shore 2013). Tuna ranching practices are additionally carried out in the EPO by Mexico; both yellowfin and Pacific bluefin are caught for this form of ranching (Sylvia *et al.* 2003).

### iii. Southern Bluefin (SBT)

Australia began fishing for southern bluefin in the SPO with the use of surface gears in the early 1950s and, in 1965, Japan entered the fishery with a DWF longline fleet (CCSBT 2011; Polacheck 2012). SPO landings of southern bluefin peaked in the early 1970s at ~19,000 t, but as a result of stock decline, a quota system for this species was implemented in the 1990s. Currently just under 10,000 t total catch (i.e., for all three oceans) is allocated proportionally to each country fishing southern bluefin (Anonymous 2012b).

Currently, a total of nine countries (including the EU as a single entity) target southern bluefin; however, Japan and Australia are responsible for the majority (68% and 28%, respectively) of southern bluefin caught in the SPO each year. Despite the use of other gears in the past, and a large surface gear component for southern bluefin ranching in the Indian Ocean, longlines are currently the primary gear used to fish southern bluefin in the Pacific (CCSBT 2011).

*Small-scale tuna fisheries of the WPO*

For many of the world's coastal regions, tuna fishing has a long and significant cultural history (Majkowski 2007). In the Pacific, Japanese and North American[7] fishers began hunting Pacific bluefin over five millennia ago (Anonymous 2013b), and people living in the Pacific Islands have fished for tuna at the subsistence level for centuries (SPC 2013). Today, tuna remains an important cultural symbol and valuable natural resource for 22 Pacific Island countries and territories (Gillett 2009; SPC 2013). However, its economic significance in the global seafood market makes it both a benefit and burden to many of these small oceanic states (Gillett *et al.* 2001; Lehodey *et al.* 2011; Hanich and Ota 2013; SPC 2013; Sumaila *et al.* 2014).

In the 1970s, less than 100,000 t was landed annually within the waters of the Pacific Islands. Today, over 1.2 million t is landed here each year (Gillett 2007). However, in addition to the industrial fleets operating in the Pacific, many Pacific Islands countries employ artisanal[8] fishing methods (e.g., trolling, handling, bonitier[9] fishing) to catch coastal tuna within national waters (Gillett 2009; 2011). While there is considerable variation in the quantity of tuna landed annually by each country (i.e., ranging from a

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[7] This refers to Aboriginal tribes on the coast of present-day Canada.

[8] Here the definition from FAO (2005) is used to define small-scale 'artisanal' fishing as "those fisheries that use vessels that are open or partially undecked, or vessels that use outboard engines or sails, or vessels that fish with handlines, rod-and-reel gear, harpoons or similar non-industrial gear". For the purpose of this work, this refers to near-shore commercial fishing (i.e., not recreational or subsistence) with the use of artisanal gears. In the Pacific, this typically pertains to (but does not exclusively refer to) tuna fishing in developing coastal regions and small-island developing states (SIDS).

[9] Inshore vessels (12m in length) targeting mostly skipjack with pole-and-line and trolling gear; still used in French Polynesia, but more common pre-1990s (Misselis 2002).

few tonnes to over ten-thousand tonnes), Kiribati is by far the largest source of small-scale tuna in the Pacific Islands. Over half of the region's catch is caught by fishers from this Island nation, even though they make up only 1% of region's total population (Gillett 2011). At the regional level, coastal (small-scale fleet) commercial tuna catches by Island countries are estimated at less than 50,000 t total each year—only 5% of the total landed offshore by foreign-based vessels (Gillett 2009).

### *Bycatch associated with tuna fisheries*

Depending on the context or study, the term 'bycatch' can have several different connotations. For the purpose of this work, 'bycatch' was defined as all non-targeted (i.e., incidental) species associated with a given fishery. Depending on the situation, bycatch may be kept onboard or thrown back to sea. As such, two types of bycatch are discussed in this chapter: retained (r-bycatch) and discarded (d-bycatch). Although considerable recent effort has been put into studying the survival rate of fish and sharks discarded by various fleets, for the purpose of this study, all animals thrown back to sea—independent of whether they were alive or dead at the time of capture or release—were considered d-bycatch. Similarly, all sharks that were finned prior to discarding were also considered d-bycatch.

While numerous factors play a role in the type of bycatch generated by a fishing vessel, bycatch is most directly related to the type of gear it uses. With regard to industrial tuna fishing, typically active gears (e.g., pole-and-line, purse seine) have lower bycatch rates than passive gears (e.g., longline and driftnet) (Lawson 1997; Ardill *et al.* 2011; Restrepo 2011; Hall and Roman 2013). This is most likely attributable to the fact that active fishing methods are directly applied to tuna schools, rather than deployed and left in the ocean for a period of time before their multi-species catch is collected (Hall 1998).

Nonetheless, even within gear types, there can be varying degrees of selectivity based on the primary targeted species (Broadhurst *et al.* 2010). For purse seiners, more bycatch will be caught with the use of FADs, since these objects attract both targeted and non-targeted fish (Bailey *et al.* 1996; Fonteneau *et al.* 2000; Hall and Roman 2013). Similarly, variation in hook size and shape on longlines, and the size of mesh used in gillnets both naturally exclude some species while making others more prone to capture (Løkkeborg and Bjordal 1992; Jude *et al.* 2002). In addition to the fishing gear used, additional factors strongly influencing the amount and type of bycatch incurred by a fleet include where it fishes, and the size of its vessels.

### i. R-bycatch

Although not the directed focus of a fleet's effort, many non-target species are incidentally caught but retained due to their economic value (Alverson *et al.* 1994). In the Pacific, many industrial vessels will land off-shore fishes such as mahi mahi (*Coryphaena hippurus*), wahoo (*Acanthocybium solandri*), baraccuda (*Sphyraena* spp.), and numerous species of small scombrids (Bailey *et al.* 1996; SPC 2010). Many incidentally caught sailfish and marlins are also retained, again for their value in the global seafood market (Hall and Roman 2013).

While some small-scale coastal tuna fleets are highly selective, others generate high levels of incidental catch (Gillett 2011). However, nearly all of this bycatch is retained (Kelleher 2005; Ardill *et al.* 2011; Gillett 2011). Even the heads of some fish that have sustained body damage by sharks are kept; in many cases, only if fish are known to be poisonous or toxic are they entirely discarded (Hall and Roman 2013).

ii. D-bycatch

Fish that are damaged[10] or species that cannot be sold in the international market are routinely discarded at sea (Bailey *et al.* 1996; Kelleher 2005). High seas DWFs, which have sailed far from their EEZ waters, will discard in order to maximize the value of their catch within the limited hold space available in their vessels (Bailey *et al.* 1996). Similarly, smaller vessels fishing within territorial waters may also be prone to discarding if they fish exclusively for the fresh seafood market and do not have freeze capabilities onboard (Hall and Roman 2013).

As is the case with r-bycatch, the d-bycatch is highly variable depending on the fleet: discarding by industrial pole-and-line vessels is minimal (i.e., <1% of the total catch), these operations are most likely to discard small quantities of forage fish (used for bait)[11], and non-tuna small pelagics such as rainbow runner (*Elagatis bipinnulata*) (Kelleher 2005). Conversely, DWF longliners typically have very high discard rates (i.e., upward of 30-40% of the total catch) and pelagic sharks constitute the majority of this unwanted catch (Kelleher 2005; Xiaojie *et al.* 2006; Huang 2009; SPC 2010).

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[10] Damage can be a result of either human error or natural predation. In the Australia longline fishery, about 20% of the target catch is lost due to shark damage.

[11] This study focused on the bycatch and discards associated directly with pole-and-line vessels and did not reconstruct any bycatch or discards associated with the separate pole-and-line baitboat fishery. Estimates from the Indian Ocean suggest that fish caught for use as bait by pole-and-line fisheries amounts to about 12% of the target tuna catch (Ardill *et al.* 2011).

### iii. Discarded target species (D-target)

In addition to discarding incidentally caught species, dumping some target catch is also common practice in industrial tuna fleets (Bailey *et al.* 1996; Kelleher 2005). While d-target is generally lower than d-bycatch, this practice also goes largely under- or mis-reported, and has been a primary focus of observer programs initiated in recent years (Bailey *et al.* 1996; Lawson 2001; Román-Verdesoto and Orozco-Zöller 2005; SPC 2010).

In today's purse seine fisheries, the primary reasons for discarding target species are insufficient well holding space and gear or landing damage[12] (Hall and Roman 2013; WCPFC 2013c). In addition, purse seining with the use of FADs attracts both adult target yellowfin and skipjack tunas, but also large numbers of juvenile tunas (including non-target bigeye), which use the structures for shelter and protection (Fonteneau *et al.* 2000; Hall and Roman 2013). As such, these small fish are often caught, but subsequently discarded (Coan *et al.* 1999; Hall and Roman 2013); a practice known as 'high grading'. High grading occurs when smaller or damaged target fish are discarded in favour of preserving space on a vessel for a more valuable catch (i.e., larger and/or undamaged individuals) (Bailey *et al.* 1996; Cochrane 2002).

Damaged target fish (i.e., self-inflicted injuries while trying to escape, or individuals that have been predated upon by sharks) are common to gears such as longlines and driftnets, and these fish are also typically discarded (Bailey *et al.* 1996).

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[12] Typically this would include being squished under a purse seine beam, or mangled from getting snared in the mesh of the net.

*Stock management and monitoring*

Given the highly transient and off-shore nature of pelagic fishes, it would be nearly impossible to manage stocks on a domestic basis in the same way coastal species are managed. Thus, in 1982, the United Nations devised the 'Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea (UNCLOS) of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks'. This agreement, which

> promotes good order in the oceans through the effective management and conservation of high seas resources by establishing, among other things, detailed minimum international standards for the conservation and management of straddling fish stocks and highly migratory fish stocks; ensuring that measures taken for the conservation and management of those stocks in areas under national jurisdiction and in the adjacent high seas are compatible and coherent; ensuring that there are effective mechanisms for compliance and enforcement of those measures on the high seas; and recognizing the special requirements of developing States in relation to conservation and management as well as the development and participation in fisheries for [straddling fish stocks and highly migratory fish stocks][13]

was adopted in 1995 before entering into force six years later. At present, 166 parties, including 163 UN member states, as well as the Cook Islands, Niue, and the European Union, have ratified UNCLOS. Notably, the United States signed this convention, however they have yet to ratify it due to concerns over its impact to national sovereignty and universal access to seabed minerals (Malone 1983).

Additionally, in 1993, the United Nations enacted the 'Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas', which aims to increase fleet transparency on the High Seas,

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[13] From the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks, Sixth session, New York, 24 July – 4 August 1995.

particularly with regard to flag and vessel ownership (FAO 1995). Combined with the more generic (i.e., pertaining to both High Seas and coastal fishing practices) FAO Code of Conduct for Responsible Fisheries[14], these measures encourage responsible international behaviour, relations, and sustainable fishing on the High Seas as a collective entity, the marine resources in each ocean are additionally managed at a finer scale.

Although they cover a much larger area, the world's Regional Fisheries Management Organizations (RFMOs) fill a similar role in the High Seas as national fisheries management bodies do in coastal waters, and each aims to provide international governance for a specific region of the world's oceans (Figure 3-1). With regard to fishing, the primary responsibilities of RFMOs are to acquire and assemble catch statistics from their members, perform stock assessments for species within their jurisdiction, and enact any conservation and management measures (e.g., member country quota allocation) (Allen 2010; Cullis-Suzuki and Pauly 2010).

Three RFMOs in the Pacific Ocean manage tuna stocks: the Inter-American Tropical Tuna Commission (IATTC), the Western and Central Pacific Tuna Commission (WCPFC), and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT). Both the IATTC and the WCPFC are responsible for collecting data pertaining to multiple species with populations within their geographical jurisdiction, while the CCSBT exclusively manages the fishing fleets associated with only southern bluefin across its entire circumpolar range. As such, the CCSBT operates in the Indian and Atlantic Oceans

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[14] Available online from FAO: http://www.fao.org/docrep/005/v9878e/v9878e00.htm [accessed 9 September 2013].

as well; landings of southern bluefin in the Pacific Ocean amount to roughly 17% of the total annual catch (CCSBT 2011).

In addition to the RFMOs, smaller independent research and management bodies also exist in the Pacific, at both the levels of data collection and research within EEZs, and throughout the High Seas. Although each is defined by a different set of objectives and administrative structure, these organizations are typically either i) independent bodies that focus on fisheries monitoring and research on specific geographical regions (e.g., the Oceanic Fisheries Programme of the Secretariat of the Pacific Community; OFP-SPC); ii) international organizations that focus on specific species stock assessments and research (e.g., the International Scientific Committee; ISC), or iii) associated divisions of national or regional management programs, which

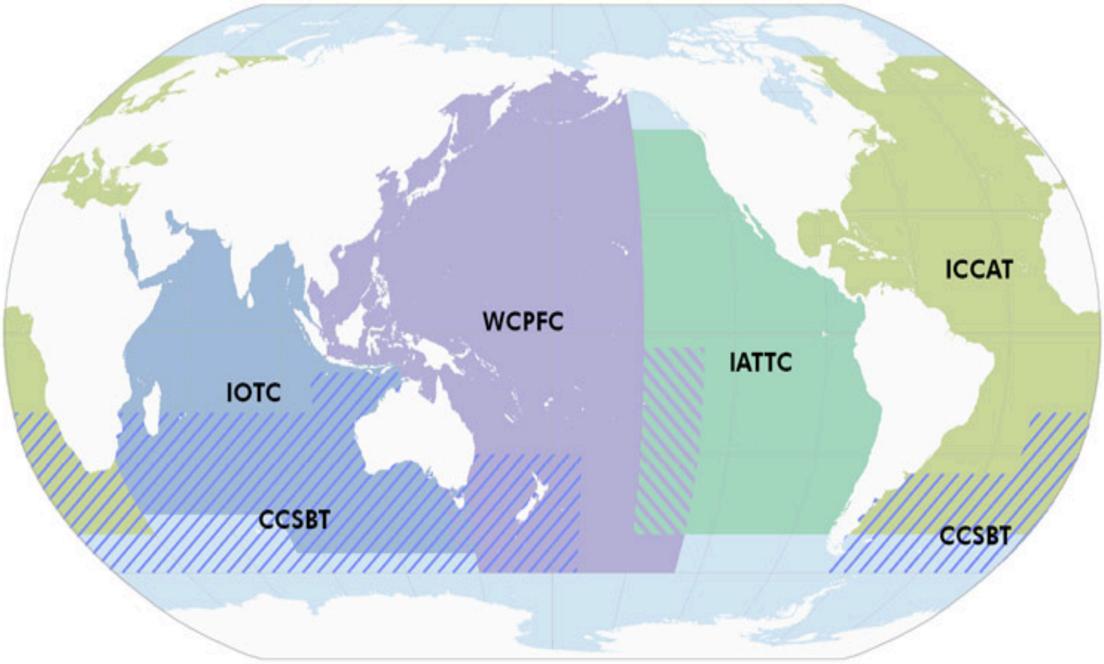

**Figure 3-1. Boundaries of jurisdiction of the Regional Fisheries Management Organizations (RFMOs) responsible for managing tuna (Source: The Pew Charitable Trusts, 2011).**

collect data pertaining to the specific fisheries of its member countries (e.g., Pacific Islands Forum Fisheries Agency; FFA, Western Pacific Regional Fishery Management Council; WPRFMC).

### *Purpose of study*

Attention toward bycatch and discards is becoming increasingly prevalent both within the scientific community, across fisheries management organizations and governing bodies, and also within the general public. Although many surface tuna fishing gears are considered low-impact or 'clean' (Kelleher 2005; Ardill *et al.* 2011), the fact remains that tuna are the main target of the largest commercial fleets in the world, and the predominant focus of High Seas effort. As such, their magnitude alone likely makes these fisheries some of the largest producers of bycatch and discards in the world. Given their remote nature, it is often difficult to maintain adequate observer coverage for High Seas fleets, a challenge that is ultimately reflected in the reporting accuracy and consistency of both target and non-target catches.

Using observer data, and any other available information from both primary and grey literature, this study aims to quantify and taxonomically disaggregate the retained bycatch and discards (of both bycatch and target species) associated with the commercial tuna fisheries of the Pacific Ocean.

## METHODS

### *Baseline species catch data*

The target species landings and associated gears (Table 3-1) used as the catch baseline were obtained online from publically available data provided by the WCPFC, IATTC, CCSBT, and ISC. With the exception of southern bluefin (see below), it was assumed that all target species commercial landings were accurately reported to these organizations by each country; all catch that was explicitly stated as 'recreational' was excluded from this analysis.

**Table 3-1. Target species, associated primary gears and sources of data for the fisheries in the Pacific Ocean.**

| Target species | Gear | Baseline data source |
|---|---|---|
| Bigeye tuna | Longline, purse seine | WCPFC, IATTC |
| Yellowfin tuna | Longline, purse seine, pole and line, handline | WCPFC, IATTC |
| Albacore tuna | Gillnet, longline, pole and line, troll | WCPFC, IATTC |
| Skipjack tuna | Gillnet, longline, pole and line, purse seine | WCPFC, IATTC |
| Pacific bluefin tuna | Longline, purse seine, troll, pole and line | IATTC, ISC[a] |
| Southern bluefin tuna | Longline, purse seine, handline, pole and line | CCSBT[b] |
| Swordfish | Longline | WCPFC, IATTC |
| Sharks[c] | Gillnet, longline | IATTC |

[a] Catch data from ISC were used as the targeted landed catch. All Pacific bluefin catches included in the IATTC data for countries other than those included in the ISC time series (i.e., other than Japan, Korea, Taiwan, USA, Mexico) were assumed to be r-bycatch.

[b] Originally, southern bluefin catch data including both country and gear were not available for the Pacific Ocean alone. Upon written request, these data were provided by the CCSBT.

[c] The only catch assumed to represent targeted shark fishing was from the US and Mexico (gillnet), and the artisanal fleets of Peru and Guatemala.

*Unreported target tuna landings*

Using Japanese market and import statistics, Polacheck (2012) recently estimated that a total of 178,000 t of southern bluefin caught by longliners (all oceans) was under-reported between 1985-2005 (Table 3-2); these landings were not included in the data provided by the CCSBT. GraphClick software was used to extract the annual percent overcatch values from Polacheck (2012; see Fig. 3), and these data were then applied to the total annual longline catch in the Pacific to estimate the unreported catch. This unreported catch was then allocated proportionally by fleet and included in the baseline for future calculations of associated bycatch and discards.

*Accounting for regional differences of reported r-bycatch*

Independent studies suggest variability in r-bycatch rates, which typically range from 10-40% of the total catch for industrial longline fleets (Bailey *et al.* 1996; Lawson 2001; Huang 2009; SPC 2010), and less than 5% for purse seiners (Lawson 2001; Restrepo 2011; Hall and Roman 2013).

**Table 3-2. Reconstructed unreported catch of southern bluefin in the Pacific Ocean. Overcatch values were extracted from Polacheck (2012) using GraphClick.**

| Year | Overcatch (%) | Unreported catch | Year | Overcatch (%) | Unreported catch |
|---|---|---|---|---|---|
| 1986 | -12 | - | 1996 | 138 | 2,015 |
| 1987 | 0 | - | 1997 | 179 | 2,824 |
| 1988 | 6 | 67 | 1998 | 211 | 3,919 |
| 1989 | 0 | - | 1999 | 122 | 2,806 |
| 1990 | 33 | 720 | 2000 | 105 | 2,012 |
| 1991 | 65 | 1,451 | 2001 | 141 | 3,263 |
| 1992 | 53 | 1,326 | 2002 | 139 | 3,616 |
| 1993 | 45 | 1,387 | 2003 | 124 | 2,872 |
| 1994 | 91 | 2,032 | 2004 | 98 | 1,697 |
| 1995 | 149 | 3,728 | 2005 | 59 | 865 |

In addition to landings of target species, both the WCPFC and the IATTC databases also included landings of r-bycatch for several non-target species. The average r-bycatch longline rates from these RFMOs were 10% and 16% respectively, and 0.1% and 3% for purse seine catches. The last two decades show these rates to be more consistent with the independent values, and this is likely attributable to both improved observer coverage (i.e., more realistic estimates) and the impact of geographical fleet expansion (i.e., more discarding).

Given this information, it was assumed that each country accurately reported r-bycatch to the IATTC and WCPFC. However, although larger species (e.g., istiophorids) common to longline fisheries were found in the r-bycatch of both the IATTC and WFPFC, the non-target species reported by the two RFMOs differed for small pelagics and other bony fishes that would primarily be caught incidentally by purse seiners (Table 3-3). To

**Table 3-3. Non-target species r-bycatch as reported by the Pacific RFMOs.** CCSBT does not report any r-bycatch.

| Species | WCPFC | IATTC |
|---|---|---|
| Blue shark (*Prionace glauca*) | Yes | No |
| Mako sharks (*Isurus* spp.) | Yes | No |
| Oceanic whitetip shark (*Carcharhinus longimanus*) | Yes | No |
| Thresher sharks (*Alopias* spp.) | Yes | No |
| Silky shark (*Carcharhinus falciformis*) | Yes | No |
| Misc. sharks (Elasmobranchiii) | No | Yes |
| Black skipjack (*Euthynnus lineatus*) | No | Yes |
| Black marlin (*Makaira indica*) | Yes | Yes |
| Blue marlin (*Makaira nigricans*) | Yes | Yes |
| Striped marlin (*Tetrapturus audax*) | Yes | Yes |
| Indo-Pacific sailfish (*Istiophorus platypterus*) | No | Yes |
| Shortbill spearfish (*Tetrapturus angustirostris*) | No | Yes |
| Misc. bonitos (*Sarda* spp.) | No | Yes |
| Misc. jacks, runners, jack mackerels, and pompanos (Carangidae) | No | Yes |
| Dolphinfishes (Coryphaenidae) | No | Yes |
| Misc. billfishes (Istiophoridae) | No | Yes |
| Misc. tunas (Thunnini) | No | Yes |
| Misc. bony fishes (Osteichthyes) | No | Yes |

account for this difference, the r-bycatch of eight non-reported species in the WCPFC was estimated by applying the average annual gear and country specific rates from the EPO to catches in the WPO. Although purse seining with the use of FADs varies in each region of the Pacific Ocean, it was assumed that this difference in FAD usage would not significantly influence the species composition of r-bycatch.

While sharks were included in both databases, the IATTC records begin roughly twenty years before those of the WCPFC. It was assumed this difference in species composition between the databases was a function of reporting differences between the RFMOs, rather than an absence of r-bycatch of sharks prior to 1990 in the WPO. Thus, for missing years, the r-bycatch rate of 'Elasmobranchii' from the EPO was applied to the WPO. In order to disaggregate the generic group of 'Elasmobranchii' from the IATTC data, the r-bycatch proportions of the five species reported by fleets in the WCPFC were used.

No data pertaining to retained non-target fish and shark species were available from the CCSBT or ISC. As such, r-bycatch rates and the associated annual species compositions based on gear from the IATTC were applied to both bluefin fisheries.

### *Discarded catch of industrial fleets*

Two types of discards were considered for this study: discards of target species (d-target) and discarded bycatch (d-bycatch). Most sources gave discard information in terms of either a discard to landing ratio (i.e., discards /landings) or as a percentage of the total catch (i.e., discards/ (landings + discards). To ensure uniformity across data sources, all information was converted to the latter before being applied to the target catch time series.

Given that discard information was difficult to obtain from the literature, the average weighted discard rates associated with each gear from Kelleher (2005) were held constant over time for many cases since time series could not be obtained. Although differences between fleets using the same gear will differ depending on whether they are local or distant-water operations, it was not possible to separate these fleets using the RFMO country baseline catches. Therefore, for countries where more than one rate was obtained (i.e., near-shore and off-shore), the average of these rates was used.

In addition to pelagic fishes and sharks, the d-bycatch associated with industrial tuna fisheries often consists of cetaceans, sea turtles, and seabirds. While these species are common in the High Seas, and numerous fisheries-specific case studies exist for d-bycach of non-fish species, this study did not quantify the d-bycatch of any animals other than pelagic fishes and sharks.

### *Estimating artisanal bycatch and discards*

Since the majority of fishing for tunas and billfishes is carried out at an industrial-scale, it was assumed (unless otherwise specified) that the associated r-bycatch applied to these large-scale practices, rather than artisanal fleets. Gillett (2011) recently attempted to quantify the global r-bycatch associated with small-scale tuna fisheries. Thus, for assumed small-scale commercial catches in Pacific Island countries, independent r-bycatch values and species breakdowns were applied on a per-country basis to certain gears listed in the WCPFC database (Table 3-4). When a specific value was not available, the average of known small-scale gears was used. With this in mind, for many artisanal fisheries, it can be difficult to make a distinction between artisanal fisheries that specifically target tuna and artisanal fisheries where tuna is a merely a component of whatever is opportunistically caught during a trip (Gillett 2011). This study assumed that the RFMO baseline catch data applied to fisheries specifically targeting tuna.

Little numerical information was available regarding small-scale discard rates, but anecdotes suggest negligible discarding by artisanal fleets (Gillett 2011). Thus, despite high levels of r-bycatch in many of the Pacific Island countries, a discard rate of 0.5% was assigned to all of the previously identified artisanal fishing fleets for both d-bycatch and d-target. Whenever possible, species breakdowns for both r- and d-bycatch were assigned on a case-by-case basis, using country-specific information (see Table 6).

While both bycatch and discards associated with the commercial small-scale Pacific tuna fleets were estimated in this study (based on the data reported by the RFMOs), no subsistence or recreational tuna catches were reconstructed. Specific national reconstructions of unreported tuna catches for these sectors can be found in Pauly and Zeller (in prep.).

### *IATTC and WCPFC overlap zone*

While the majority of tuna caught in the Pacific Ocean are reported to one RFMO or the other (based on the region in which they were caught), there is a small area (150°W to 130°W; 4°S to 50°S)— which encompasses High Seas waters as well as

**Table 3-4. R-bycatch associated with certain WCPFC Pacific Ocean smalll scale fleets.** Species breakdowns were also estimated based on these sources.

| Gear listed in WCPFC database | Country fishing | Assumed artisanal gear | r-bycatch (as % of total catch) | Source |
|---|---|---|---|---|
| Handline/ Small-scale hook and line[1] | USA (Hawaii) | Handline | 12 | Gillett (2011) |
| | Indonesia | Handline | 50 | Gillett (2011) |
| | Philippines | Handline | 15 | Gillett (2011) |
| Ringnet | Philippines | Ringnet | 25 | Anonymous (2012) |
| Troll | French Polynesia | Bonitier fishing (troll and mixed gears) | 21 | Gillett (2011) |
| | American Samoa | Troll | 3 | Average of known years in Gillett (2011), WCPFM (2011) |
| | Cook Islands | Troll | 25 | Gillett (2011) |
| | Fiji | Troll | 25 | Gillett (2011); suggesting similar to Cook Islands |
| | Guam | Troll | 42 | Gillett (2011); combined rate of both commercial and recreational troll fishing |
| | Nauru | Troll | 4 | Gillett (2011) |
| | Tuvalu | Troll | 15 | Tupau (2006) |
| | Tokelau | Troll | 15 | Used same rate as Tuvalu in Tapau (2006) |
| | USA (Hawaii) | Troll | 50 | Gillett (2011) |
| Other | Japan | Mixed gears | 45 | Gillett (2011) |
| | Kiribati | Troll | 12 | Gillett (2011) |
| | Niue | Troll | 67 | Gillett (2011) |
| | Taiwan | Unknown | 30 | Average of known rates for all 'Other' gears |
| | French Polynesia | Bonitier fishing | 21 | Gillett (2011) |
| | Indonesia | Mixed gears (~15 types) | 50 | Gillett (2011) |
| | Philippines | Mixed gears | 18 | Gillett (2011); average of all artisanal gears in the Philippines |

[1] No information specifically pertaining to hook and line bycatch in the Philippines or Indonesia could be found. Thus, it was assumed this method of fishing was most similar to handlining.

the EEZ of French Polynesia—where the jurisdictions of the IATTC and WCPFC geographically overlap. While the IATTC convention and its associated boundaries have existed since 1949, the boundaries of the WCPFC Convention were officially designated only in 2004. Thus, reported landings from this overlap zone are available only from 1995 (see Table 1 in Appendix).

Overall, landings from the Pacific Ocean overlap area have amounted to 15,000-20,000 t annually (IATTC 2012); i.e., less than 0.2% of the total catch. These landings pertain primarily to the distant-water longline fleets of Japan, the United States, Taiwan, and Korea, and the purse seine fleets of Mexico, the United States, Ecuador, Spain, Korea, and El Salvador. IATTC vessels have conducted the majority of purse seining in the overlap zone, while most of the longline vessels are related to the WCPFC. To avoid double counting, Eastern Pacific USA purse seine catches were removed from the WCPFC baseline data, but no other adjustments regarding the overlap zone data were made.

## RESULTS

The reconstructed catch of target tunas and associated bycaught and discarded pelagic species in the Pacific Ocean between 1950 and 2010 is 107 million t (Figure 3-2). This represents an increase of 14% when compared to the baseline target species catch (94 million t); fish previously unaccounted for include 1.4 million t of r-bycatch, 3.6 million t of d-target, and 7.9 million t of d-bycatch.

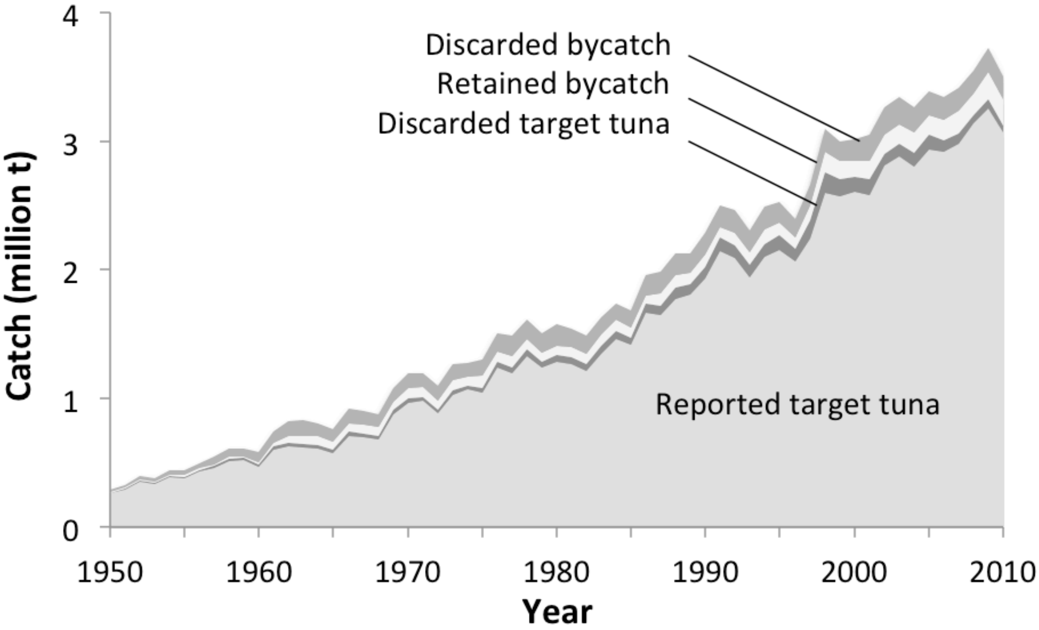

**Figure 3-2. Total reconstructed catch of tunas and associated bycatch and dicards in the Pacific Ocean from 1950-2010.** Total retained bycatch equaled 5.2 million t (1.4 million t from the WPO were previously unreported), and unreported discards equaled 11.5 million t (3.6 million t d-target; 7.9 million t d-bycatch).

*Total retained bycatch*

The r-bycatch of the tuna fleets of the Pacific Ocean amounted to 5.2 million t. Since some associated r-bycatch species were already included in the data provided by the RFMOs, this includes a reported landed value of 3.8 million t plus a reconstructed r-bycatch of 1.4 million t for species missing from the WCPFC, CCSBT, and ISC data (Figure 3-3). The r-bycatch is composed primarily of bonitos (23%), black marlin (21%), and striped marlin (14%). Cumulatively, billfish make up 45% of the total r-bycatch in the Pacific Ocean.

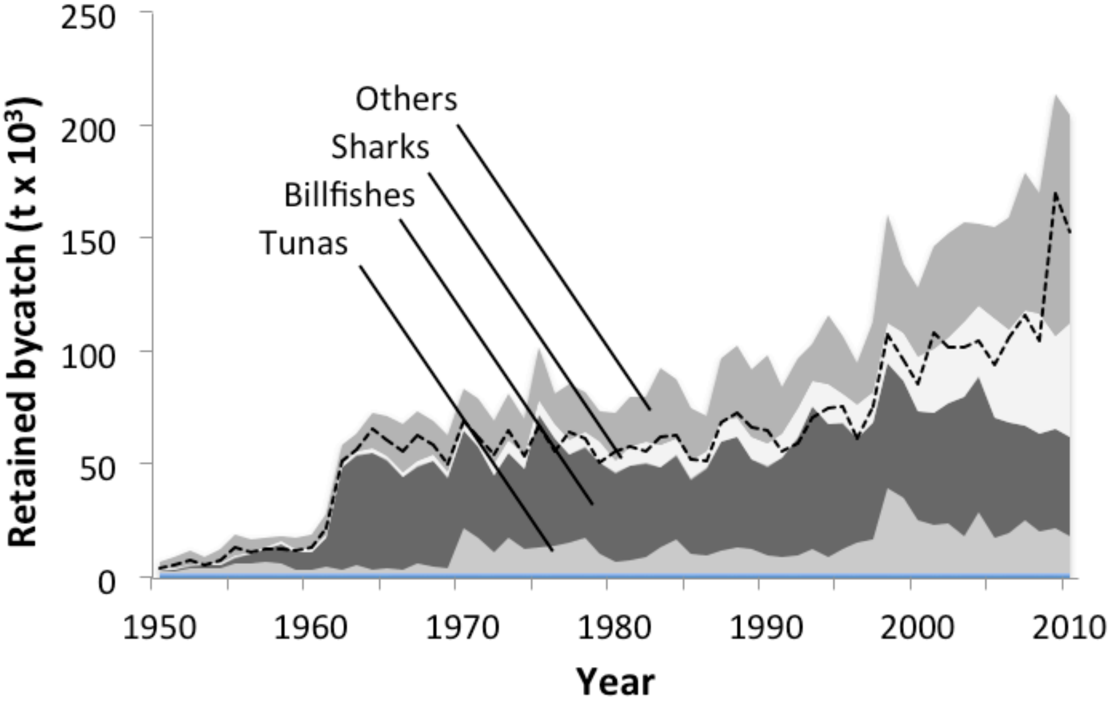

**Figure 3-3. Reconstructed retained bycatch of species associated with Pacific Ocean tuna fleets.** Billfish constitute 45% of the total r-bycatch in the Pacific Ocean by weight. Low levels of bycatch prior to 1960 are attributable to the prominence of pole-and-line fisheries at this time, which generate little bycatch. With the onset of purse seining and increased longlining in the 1960s, associated bycatch became more prevalent, and has increased ever since. Dashed line refers to total reported catch (of both target species and reported r-bycatch). (For complete species breakdown, see Appendix Table 2, and for breakdown by gear, see Appendix Table 5).

### *Discarded target species and discarded bycatch*

This reconstruction determined a total of 3.4 million t of unreported target species discards since 1950 (Figure 3-4). When compared to the total reported target catch over this time period, target discards amount to 4%.

Conversely, the reconstructed d-bycatch is 7.9 million t (Figure 3-5), the majority (60%) of which was sharks, specifically blue shark (*Prionace glauca*) and silky shark (*Carcharhinus falciformis*). Alone, these two species make up 50% of the total reconstructed d-bycatch. Non-shark d-bycatch was primarily unknown marine fishes (22%), and scombrids (6%).

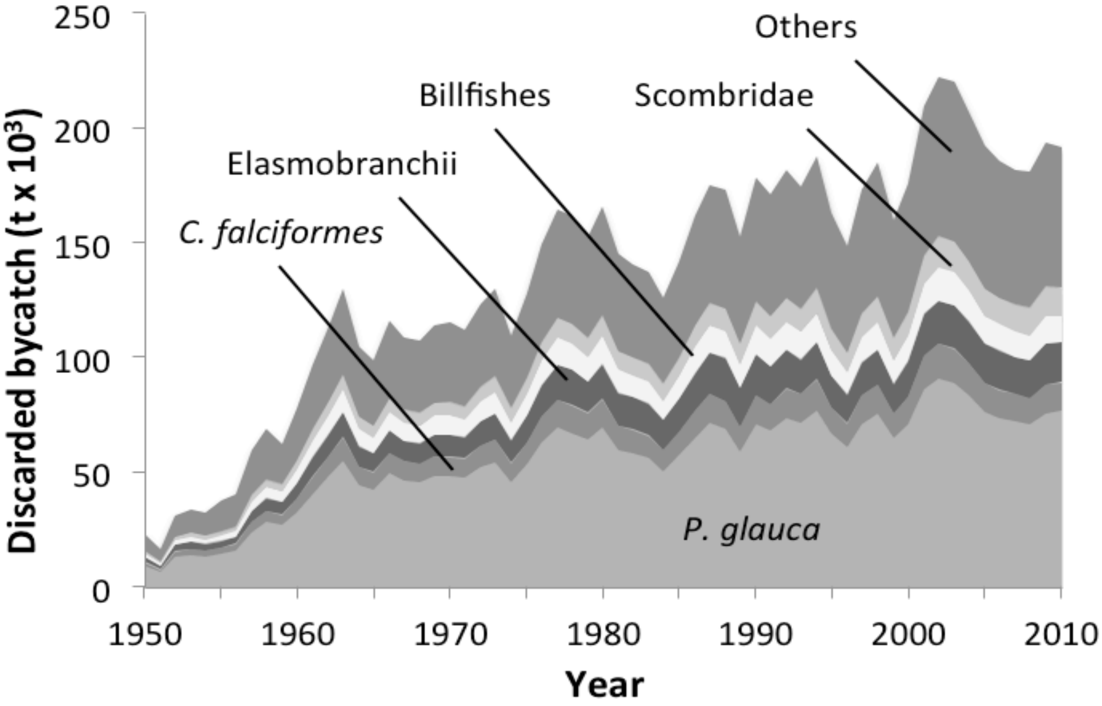

**Figure 3-4. Species composition of d-bycatch between 1950-2010.** Sharks are the most commonly discarded species (60%), and blue shark alone makes up 36% of all discards. (For complete species breakdown see Appendix Table 3, and for breakdown by gear, see Appendix Table 7).

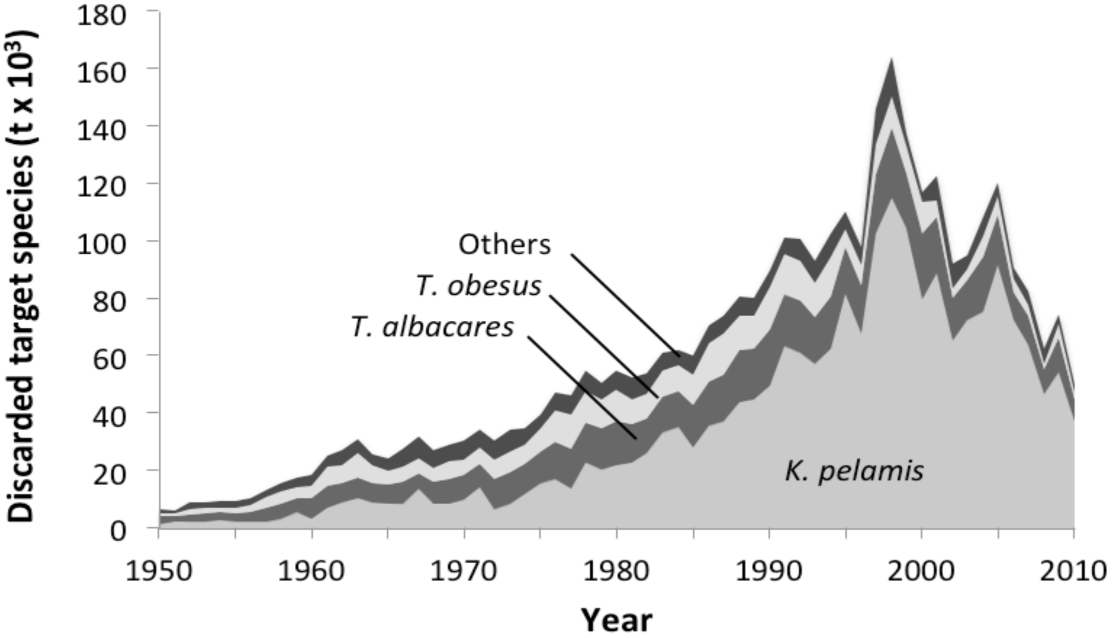

**Figure 3-5. Discards of target species in the Pacific Ocean between 1950-2010.** Skipjack has the highest discard rate among the tuna species, and due to its prominence in the purse seine catch, it also constitutes 58% of the discarded target catch. Tuna discards appear to have decreased since 2000, a trend possibly attributable to increased management measures, including improved observer coverage (that reached 100% in 2010) on industrial purse seiners in both the Eastern and Western Pacific. (For complete breakdown of 'Others', see Appendix Table 4 and for breakdown by gear, see Appendix Table 7).

## DISCUSSION

As Alverson *et al.* (1994) point out, discarding unwanted marine life has occurred for at least two millenia:

> Again, the Kingdom of Heaven is like a dragnet cast into the sea, and gathering fish of every kind; and when it was filled, they drew it up on the beach; and they sat down and gathered the good fish into baskets, but the bad they threw away (Matthew 13:47-48).

Nonetheless, with a greater dependency on marine resources for protein, and the present state of overcapacity of the world's fishing fleets, the amount of fish being thrown back to the sea today is estimated at over 7 million t annually (Kelleher 2005). For Pacific Ocean tuna fleets, Kelleher (2005) additionally calculated a discard rate of 7.7% between 1991-2001. In using some of the same sources, but also several new ones, this reconstruction has elaborated on this estimate (in terms of species composition) and also incorporated information from the past decade. Here, the discard rate (including both d-target and d-bycatch) for tuna fleets in the Pacific Ocean determined in this study between 1950-2010 is 10.8%.

Predatory fish larger than 1.75 m in length have decreased from 5% to 1% of the total population as a result of commercial fishing in the Pacific Ocean, and the current biomass of these species is between 36-91% of the predicted biomass in the absence of fishing (Sibert *et al.* 2009). Polovina and Woodworth-Jefcoats (2013) recently showed that declines in the abundance and size of large marine predators (e.g., tunas, billfish, and sharks) have resulted in increased abundance of smaller and commercially less valuable species (e.g., lancetfish and snake mackerel). These species now have higher catch rates than the target species, which has naturally led to higher discard rates in the fishery as well[15]. Not only does removing top predators and prey species impact the overall biodiversity and community structure of the surrounding environment, it also changes the foraging behaviour of species that learn to take advantage of discards (Gilman *et al.* 2008a).

In connection to the reconstructed numerical estimates, this study highlights four main areas of concern with regard to bycatch and discards associated with commercial tuna fisheries in the Pacific Ocean: i) uncertainty in the degree of catch under-reporting by tuna fleets; 2) the volume of unreported discarded catch; 3) the composition of unreported discarded catch; and 4) the absence of standardization pertaining to management records and terminology.

### *Unreported landings and illegal tuna fishing*

Although this study reconstructed r-bycatch for species missing from the WCPFC and CCSBT databases, it is possible that r-bycatch reported to all of the tuna RFMOs in the Pacific is also under-reported. Specifically, certain large Asian fleets (e.g., Japan, Taiwan, China, Korea) did not report the r-bycatch of some species (e.g., carangids, and small scombrids) to the IATTC. Thus, it was impossible to calculate r-bycatch of these species in the WPO as well. Nonetheless, this method was chosen in order to remain conservative with r-bycatch estimates and to avoid losing species resolution at the country level. Since r-bycatch information for tuna fleets is sporadic, focused primarily on the most prominent fleets, and largely from the last two decades, this methodology

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[15] Based on time series catch information from with the Hawaiian deep-set longline fishery.

decision was able to ensure a time series with an observable trend for the entire duration of the study.

Given the uncertainty pertaining to unreported target tuna landings, no estimates other than those for southern bluefin provided by Polacheck (2012) were included here. Nonetheless, illegal[16] fishing for tuna is known to occur throughout the Pacific, especially with longline vessels (OECD 2004; Anonymous 2012a). Although specific tonnages associated with illegal (and mis-reported) catches are uncertain, Agnew *et al.* (2009) suggest that from 2000-2003, between 2-12% of the global tuna catch was unreported. Based on a total global tuna catch of 4 million t in 2010, this would presently amount to between 80,000-480,000 t of tuna annually missing from national and RFMO catch records; with 70% of the global catch, this means between 55,000-335,000 t of tuna are illegally caught in the Pacific every year. The absence of these data also results in an absence of associated bycatch and discard estimates. While monitoring and enforcement efforts are improving in the coastal waters of the WPO, the SPC estimates that illegal fishing occurring solely within the territorial waters of Pacific Island nations amounts to upward of $US 1billion annually[17].

Although they typically employ small vessels, small-scale commercial fisheries are far from insignificant—artisanal gears annually landed just under 700,000 t of tuna (globally) in the 2000s, not to mention these fisheries are responsible for the majority of tuna caught in many developing countries, including the Philippines and Indonesia

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[16] While mis-reporting catches on the High Seas is technically not illegal behaviour (since the High Seas is common property), catching fish from within another country's EEZ without proper access agreements, or violating the terms of an existing access agreement does constitute illegal fishing.

[17] Obtained from online news: http://www.spc.int/en/home/216-about-spc-news/1076-regional-action-to-fight-illegal-tuna-fishing-in-the-pacific.html [accessed March 6 2014].

(Gillett 2011). However, fisheries managers might fail to adequately record the amount of fish caught by small-scale fishers for a number of reasons pertaining to the nature of coastal fisheries in developing nations. Based on interviews with fishers in the Philippines, 'lost' tuna can make up over 10% of the total small-scale commercial catch (Momo Kochen[18], pers. comm.). These are fish that were caught by small-scale commercial fishers, but never made it to the market because fishers either ate them during the trip, gave them away to people immediately upon landing, sold them on the side to people other than the vessel owner or middleman (to whom they sell the bulk of their catch), or kept for themselves and their family (Momo Kochen, pers. comm.). Catches associated with this practice (and other similar practices associated with small-scale fisheries in developing countries) were not included in this study.

### *Unreported discards*

Two of the main goals of fisheries stock assessments are to determine the health of a given stock (i.e., its biomass relative to the biomass at MSY), and to identify the intensity at which that stock can be fished sustainably (i.e., setting a total allowable catch (TAC) for a given year or time period). Recent assessments suggest that Pacific skipjack, albacore and yellowfin are healthy and not experiencing overfishing (Hoyle *et al.* 2011; ISC 2011; Langley *et al.* 2011; Hoyle *et al.* 2012); however, analyses of bigeye, and bluefin stocks suggest that these tunas are all currently being overfished to varying degrees (CCSBT 2011; Davies *et al.* 2011; ISC 2013c). Along with species-specific

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[18] Project Leader at 'Fishing & Living', an on-the-ground collaborative initiative that focuses on small-scale Indonesian fisheries research and enhancements to their surrounding socioeconomic environment.

biological parameters, catch statistics are one of the most important components to be incorporated into these assessments. However, as a result of uncertainty, discarded catch is rarely included.

In general, discards of target tunas appear to be in decline over the last decade, a trend possibly attributable to increased observer coverage on purse seine vessels. Additionally, since the total reconstructed discards of target species is less than 4% of the retained target catch over the last sixty years, the inclusion of this omitted fishing mortality may not significantly alter the outcomes of these stock assessment reports. There is additional question within the scientific community about the many implications imposed by discards and Punt *et al.* (2006) demonstrate that the inclusion of discard information can lead to contradictory assessment results, depending on the fishery and species considered. Nonetheless, if the underlying reason for discarding is understood, and sufficient discard data exist, then this information should be considered. Additionally, since a significant component of discarded tuna are juveniles, this may have a disproportionately large ecological and economic impact. In discarding fish that have not yet had an opportunity to contribute to the breeding stock, nor reached their maximum weight, fleets are inducing both recruitment and growth overfishing, which simultaneously diminish their catch potential (i.e., profit) for the future.

While the very nature of discarding suggests the release of fish that are deemed worthless because of size or damage, tuna that are discarded due to lack of vessel hold capacity (i.e., high grading) would have some commercial value. This reconstruction did not attempt to estimate the potential market value of the discarded catch (given the uncertainty surrounding the quality of fish and fleet-specific rationales of discarding). However, it is important to point out that the current market prices for skipjack and yellowfin range from US$ 2000-2,900 $t^{-1}$, (Williams and Terawasi 2013). A subset of the purse seine fleets in the WPO between 2010-2013 reported just over 10,000 t of discarded target tuna; the primary reason (82%) for these discards was insufficient space. Although this represents 0.1% of the total tuna landed by purse seiners during this time, a simple calculation suggests that these fleets wasted between US$ 16-24 million worth of marketable fish as a result of an entirely avoidable practice.

For longliners especially, bycatch also presents both economic losses and safety concerns. Not only are bycatch species typically less valuable to the market, but as Gilman *et al.* (2008a) discuss, lost revenue can also occur as a result of gear damage or loss (e.g., engtanglements or broken lines) and excess hauling time spent on dealing with these entanglements and repairing gear. In the case of sharks, these species can also be dangerous to fishers who have to handle their removal from the line when they are still alive.

### *Composition of discarded bycatch*

Only about 6% (30 species) of the world's sharks are found in the open ocean (Camhi *et al.* 2009), yet 21 of these species are known to interact with industrial fishing fleets (Dulvy *et al.* 2008). Based on information available in the literature, this reconstruction estimated that between 1950-2010, 4.7 million t of the total discarded bycatch from Pacific Ocean tuna fisheries are sharks, of which 3.4 million t was blue shark and 578,000 t was silky shark. These cumulative catches seem high. However, Worm *et al.* (2013) suggested that in 2010, the global shark catch (including unreported landings and discards) was 1.44 million t. The reconstruction presented in this study pertains exclusively to Pacific Ocean tuna fleets, and the calculated catch (both r- and d-bycatch) for this year was only 125,000 t[19]. Assuming this represents roughly 50% of the total shark bycatch in all the oceans (based on the area of the Pacific relative to all oceans), the global total for 2010 would be only 250,000 t—approximately 6 times less than the estimate of Worm *et al.* (2013). Since the estimate in this reconstruction only accounts for sharks caught in association with tuna fleets, it is possible that a huge amount of targeted illegal (and unreported) shark fishing is occurring and these practices account for this difference. It is also possible that the variation in the resulting estimates between these two studies is attributable to substantial differences in research methodology.

Worm *et al*. (2013) calculated their value from various broad assumptions pertaining to illegal fishing and degrees of catch underreporting to expand on existing reported shark landings whereas this reconstruction used discard ratios from the literature applied to target industrial landings (for species other than sharks). Worm *et al.* (2013) also attempted to reconstruct artisanal shark fisheries, which this study did not do. With regard to their estimate of total longline catch, Worm *et al.* (2013) used observed regional shark catch-per-unit-effort (CPUE) data and associated regional hook effort to calculate the shark discards associated with each ocean. However, upon

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[19] Since this reconstruction did not address the issues of mortality at capture or post-discard mortality, this represents a cumulative discarded tonnage, not all of which would have been killed.

examination of this method, it appears that the total annual hook effort was cumulative (rather than averaged for a given time period). Additionally, the calculated average CPUE per ocean was not weighted by the scale of each fleet (i.e., total hooks per fleet), nor target species, nor was it specific to commercial fleets (e.g., a CPUE of 91.1 sharks · 1000 hooks$^{-1}$ from a research vessel shark survey off Japan that used only 28,800 hooks was made comparable to a CPUE of 0.6 sharks · 1000 hooks$^{-1}$ from the industrial Taiwanese tuna fleet with 14.1 million hooks). These biases toward large CPUE estimates associated with small fleets were undoubtedly further amplified upward as the scale of the computation was raised to 1.4 billion hooks (i.e., the global estimated effort in 2010).

Sharks are well-known for their ecological role as top predators in the open ocean, and research suggests significant cascading ecosystem effects as a result of their removal from the pelagic environment (Stevens 2000; Myers *et al.* 2007; Dulvy *et al.* 2008; Ferretti *et al.* 2010). The life history characteristics—specifically growth rate and fecundity—of each species differ widely (Cortés 2005); thus the observed impact of their removal (as well as their resilience to fishing pressure) will also be highly varied. However, in general, shark populations decline faster and rebound slower than teleosts under the same fishing pressure (Musick 2005a). In addition to typically K-selected life histories and low-abundance when compared to most tunas, Cailliet *et al.* (2005) explain that the nature of many sharks to congregate at certain age classes, or by sex, might make them further susceptible to overfishing and recovering from declines in stock size. Different estimates of population decline have been suggested in the last decade, and

32% of pelagic sharks and rays are considered ‘Threatened’ with regard to IUCN criteria (Camhi *et al.* 2009). However, only recently has an effort to undertake stock assessments on Pacific Ocean sharks become a focus.

Since sharks are not targeted species, researchers in charge of these assessments also face the challenge of estimating bycatch and (dead) discards. Nonetheless, using a surplus-production model in combination with information from the literature to reconstruct a catch time series from 1971-2011, the 2013 assessment of the North Pacific stock of blue shark suggests it is not currently being overfished (ISC 2013a)[20]. Conversely, the 2012 stock assessment for silky shark found that overfishing is occurring within the waters of the WPO (Rice and Harley 2012). Although, this reconstruction shows that the catch of blue shark is much higher than that of silky shark, it is important to note that different sharks also incur different levels of mortality associated with discarding, and studies show tuna longline fleets with upward of 94% of sharks still alive by the time they are retrieved (Gilman *et al.* 2008a). Although in this study, discards were not further divided into dead and survived categories, Beerkircher *et al.* (2002) show that blue sharks are actually much less likely to be dead upon retrieval than are silky sharks in some longline fisheries (12.2% mortality in blue sharks compared to 66.3% in silky). Other research suggests the capture mortality of blue sharks in industrial fisheries may actually range from 5-35% and post-release mortality is an additional 19% (Campana *et al.* 2009). Nonetheless, this ability to survive incidental

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[20] Comparison between the catch data used for this population assessment and the data in this reconstruction was not possible since the reconstructed values apply to the total Pacific Ocean blue shark catch (i.e., North and South stocks).

capture, combined with the resilient life history of the blue shark, may contribute to its ability to withstand such high levels of catch.

In addition to interactions with longline fleets, silky sharks are the most commonly bycaught shark by purse seiners in the Pacific (IATTC 2009). As a result of concerns over silky shark populations, both the IATTC and WCPFC have recently implemented conservation measures protecting this shark in the Pacific. These measures prohibit targeted capture of this species, as well as the retention of any incidentally caught individuals (IATTC 2013a; WCPFC 2013a). Since the majority of silky shark bycatch occurs in the northern part of the EPO, the IATTC has additionally discussed time-area closure measures in this region (IATTC 2009). However, the implementation of any temporal or spatial restrictions has yet to occur.

Due to its high concentration of urea, shark meat typically has very little commercial value, which is why these animals are so commonly discarded dead at sea (Musick 2005b). Conversely, shark fins[21] are worth upward of US$ 400 $\cdot$ $kg^{-1}$, and Chinese demand for their cartilage has resulted in widespread illegal shark finning operations (Jacquet *et al.* 2008). This practice is undoubtedly putting additional pressure on shark populations, and many industrial longline fleets are now specifically targeting sharks instead of tuna (Gilman *et al.* 2008a). Several countries have national laws and both the WCPFC and IATTC have Conservation and Management Measures (CMMs) to prohibit or limit shark finning (Biery and Pauly 2012; Gilman *et al.* 2012). These efforts

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[21] A standard ratio of 5% for fin to total body weight is commonly used in legislative documents and regulations. However, in reality, this ratio varies substantially by species: the fin to body weight ratio is 2.06 for the common thresher shark, 5.65 for blue shark, 4.46 for the silky shark, and 7.34 for the oceanic whitetip shark (Biery and Pauly 2012).

have resulted in decreased shark mortality in many fisheries, since there is increased economic incentive to avoid shark bycatch altogether (Gilman *et al.* 2008a). However, since not all waters have shark fishing regulations, finning operations are still pervasive in the Pacific Ocean, especially in South American countries (NOAA 2013), and the effectiveness of RFMO legislation regarding this practice is questionable (Gilman *et al.* 2012).

### *Impacts of tuna fisheries on air-breathing marine animals*

While this study did not analyse the impacts of tuna fisheries on marine mammals, sea birds, or sea turtles, it is important to mention that these air-breathing marine megafauna can also be significant components of tuna fleet bycatch. Similar to some sharks, these animals are particularly vulnerable to unnatural mortality due to characteristics of their life histories (i.e., long lifespan, delayed age of maturity, low reproductive rates) (Gilman *et al.* 2008a). Since they have no commercial value, and typically drown before they can be released from gear or sustain life-threatening injuries as a result of entanglement, the mortality associated with bycatch of these species is high (Lewison *et al.* 2004a; Larese and Coan 2008; NMFS 2011). Bycatch of air-breathing marine megafauna is especially concerning, given high levels of vulnerability and 'Endangered' status associated with many families of marine birds and sea turtles (Gales *et al.* 1998; Lewison *et al.* 2004b).

The most recent global[22] study of bycatch on air-breathing marine megafauna

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[22] Meta-analysis that assessed the impacts of both industrial and small-scale coastal fishing (not only tuna) with driftnets, longlines, and trawls.

showed a high prevalence of both marine mammal and sea turtle bycatch intensity in the Eastern Pacific, compared to other ocean regions (Lewison *et al.* 2014). This meta-analysis also showed that while the impacts of driftnets appear to be uniform throughout the world, bycatch intensity and composition associated with both longline and trawl gear does vary by region. This is attributable to both the gear required to land the target species, as well as the abundance of non-target marine life in the area. Crowder and Myers (2001) found that Atlantic high seas longline fleets targeting swordfish are 10 times more likely to catch loggerhead sea turtles than tuna longline fleets, and Gales *et al.* (1998) showed that Japanese tuna longline fleets operating around Australia, are responsible for high mortalities of albatross and other seabirds. Similar to bycatch and discard issues associated with sharks and other fish, notable concerns with regard to understanding the impact of fisheries on air-breathing megafauna are incomplete data sets, a lack of observer coverage, and inadequate bycatch reporting by fleets (Lewison *et al.* 2004a).

### *Bycatch mitigation efforts*

If on-board vessel mentality and behaviour pertaining to discarding does not change, then one way to decrease the amount of sharks (and other d-bycatch species) thrown back to sea is to prevent their capture in the first place. Attempts to minimize bycatch of both non-target fish, and air-breathing marine megafauna are becoming more prevalent in industrial fisheries, primarily through the modification of gears and fishing strategies. However, as Gilman *et al.* (2008a) point out, substantial progress has been made in reducing seabird and sea turtle bycatch in longline fisheries, yet relatively little focus has been given to reducing marine mammal and shark interactions with this gear. Modifications to longline hooks are additionally believed to decrease the number of sea turtles caught by these vessels (Read 2007), and the use of seabird avoidance fishing methods (i.e., side setting and weighted hooks) has seen a 67% decline in seabird bycatch in the Hawaiian longline fleet since these regulations were implemented (Gilman *et al.* 2008b). Recent research suggests that using circle hooks instead of J-hooks may reduce the catch mortality of blue sharks and swordfish as well (Kerstetter and Graves 2006; Carruthers *et al.* 2009). In addition to gear type, blue shark survival is also dependent on soak time, depth of hooks, water temperature, and size of the individual (Campana *et al.* 2009).

In the Eastern Pacific Ocean, yellowfin schools are commonly associated with pods of dolphins, and in the early days of purse seining, estimates of dolphin mortality associated with this gear were between 300,000-600,000 individuals per year (Edwards and Perkins 1998; Hall 1998). However, as a result of improved fishing technique (i.e., decreasing the kill-per-set rather than decreasing the number of sets), protective legislation led by the United States, and improved observer coverage, dolphin mortality due to purse seining declined substantially to about 25,000 individuals per year in 1991, and currently equates to less than 1,200 dolphins per year (IATTC 2008). As such, EPO dolphin populations are not currently threatened by this incidental take (Lennert-Cody *et al.* 2012).

*Limitations of study*

Given both the temporal and spatial extent of this work, numerous challenges were uncovered with regard to both the quantity and quality of data available (i.e., origin and number of reference materials) and the accuracy of these sources. As such, several assumptions regarding the data had to be made throughout the duration of this study. These assumptions were made based on all available information within the specific context of this work (i.e., tuna fisheries in the Pacific) as a whole.

Even before any RFMO baseline data were made publically available, they first had to be collected (i.e., through tuna fishing) and provided by the fleets of each country. As was discussed above, under-reported tuna landings are not uncommon. The accuracy of vessel logbooks has been questioned on numerous occasions (Babcock and Pikitch 2003), and studies have shown serious under-reporting by industrial fleets, primarily with regard to amounts of bycatch and discards (Bailey *et al.* 1996), but also in terms of incorrect species identification (Walsh *et al.* 2005). Given this heavy dependency on honest reporting, not to mention natural human error in doing so, it is possible that the baseline data upon which bycatch and discards were calculated may already have been a misrepresentation of the total catch.

Additionally, since observer coverage is lowest on High Seas and DWF vessels (<1%), and also varies significantly between fleets and countries (Lawson 2001; SPC 2010), observed bycatch and discard rates often pertain to only a small subsection of the total fishing effort in a given area (Bailey *et al.* 1996). As has been demonstrated in several cases, seasonality and location often play a significant role in both the amount and type of bycatch obtained by a given fleet (Bailey *et al.* 1996; Harrington *et al.* 2005; Román-Verdesoto and Orozco-Zöller 2005). Nonetheless, given the (theoretically) unbiased nature of independent fisheries observers and notwithstanding human observation error, this study typically accepted their data as being the most reliable source of information.

In terms of the data that were used, short-term studies and a general lack of sequential time-series forced the application of only one discard rate from a single year that was then held constant over time. When no discard rate was available for a given fleet, assumptions regarding their behaviour were inferred from the behaviour of similar fleets (i.e., same gear or nationality). Data pertaining to fleet bycatch and discards were almost entirely non-existent before the 1980s, which ultimately resulted in an inability to capture a change in discarding behaviour over time for most fleets. Specifically, the application of a single rate masks any changes in fleet discarding practices due to advancements in gear technology and the pressures of vessel space limitations, which are heightened by fleet spatial expansion.

Also with regard to data sources, a more uniform definition of 'bycatch' and 'discards' would be useful for future work in this area. Although they were specifically defined for this study (see page 56), inconsistencies in the literature regarding these terms undoubtedly resulted in less efficient interpretation of data, as well as the need for additional assumptions regarding the application of some information. As Davies *et al.* (2009) discuss, perceptions of target and non-target catch vary widely depending on the source and fishery, and these perceptions are additionally inconsistent through time. Thus, even if a standardized form cannot be agreed upon (e.g., discard rate as a percentage of total landed catch vs. total catch vs. species specific catch), a standardized definition of these two terms is essential for ensuring an accurate depiction and understanding of the impacts of bycatch and discards (for any fishery at any level) in future studies. Since tuna fisheries landings are typically considered in terms of tonnage, it would also be highly beneficial if the standard form of reporting associated discarded fish was to calculate them in weight rather than report them in terms of number of individuals.

Lastly, despite the multinational nature of Pacific Ocean tuna fleets, this study relied exclusively on data published in English. As such, it is possible that more accurate and/or complete information or specific fleet data published in different languages were overlooked. In order to mitigate this, closer coordination with country-based reconstruction authors for a similar study in the future would be useful.

## CONCLUSIONS

The IATTC has had 100% purse seine observer coverage[23] on large vessels (> 363 t) since the 1990s, and at the start of 2010, the WCPFC implemented 100% observer coverage on purse seiners in its waters as well (IATTC 2008; Hampton 2009). While these efforts are highly encouraging, additional focus should be given to longliners, since these vessels have the highest rates of bycatch and discards (and are more prone to capturing sharks than are purse seiners). While there are exceptions as a result of

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[23] At least half of the observers on each Party's vessels must be IATTC observers; the remainder may be from the Party's national observer program.

national legislation (e.g., 100% observer coverage on Hawaii-based longline swordfish vessels since 2004), both the IATTC and WCPFC require only 5% regional observer coverage for longline vessels under their jurisdiction and in the high seas (IATTC 2011b; WCPFC 2013b). Although this measure has only existed for a couple of years, in addition to the obvious issue of coverage inadequacy, it has already come under criticism by WCPFC members due to a lack of clearly defined fleet obligations and ambiguity in the spatial extent of this measure (WCPFC 2013b).

The IATTC, which ranks among the top RFMOs with regard to performance in governing bycatch and discards (Gilman *et al.* 2012), is the only RFMO providing cumulative annual data sets on discarding within its fisheries statistics[24]. On the other hand, while the WCPFC does undertake various studies with regard to bycatch and discard rates, these data are neither consistent nor standardized, which often makes them difficult to interpret and apply.

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[24] Since 1993, the IATTC has included reported discards of both tuna and bycatch associated with the purse seine vessels larger than 350 GT in its annual Fisheries Report.

# 4 | THE BEAUTIFUL SIMPLICITY OF THE THING

Here, then, is a great mystery. For you who love the little prince, as for me, nothing in the universe can be the same if somewhere—we do not know where—a sheep we have never met has, or has not, eaten a rose.

-Antoine de Saint-Exupéry, *The Little Prince*

## INTRODUCTION

### *The role of stock assessments*

Studying and monitoring animals in an aquatic environment is an innately challenging task; one that is perhaps best encapsulated by fisheries scientist John Shepherd who said that managing fish stocks was analogous to "managing a forest, in which the trees are invisible and keep moving around"[1]. Nonetheless, understanding the dynamics of any commercially valuable fish stock is essential for both the people who depend on the productivity of a fishery for income and food, and also for maintaining the health of the marine ecosystem as a whole. Although scientists and managers typically cannot count each individual fish, this does not mean that stock size is impossible to estimate. Rather, it simply means that a different methodology is required for accomplishing this task. Therefore, one way in which scientists and fisheries managers attempt to understand the structure and health of fish populations is through the undertaking of stock assessments using mathematical models.

At their most basic, technical stock assessments are meant to offer a detailed array of information to fisheries managers such that they can analyse policy trade-offs and make the best choices for a given stock depending on the objectives of its associated fishery and/or its ecological status (Walters and Martell 2004). Quantitative stock assessments help determine the maximum possible catch that can be attained and maintained indefinitely without overexploitation (Walters and Martell 2004). This target (or limit) value is known as the maximum sustainable yield (MSY).

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[1] From an unpublished lecture at Princeton University (c. 1978). Full quote available from: http://jgshepherd.com/thoughts

*Population dynamics of fish stocks*

When a new environment is first inhabited by a group of individuals, the size of this population has the potential to increase in biomass until it can no longer expand because of environmental limitations (i.e., resource availability and space) (Odum 1953). The rate at which this population grows is known as the intrinsic rate of population increase ($r$), and the upper biomass limit of this population is referred to as its carrying capacity ($k$).

i. Carrying capacity ($k$)

Whether aquatic or terrestrial, all biological systems have a carrying capacity. (This level may vary around some mean, but here it will be assumed constant.) In the case of fish, adequate consideration of the underlying biological conditions of this state for a given stock has important applications for fisheries and management. Typically, a virgin (i.e., unfished) stock is considered to be at carrying capacity. In this state, natural mortality (i.e., death due to predation or old age) is equal to recruitment (i.e., the number of young fish that survive to enter the stock each year[2]). However, with the onset of fishing effort (and thus additional mortality from fishing), a stock's biomass decreases to below its carrying capacity, and the dynamics of the system (i.e., the age composition of individuals and recruitment) are altered (Ricker 1975).

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[2] The age of recruitment varies by species, but it is typically considered to be when an individual is capable of being caught by fishing gear or at least appeared on the fishing ground (i.e., has reached a certain size).

### ii. Intrinsic rate of population increase ($r$)

One of the main population-level responses to the increased space and resources incurred by fishing mortality changes is in growth. The speed at which this biomass expansion occurs in a given environment in the absence of density-dependent forces (e.g., competition) is known as the intrinsic rate of population increase ($r$) (Birch 1948; Odum 1953).

Depending on the taxon (i.e., viruses to whales) to which a species belongs, differences between respective intrinsic rates of population increase can span over twenty orders of magnitude (Blueweiss *et al.* 1978; Pauly 1984). This variation is due to a variety of life history traits, especially the underlying key factor that influences growth: body size (Fenchel 1974; Blueweiss *et al.* 1978). Species with lower mean adult body weights will tend to have faster rates of population growth. Thus, in terms of marine organisms, the intrinsic rate of population increase for fishes is much higher than for whales (Pauly 1984). However, even within the families of these classes, differences in $r$ exist.

Among the fishes, there is a correlation between life history traits and population growth (Denney *et al.* 2002). Specifically, tunas have different life history strategies, depending on their primary habitat. At the individual level, tropical tunas (e.g., yellowfin and skipjack) grow faster but ultimately attain a lower mean body weight than sub-tropical (e.g., albacore) and temperate species (e.g., bigeye and bluefin) (Fromentin and Fonteneau 2001). Combined with year-round breeding in a warm and productive environment, these attributes allow for fast population growth. Conversely, temperate tunas live longer and have a later age of maturity than those found in tropical waters. In addition, some temperate tunas (i.e., the bluefins: *T. orientalis* and *T. maccoyii*) make seasonal migrations to specific warm-water spawning grounds (Shadwick *et al.* 2013), thus further affecting reproduction frequently.

*The Schaefer production model*

In 1954, Milner B. Schaefer developed one of the most simple—yet useful—fisheries dynamics models. This model is capable of explaining the relationship between stock-recruitment dynamics, compensatory density-dependence in population growth which results in surplus production[3], and the way in which fisheries can operate sustainably by utilizing such surplus yield at its maximum (i.e., fish at MSY).

As is true for most biological systems, population growth in fish is assumed to be logistic in nature (Fig. 4-1):

$$B_t = \frac{k}{1 + \frac{k - B_o}{B_o} e^{-rt}}$$

...Eq. 1

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[3] Surplus production occurs when recruitment to the population is greater than mortality, thus allowing for population growth.

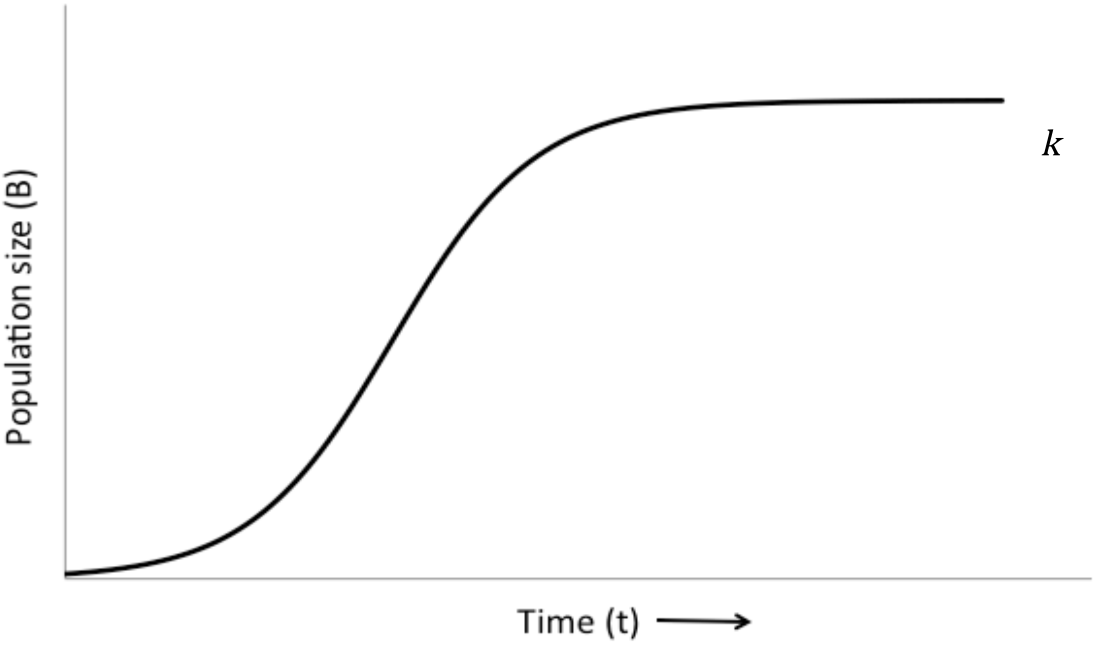

**Figure 4-1. Logistic growth curve of a hypothetical fish population.**

where $B_t$ is the biomass at time $t$, $k$ is the carrying capacity, $B_o$ is the initial biomass (at $t$ = 0) and $r$ is the intrinsic rate of population increase. This shows the propensity of a population to grow slowly when there are few individuals (since it is limited by successful reproduction events) until a density threshold is reached allowing for the population biomass to rapidly increase. As the population size approaches carrying capacity, growth slows and ultimately reaches equilibrium at $k$.

To express the way in which the rate of population growth changes with respect to the size of the population, we use the first derivative of Equation 1:

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{k}\right)$$

…Eq. 2

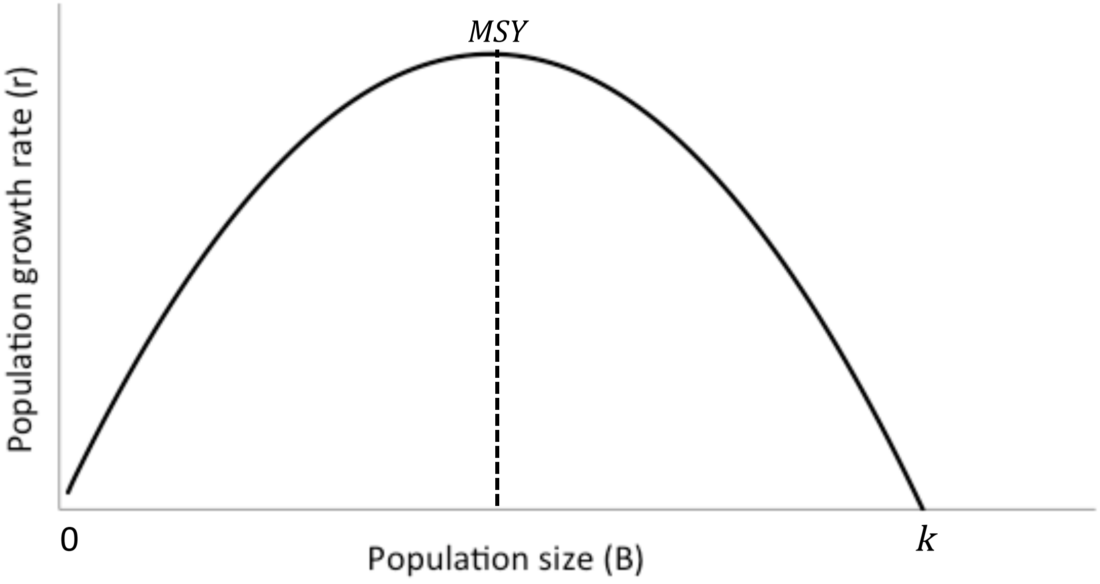

**Figure 4-2. Schaefer's surplus-production function.**

This parabolic function (Fig. 4-2) shows that when the population has few individuals, the biomass is too small to result in a high growth rate (i.e, $rB \approx 0$). Conversely, the growth rate also decreases to 0 when the biomass approaches carrying capacity (i.e., $1-\frac{B}{k} \approx 0$) since there is no room left for new individuals to enter the population. While all values along the curve represent surplus production, population growth is at its maximum when the population biomass is at half of the carrying capacity.

Sustainable fishing occurs when the yield ($Y$) is equal to surplus production (see Eq. 3), since it is here when recruitment is equal to total mortality (natural + fishing):

$$Y = rB(1-\frac{B}{k})$$

…Eq. 3

Since surplus production is a function of population size (see Fig. 4-2), the sustainable yield can be maximized when $B_{MSY} = \frac{k}{2}$. Substituting $B_{MSY}$ in Eq. 3:

$$MSY = r\frac{k}{2}(1 - \frac{\frac{k}{2}}{k})$$

…Eq. 4

$$\mathrm{MSY} = \frac{r * k}{4}$$

...Eq. 5

Thus, given only two key population growth parameters: $r$ and $k$, it is possible to estimate MSY for a given stock.

*The Catch-MSY method*

Based on the Schaefer (1954) production model described above, the Catch-MSY method was designed by Martell and Froese (2012) in an effort to estimate the MSY for data-poor or previously unassessed fish stocks. In many regions of the world (e.g., developing countries with remote coastal fisheries), catch data may be the only available information (Pauly 2013) and the personnel, funding, and/or technology required to conduct a comprehensive population analysis may not be available. As such, this method may serve as a valuable first step in fisheries management. From only a time series of catch, ranges of potential $r$ and $k$ values, and a range of the current stock level relative to its initial biomass ($B_{current}/B_o$), this model is capable of estimating more precise values of $r$ and $k$, and generating the MSY for a given stock.

For the Catch-MSY method, the intrinsic rate of population increase is assumed to be synonymous with a stock's ability to rebound following depletion fishing (i.e., its

**Table 4-1. Default values for the maximum intrinsic rate of population growth based on resilience classifications (very low to high) from FishBase. (Source: Martell and Froese 2012).**

| Resilience | High | Medium | Low | Very low |
|---|---|---|---|---|
| **$r$ (year$^{-1}$)** | 0.6-1.5 | 0.2-1 | 0.05-0.5 | 0.015-0.1 |

**Table 4-2. Default values for initial and final biomasses (Martell and Froese 2012).**

| | Catch/max catch | *B/k* |
|---|---|---|
| **Initial year** | < 0.5 | 0.5-0.9 |
| | ≥ 0.5 | 0.3-0.6 |
| **Final year** | > 0.5 | 0.3-0.7 |
| | ≤ 0.5 | 0.01-0.4 |

resilience). As such, in order to approximate $r$, resilience classifications from FishBase (www.fishbase.org) are each given a default range (Table 4-1), and this range is applied to the stock based on its resilience.

To estimate the carrying capacity, the default limits are defined as the maximum recorded catch (lower limit) and 100 times the maximum observed catch (upper limit) for the observed stock ($k = C_{max}$ to $100 * C_{max}$).

For the first and last years in the time series, a default range of relative biomasses ($B_o$ and $B_{current}$) is applied based on the ratio of total catch to maximum catch (Table 4-2).

The model is then used to calculate annual biomass estimates from randomly selected $r - k$ pairs (see Eq. 6) and to eliminate any pairs that result in the stock collapsing or exceeding the carrying capacity when fitted with the observed catch time series (Fig. 4-3):

$$B_{n+1} = [B_t + r\,B_t\left(1 - \frac{B_t}{k}\right) - c_t]e^{vt}$$

…Eq. 6

From the viable $r - k$ pairs (i.e., likelihood = 1), the geometric means of $r$ and $k$, and the corresponding MSY value are computed (see Eq. 5).

*Purpose of study*

This method lends further evidence that catch data can be translated into stock monitoring principles. Since most full stock assessments are conducted for fish populations with limited distribution in coastal ecosystems, they typically encapsulate

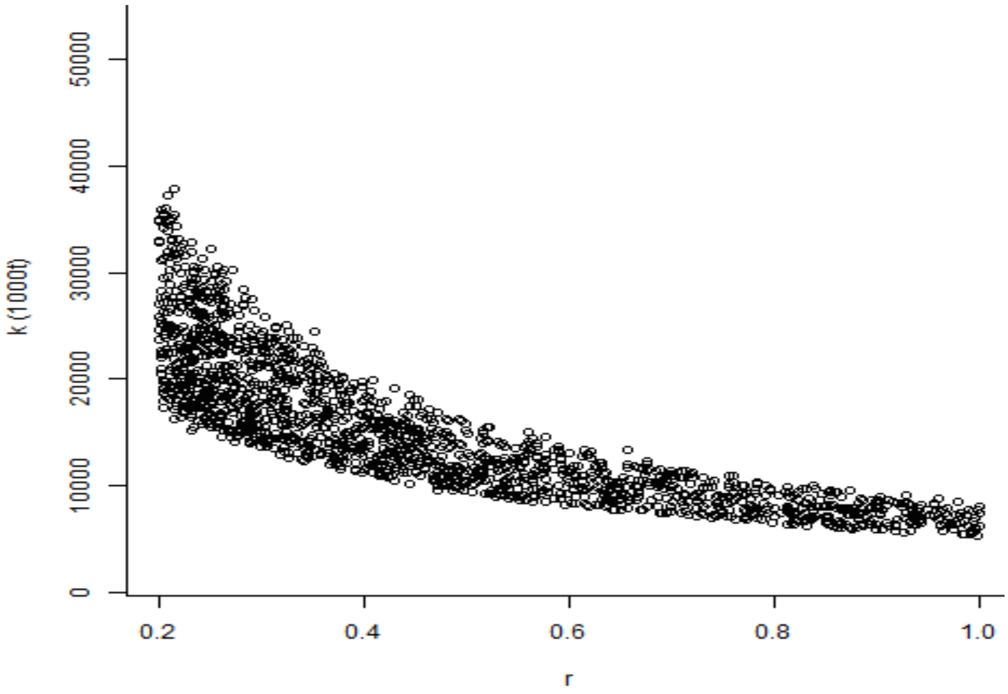

**Figure 4-3. Initial ranges of $r$ and $k$, and the $r$– $k$ combinations that are compatible with the time series of catch (n= 2,897) for albacore tuna in the South Pacific Ocean.** The geometric means of viable $r$ and $k$ values are used to compute MSY, and their variance is used to estimate the uncertainty of the estimate.

only a few fisheries and rarely more than two counties. Given their highly migratory nature, ocean-wide distribution, and unique life histories, as well as the multinational nature of the associated fisheries, assessing pelagic fish stocks is an especially challenging task for fisheries managers. Although Martell and Froese (2012) suggest that the Catch-MSY method is not a substitute for stock assessments, this study explores the accuracy and application of this relatively simple method with regard to Pacific Ocean pelagic species by comparing estimated MSY targets to those from complete stock assessments. Since the majority of species assessed in Martell and Froese (2012) were classified to have ‘medium’ resilience, the further analysis of ‘low’ and ‘very low’ species such as sharks and tunas should provide additional understanding of the accuracy of this model.

## METHODS

### *Catch data*

Catch time series for seven commercially important tuna stocks (five species), two shark species, and three billfishes were used in this analysis. With the exception of southern bluefin tuna, all of these species were from populations found exclusively in the Pacific Ocean.

In order to ensure that the output estimate of MSY from the Catch-MSY algorithm could be directly compared with the stock assessment estimates, the catch data provided in the most recent publically available stock assessments for these species were used: southern bluefin (CCSBT 2011), Pacific bluefin (ISC 2013b), South Pacific albacore (Hoyle *et al.* 2012), North Pacific albacore (ISC 2011), West Pacific bigeye (Davies *et al.* 2011), East Pacific bigeye (Aires-da-Silva and Maunder 2012), West Pacific yellowfin (Langley *et al.* 2011), East Pacific yellowfin (Aires-da-Silva and Maunder 2012a), silky shark (Rice *et al.* 2012), blue shark (ISC 2013a), swordfish (Brodziak and Ishimura 2010), blue marlin (ISC 2013b), and striped marlin (Lee *et al.* 2013).

Although all of these stock assessments presented multiple fishing scenarios and, in some cases, different catch time series, the catch data used in this analysis and the projected MSY used as for comparison were from the 'reference' case in each assessment. Since all of the stock assessments provided only graphical representation of the catch over time, GraphClick software was used to extract the data (see Tables 8 and 9 in Appendix).

*Catch-to-MSY analysis*

The original algorithm developed by Martell and Froese (2012) has since been incorporated into the 'Tools' section of FishBase, the publicly available online encyclopedia of fish. As such, in order to simultaneously test the efficiency and usability of this open-source feature, this analysis was performed through the FishBase website (see www.fishbase.org).

Resilience estimates that served as the life history input variable for estimating the rate of population increase ($r$) were obtained from FishBase for each species (Table 4-3). The reference case catch data were uploaded to FishBase in the same annual format in which they were extracted from the stock assessments. No additional assumptions about population dynamics or stock structure were made for any of the Catch-MSY analyses, nor were any process errors added.

## RESULTS

A comparison of the stock assessment estimates and the values calculated using the Catch-MSY method is provided in Table 4-3. From 10,000 iterations of the algorithm, the number of viable $r - k$ combinations for each species ranged from 82 (striped marlin) to 3,108 (blue shark), with an average of 1,800 possible $r - k$ pairs per species. Overall, half of the mean MSY values predicted by the Catch-MSY method were overestimated (by 1-63%), and half were underestimated (by 8-200%). Nonetheless, the overall difference between the MSY suggestion provided in the complete stock assessment and the average MSY output from the Catch-MSY method was almost negligible for most species (Figure 4-4, Table 4-3).

**Table 4-3. Input resilience classifications from FishBase and mean MSY predictions from the stock assessment and Martell and Froese method (2012).**

| Stock | Resilience | Stock assessment MSY (t) | Catch-input MSY (t) | Stock status |
|---|---|---|---|---|
| Pacific bluefin (PBT) | Low | - | 21,450 | Overfished |
| Southern bluefin (SBT) | Low | 34,500 | 28,087 | Overfishing no longer occurring |
| WPO bigeye (BET-W) | Low | 76,760 | 125,306 | Overfished |
| EPO bigeye (BET-E) | Low | 82,246 | 94,004 | Overfished |
| WPO yellowfin (YFT-W) | Medium | 538,800 | 498,613 | Not overfished |
| EPO yellowfin (YFT-E) | Medium | 262,642 | 265,336 | - |
| NPO albacore (ALB-N) | Medium | - | 88,517 | Not overfished |
| SPO albacore (ALB-S) | Medium | 133,200 | 65,878 | Not overfished |
| WPO skipjack (SKJ) | Medium | 1,500,000 | 1,511,848 | Not overfished |
| Blue shark (B-SHK) | Very low | 58,000 | 36,207 | Not overfished |
| Silky shark (S-SHK) | Very low | 1,885 | 2,929 | Overfished |
| Blue marlin (B-MAR) | Low | 19,459 | 18,690 | Not overfished |
| Striped marlin (S-MAR) | Medium | 5,378 | 6,793 | Overfished |
| Swordfish (SWO) | Low | 34,500 | 15,674 | Not overfished |

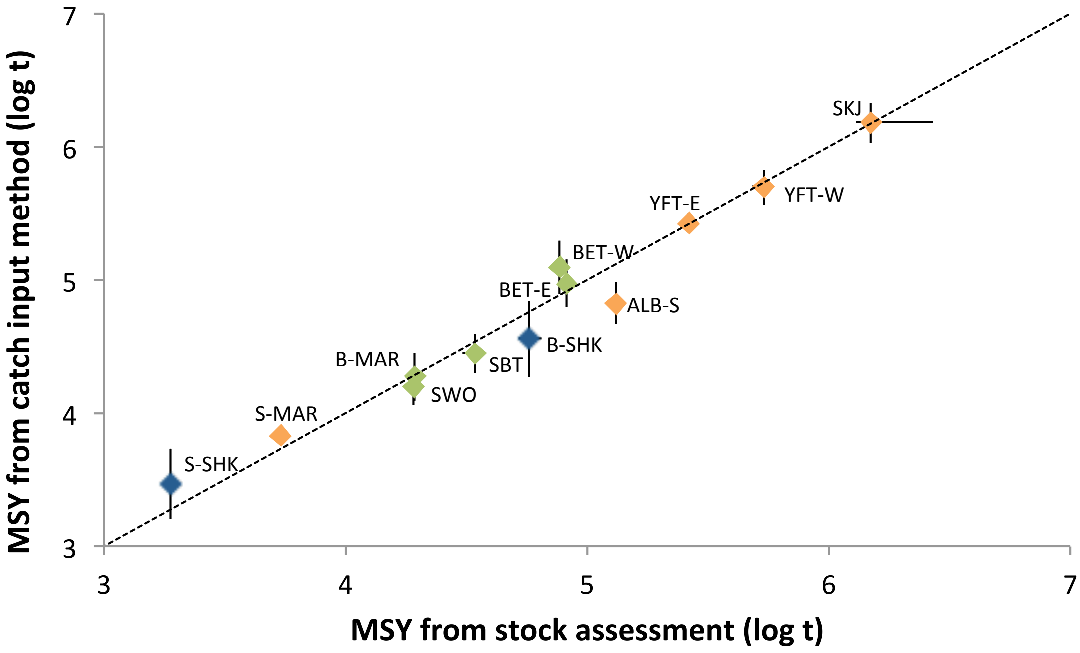

**Figure 4-4. Comparison of MSY estimates (log t) using stock assessment and Martell and Froese (2012) Catch-MSY method.** Error bars represent “high” and “low” ranges defined in the stock assessments and 2 standard deviations in the Catch-MSY method. Species are colour-coded based on resilience classification: blue= very low, green=low, orange= medium; see Table 4-4 for species abbreviations.

Regardless of the length of the catch time series used, the MSY generated by the Catch-MSY algorithm for species with ‘very low’ and ‘low’ resilience was consistently most different (i.e., ether over- or underestimated) from the MSY suggested by the complete stock assessment report.

With regard to tuna species, the Catch-MSY model best matched the stock assessment MSY targets for yellowfin (both stocks) and skipjack. The model had the greatest overestimation of MSY for bigeye (both stocks) and underestimated MSY for southern bluefin and, more noticeably, albacore. In terms of billfish, the Catch-MSY algorithm underestimated the MSY for both swordfish and blue marlin, yet slightly overestimated the MSY for striped marlin. Similarly, the MSY target for blue shark was estimated to be lower using the Catch-MSY method, while the MSY target for silky shark was estimated to be higher.

The complete assessments for two stocks used in this analysis did not estimate MSY; therefore no comparison could be made for these species. Nonetheless, the values generated by the Catch-MSY algorithm were 21,450 t for Pacific bluefin, and 88,517 t for the North Pacific stock of albacore.

## DISCUSSION

This analysis shows that for pelagic species in the Pacific Ocean, the Catch-MSY algorithm projects a MSY value similar to that of the complete stock assessment. Independent of the length of the catch time series, MSY values for species with medium resilience were best predicted by the model, a finding that corroborates the assertions of Martell and Froese (2012).

### *Accuracy of the Catch-MSY algorithm for certain stocks*

In the context of pelagic fishes, fast population growth rates make tropical tunas more resilient than sub-tropical and temperate species. This ultimately means they are less susceptible to overfishing as well (Fromentin and Fonteneau 2001). Similar to temperate tunas, most sharks also have low resilience, a characteristic that is strongly linked to high age at maturity (Smith *et al.* 1998) and thus, a slow intrinsic rate of population increase. Like temperate tunas, elasmobranchs are therefore believed to be highly vulnerable to overfishing (Hoenig and Gruber 1990; Schindler *et al.* 2002). As discussed by Martell and Froese (2012) the Catch-MSY model is less accurate at predicting MSY for species with low or very low resilience. The findings here demonstrated this, as the MSY values for both shark species (i.e., very low resilience) were observably dissimilar compared to the stock assessments.

The south Pacific stock of albacore tuna had the worst prediction among the medium resilience species. However, it is worth pointing out that several substantial revisions were made to the assumptions in the complete stock assessment compared to the previous year, both in terms of the catch and effort data for certain fisheries and input biological parameters (Hoyle *et al.* 2012)[4]. The authors of the 2012 assessment suggest that this new information offers an improvement in the fit of key data sets, but also that there is high uncertainty surrounding the growth curve for this stock. Using this new information, the MSY suggested by the 2012 stock assessment was 133,200 t, compared to the 2011 MSY output of 85,130 t. This analysis used the MSY from 2012 estimate as its reference point, however if the 2011 value had been used instead, the accuracy of the MSY generated by the Catch-MSY model (88,517 t) would have been on par with all other medium resilience species. Given the precision of the MSY algorithm with all other stocks of medium resilience, and the substantial deviation in MSY estimates between two consecutive years in the south albacore assessment, it may be possible that (since the growth of an individual is ultimately related to overall population resilience) the revisions made to the growth estimates in the complete stock

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[4] Specifically, modifications to the stock assessment reference case from the 2011 to 2012 assessments included: 1) revision of CPUE longline indices, as well as catch and size data; 2) changes in the ogive defining spawning potential at age and the growth curve; 3) the assumed steepness was increased from 0.75 to 0.8; and 4) a lognormal bias adjustment was applied to the mean recruitment estimate.

assessment are responsible for these conflicting MSY estimates. Conversely, it is also possible that this outcome is purely coincidental.

Martell and Froese (2012) suggest another potential caveat in the Catch-MSY method: it may be less accurate in cases where catch times series are either short, or lack contrast. In this analysis, the stock with the least overall fluctuation in annual catch was swordfish. However, this did not seem to impact the accuracy of the MSY estimate in this case. The shortest time series used in this analysis was that of silky shark (1994-2009), which was one of the species with an overprediction of MSY. However, it is unclear how much of this deviation from the MSY of the full stock assessment is attributable to the length of the time series.

## CONCLUSIONS

What is unique about this approach is that despite very wide ranges of potential $r$ and $k$ estimates, the Catch-MSY model is capable of substantially narrowing these ranges upon the inclusion of only a catch time series. While, naturally, this does not answer all the questions posed by fisheries managers nor give all the outputs included in complete assessments, it represents a solid starting point for ascertaining one of the most widely recognized management targets.

Given that the results of this method are quite similar to those predicted for some of the world’s most commercially valuable fisheries, it is evident that catch data contains information that can be of value for management in the absence of other stock biomass indices. As such, obtaining accurate and complete catch time series is of paramount importance.

Although large migratory tuna and billfish are managed by RFMOs at the ocean-scale, the high correlation between the Catch-MSY estimate to the estimate from the complete stock assessment seen in this analysis suggests that this method may prove useful for regions with high neritic scombrid catches, but limited data processing capabilities and funding. In addition to testing the accuracy of the Catch-MSY method as a whole, another underlying aim of this study was to use simple, publicly available data processing tools for the analysis. The rationale behind this basic approach was to demonstrate that even if a fisheries management unit operating with limited resources (both financial and technological), a generalized picture of management targets and key population parameters could still be obtained. Naturally, this concept would apply to all species, not only tunas and pelagics.

# 5 | THE PRIVILEGE TO KNOW

’People have forgotten this truth,’ the fox said. ‘But you mustn’t forget it. You become responsible, forever, for what you have tamed.’

-Antoine de Saint-Exupéry, *The Little Prince*

### *…The Duty to Act*[5]

Despite several limitations in data availability, the reconstructions presented in Chapters Two and Three provide a viable first attempt at improving the catch data associated with fisheries in the Pacific Ocean, as well as improving our understanding of how commercial tuna fishing impacts marine ecosystems at both the local and ocean level. A more comprehensive understanding of the magnitude of these issues will only be possible with improved record keeping and data availability provided by fisheries managers. Therefore, more than anything, the work of this thesis has shown an ongoing inadequacy of fisheries management bodies (both local and international) to adhere to their mandates of protecting marine environments and sustainably exploiting fish stocks. This has resulted in the subsequent overexploitation of marine life—especially sharks—to varying degrees.

Given that between 2001-2007, 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 the Galápagos reconstruction, proactive and targeted shark conservation measures within the archipelago are currently inadequate, and their development should be of paramount importance. It is possible 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. As discussed by Villalta-Gómez (2013), the overall conservation status of the GMR is currently 'unfavourable' and its management plan should be restructured. Nonetheless, it is encouraging to note the recent attention aimed at

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[5] The full quote, "Those who have the privilege to know, have the duty to act" is commonly attributed to Albert Einstein (date and location unknown).

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, an ongoing focus on rebuilding sustainable fisheries will be essential for the long-term health of the marine resources, and people, of the Galápagos Islands.

RFMOs have come under considerable criticism in recent years, especially with regard to their inability to adequately manage stocks and enforce regulations and policies (McKelvey *et al.* 2003; Allen 2010; Cullis-Suzuki and Pauly 2010). Despite overarching objectives of providing optimal utilization and the conservation of High Seas fish stocks, there appears to be a strong disconnect between this mandate and its execution (Cullis-Suzuki and Pauly 2010). In addition to the high level of overexploited stocks that fall under their jurisdiction, the difficulties in obtaining basic data for Chapter Three suggest RFMOs provide inadequate and inconsistent catch statistics, particularly with regard to discards. Given their conceptual obligation to sustainably manage and conserve migratory fish stocks, RFMOs should be held responsible for collecting and publicizing all data pertaining to fishing practices associated with the fleets under their jurisdiction, since only they can provide this information at a spatial and temporal scale large enough to observe trends at the ocean level. With regard to enforcing quotas and minimizing opportunities for under-reported catch data, the development and implementation of adequate observer coverage, especially for distant-water longliners, should be of the highest priority for these management organizations.

Although data-limited stock assessments have come under some criticism (Carruthers *et al.* 2012), the Catch-MSY model accomplishes the job it was designed to do. Despite the fact that primary objective of every fishery on Earth is to catch fish, and that catches the only data available in some cases (Pauly 2013), additional criticism of using catch data to infer the health of a stock is ongoing (Hilborn and Branch 2013). Yet, the Catch-MSY algorithm consistently demonstrates that with minimal assumptions about life history parameters, even a time series of catch can yield results (e.g., MSY) comparable to those projected by advanced stock assessment approaches. As such, ensuring that the input catch data set is accurate is of vital importance. Still, this information can only go so far. Ultimately, the responsibility of ensuring a stock is fished sustainably (at MSY or a different target) falls upon the fisheries management body overseeing that stock.

### *Take arms against a sea of troubles*[6]

From the musings of Voltaire[7], Albert Einstein, and Antoine de Saint-Exupéry, the concept of taking responsibility for one's ability—be it power or knowledge—is suggested as a vital aspect of humanity. Unfortunately, in the case of fisheries, this is

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[6] From Act III; Scene I in Shakespeare's *Hamlet* (1603):
To be, or not to be, that is the question—
Whether 'tis Nobler in the mind to suffer
The Slings and Arrows of outrageous Fortune,
Or to take Arms against a Sea of troubles,
And by opposing end them?

[7] The quote, 'Un grand pouvoir impose une lourde responsabilité' (A great power imposes a heavy responsibility) is attributed to Voltaire (see *Œvres de Voltaire,* Vol. 48, 1832).

often not the case. Based on their highly migratory nature, specific spawning areas, and value on the global market, the tunas are likely the world's most challenging fish to manage. Although this thesis did not directly analyse these issues, the following represents a summary of the key underlying concepts I have obtained and retained in undertaking this work, and my views on some of the most important issues facing Pacific Ocean tuna fisheries today.

Given the high level of overexploitation in the Pacific, specifically with regard to larger tunas species, RFMOs are clearly unable to unilaterally manage these stocks. However, this does not mean that countries are therefore exempt from their own management responsibilities. Although the very nature of the 'tragedy of the commons' (Hardin 1968) suggests that multi-player cooperation is unlikely in a common-pool resource, such behaviour is not impossible. In the Pacific Islands, the Forum Fisheries Agency (FFA) is a testament to big picture foresight and collaboration. This international partnership (17 members[8]) is working to ensure that the position (on conservation and management measures) of Island states is better represented than it would be if each country were to be represented individually or act independently. Collectively, the FFA works to protect present and future rights to sustainable tuna fishing, as well as fair economic and social benefits for people in the region (particularly for small island states). However, more effort needs to come from larger fishing countries, particularly those with extensive distant-water fleets and substantial imports (e.g., Japan, Taiwan).

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[8] Current member nations and countries of the FFA: Australia, Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu and Vanuatu.

As discussed in the Introduction, bluefin tuna is the epitome of a luxury fish. Currently, both southern and Pacific bluefin are overfished, with the former being on classified as 'Critically Endangered' by the IUCN (Collette *et al.* 2011). Thus, these species represent a model case for such international conservation collaboration to occur. Pacific bluefin is fished almost exclusively by Japan, with Japan importing approximately 90% of Korea's Pacific bluefin catch as well (WCPFC 2010). Unfortunately, the majority of this catch consists of juvenile (i.e., immature) fish (ISC 2013c). Therefore, Japan has an opportunity to play a significant role in decreasing both the amount of underage Pacific bluefin caught and limiting the amount that is imported and sold.

A different problem with similar consequences exists for southern bluefin: 'capture-based aquaculture'. While Japan controls the majority of longline fishing for southern bluefin, Australia's quasi-aquaculture industry exports the majority of the ranched bluefin to Japan (Patterson *et al.* 2012). These operations use purse seines to capture immature southern bluefin, which are subsequently brought to large ocean pens where they are fed for several months. Once plumped up, these tuna are killed and shipped abroad where they will feed a much smaller demographic that is the wealthy, developed world clientele. If these fish had been caught and exported immediately, they would be worth about AU$ 40 million annually. However, post-ranching, these fish garner upward of AU$ 150 million instead (Patterson *et al.* 2012).

While tuna ranching impacts a stock in the same way as catching immature Pacific bluefin does (since captive individuals are under-age and will never contribute to the breeding stock) (Ottolenghi 2008b), it also impacts other fish populations from which forage fish are obtained to feed the tuna (Volpe 2005). Since tuna are active piscivores, they require large amounts of protein to maintain their daily energy requirements and grow. In terms of aquaculture, the food conversion ratio (FCR)[9] for bluefin is the highest among all fish, and can be as high as 30 (Aguado-Gimènez and Garcìa-Garcìa 2005). Therefore, although people in coastal communities in countries such as Peru and Chile rely on smaller fish species (e.g., sardines, capelin, pilchards) as a primary source of protein, these forage fish are often sold for a higher profit to ranching companies abroad. Thus, despite being a lucrative industry and a valuable component of Australia's natural resource economy, this type of aquaculture is detrimental to both the local environment (i.e., southern bluefin population) as well as at a much broader scale. Although some companies have started to use primarily locally caught sardines to feed their captive bluefin[10], Australia should take a lead in dramatically improving and restructuring the entire operation to be a more sustainable endeavour.

Beyond the concentrated issues surrounding the two bluefin species, additional focus for future work should be aimed at alleviating the disparity in the share of economic benefits between distant-water fishing countries and the Pacific Island countries and states (PICTs) with which they have fishing access agreements. Unlike the Eastern Pacific, the most productive tuna fishing grounds in the Western Pacific are actually largely contained within the EEZs of fourteen island countries. Thus, nations throughout the region have a substantial dependence on tuna fishing not only for

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[9] FCR is calculated as mass of food consumed by a fish to its mass gained; for comparison: the FCR for tilapia is 1.6-1.8 (Steinfeld *et al.* 2006).

[10] Based on information from Eyre Peninsula: http://www.seafoodfrontier.com.au/main_seafood_sub_category_page.cfm?ProductSubCategoryID=6&SubCategoryID=9&SectionID=13 [accessed 19 April 2014].

annual GDP, but for employment as well (Gillett 1997; Hanich 2011; Lehodey *et al.* 2011). Therefore, fishing access agreements are a common aspect of distant-water fishing in this region and over 85% the tuna caught in the Western Pacific is captured within national waters (Hanich 2011). Although in some cases this can result in between 10-40% of the annual revenue for a country (Lehodey *et al.* 2011), an average of only 10% of the profit generated from these landings is actually retained the PICTs (Anonymous 2013a).

Inhabitants of the Pacific Islands are already being faced with the very real threat of climate change and continued environmental shifts (i.e., sea level rise, decreased rainfall) over the next century will further impact these countries in terms of both living conditions and food security (Mimura *et al.* 2007; Barnett 2010). In addition, preliminary research suggests that both the distribution (and thus catchability) of tuna species throughout the Pacific will be altered to varying degrees as a result of changing ocean conditions (Lehodey *et al.* 2011). Specifically, ocean circulation and temperature changes will likely induce shifts in spawning location and success in the Western Pacific, and further impact foraging capabilities throughout the larval stage (Lehodey *et al.* 2011). Overall, while different species and life stages will be affected in different ways (and thus different regions may experience differences in abundance and biomass), if fishing pressure remains the same as it is presently, these changes are anticipated to result in declines in biomass of yellowfin and skipjack in the WPO, and tuna landings (all species) within the waters of the PICTs are anticipated to decline by a minimum of 5-10% between now and 2100.

Like the species they so relentlessly seek, tuna fisheries are complex, dynamic entities. While this work attempted to improve the data surrounding some of these fisheries, ultimately the most important immediate and future goals should be improving their management and fairly distributing this conservation burden amongst the fishing countries and sectors in the Pacific. With regard to mitigating bycatch and discards, improved observer coverage is essential. Additionally, more on-water enforcement as well as improved port state measures would allow for better traceability and hopefully decrease the incentive and opportunity for illegal fishing (e.g. FAO Port State Measure Agreement). Ultimately, however, it is unrealistic to assume that one governing body without judicial power or binding legislation can manage multiple countries and fleets. Thus, the ultimate responsibility for sustainable extraction of these valuable fish must fall equally upon the shoulders of all of the nations that fish, export, and import tuna from the Pacific Ocean.

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# APPENDIX

**Table 1. (Top) Annual catches of target tuna species by longline fleets in the IATTC-WCPFC overlap zone from 1995-2010; (Bottom)** Annual catches of target tuna species by purse seine fleets in the IATTC-WCPFC overlap zone from 1995-2010. (Source: Original IATTC data from IATTC, 2012.)

| Target catch (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Belize | China | Japan | Korea | French Polynesia | Chinese Taipei | Vanuatu | Total |
| 1995 | - | - | 5,126 | 6,984 | 701 | 475 | - | 13,286 |
| 1996 | - | - | 4,103 | 7,129 | 1,289 | 1,223 | - | 13,744 |
| 1997 | - | - | 3,620 | 5,607 | 2,441 | 2,548 | - | 14,216 |
| 1998 | 18 | - | 8,516 | 8,667 | 3,324 | 3,030 | - | 23,555 |
| 1999 | 29 | - | 5,039 | 7,894 | 2,527 | 2,124 | - | 17,613 |
| 2000 | 82 | 4 | 7,847 | 9,340 | 4,932 | 2,631 | - | 24,836 |
| 2001 | 168 | 1 | 5,039 | 9,548 | 4,930 | 5,432 | 108 | 25,226 |
| 2002 | 692 | 194 | 4,185 | 5,158 | 4,373 | - | 235 | 14,837 |
| 2003 | 456 | 6,704 | 2,116 | 4,604 | 4,003 | 10,952 | 193 | 29,028 |
| 2004 | - | 163 | 3,316 | 4,169 | 3,154 | 7,423 | 1,469 | 19,694 |
| 2005 | - | 111 | 2,455 | 3,251 | 3,334 | 4,508 | 785 | 14,444 |
| 2006 | - | - | 2,867 | 1,732 | 3,274 | 3,237 | 1,522 | 12,632 |
| 2007 | - | - | 2,911 | 496 | 3,572 | 2,959 | 1,336 | 11,274 |
| 2008 | - | - | 1,661 | 1,410 | 3,072 | 1,471 | 1,068 | 8,682 |
| 2009 | - | 1,610 | 2,086 | 465 | 4,104 | 1,060 | 1,391 | 10,716 |
| 2010 | 29 | 1,870 | 1,732 | 1,785 | 3,207 | 2,513 | 1,783 | 12,919 |

| Target catch (t) | | | | | | |
|---|---|---|---|---|---|---|
| Year | Ecuador | Spain | Federated States of Micronesia | El Salvador | USA | Total |
| 1995 | - | - | - | - | 42 | 42 |
| 1996 | - | - | - | - | - | 0 |
| 1997 | - | - | - | - | - | 0 |
| 1998 | - | 1,624 | - | - | - | 1,624 |
| 1999 | - | 277 | - | - | 73 | 350 |
| 2000 | - | 398 | - | - | - | 398 |
| 2001 | - | 1,860 | - | 109 | - | 1,969 |
| 2002 | - | 1,110 | - | 724 | - | 1,834 |
| 2003 | - | 2,031 | - | 0 | - | 2,031 |
| 2004 | - | 1,290 | 4 | - | - | 1,294 |
| 2005 | - | 437 | - | - | 0 | 437 |
| 2006 | - | 2,414 | - | - | - | 2,414 |
| 2007 | 345 | 985 | - | 297 | - | 1,627 |
| 2008 | 5,708 | 575 | - | 1,957 | - | 8,240 |
| 2009 | 851 | 0 | - | 447 | 0 | 1,298 |
| 2010 | - | 53 | - | 715 | - | 768 |

**Table 2. Estimated retained bycatch by species for WPO: 1950I  2010.**

| | Reconstructed retained bycatch (t) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | ***T. orientalis*** | ***T. obesus*** | ***T. albacares*** | ***T. alalunga*** | ***K. pelamis*** | **Thunnini** | ***X. gladius*** | ***M. nigricans*** | ***M. indica*** | ***T. angustirostris*** |
| 1950 | - | 646 | - | - | 34 | - | 19 | 508 | 32 | - |
| 1951 | - | 729 | - | - | 12 | - | 20 | 539 | 34 | - |
| 1952 | - | 2,123 | - | 154 | 54 | - | 22 | 733 | 36 | - |
| 1953 | - | 2,433 | - | 38 | 1 | - | 23 | 787 | 38 | - |
| 1954 | - | 2,132 | - | 23 | 1 | - | 24 | 1,389 | 85 | - |
| 1955 | - | 4,029 | - | 8 | 159 | - | 26 | 2,502 | 136 | - |
| 1956 | - | 4,444 | - | - | - | - | 27 | 3,709 | 100 | - |
| 1957 | - | 5,221 | - | 83 | 30 | - | 29 | 4,868 | 260 | - |
| 1958 | - | 4,229 | - | 8 | 31 | - | 30 | 5,636 | 2,084 | - |
| 1959 | 88 | 1,713 | - | 1 | 65 | 15 | 32 | 5,257 | 1,462 | - |
| 1960 | - | 1,514 | - | 106 | 28 | - | 34 | 5,131 | 1,615 | - |
| 1961 | 16 | 1,924 | - | 875 | 46 | - | 36 | 8,489 | 1,694 | - |
| 1962 | 204 | 1,135 | - | 264 | 49 | - | 38 | 23,349 | 2,683 | - |
| 1963 | 28 | 1,969 | - | 1,401 | 185 | - | 41 | 25,439 | 3,048 | - |
| 1964 | 39 | 1,298 | - | 274 | 107 | - | 47 | 17,772 | 2,410 | - |
| 1965 | 83 | 1,509 | - | 258 | 263 | 9 | 46 | 15,513 | 3,037 | - |
| 1966 | 12 | 1,422 | - | 130 | 293 | - | 49 | 13,909 | 3,208 | - |
| 1967 | - | 4,141 | 8 | 343 | 271 | - | 52 | 12,904 | 3,266 | - |
| 1968 | 8 | 2,418 | 35 | 424 | 323 | - | 55 | 12,541 | 3,902 | - |
| 1969 | 9 | 1,702 | 4 | 529 | 357 | - | 58 | 14,058 | 3,451 | - |
| 1970 | 1 | 1,731 | 9 | 386 | 1,772 | 16,037 | 97 | 16,538 | 4,408 | - |
| 1971 | - | 1,162 | 1 | 978 | 1,662 | 12,235 | 109 | 12,227 | 4,611 | - |
| 1972 | 49 | 2,060 | - | 730 | 1,786 | 4,627 | 167 | 13,050 | 4,680 | - |
| 1973 | 23 | 1,689 | 8 | 1,353 | 2,068 | 10,946 | 854 | 14,354 | 4,990 | - |
| 1974 | 33 | 1,311 | 14 | 161 | 2,219 | 7,293 | 1,461 | 13,773 | 3,941 | - |

**Table 2. Cont,**

| | Reconstructed retained bycatch (t) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | ***T. orientalis*** | ***T. obesus*** | ***T. albacares*** | ***T. alalunga*** | ***K. pelamis*** | **Thunnini** | ***X. gladius*** | ***M. nigricans*** | ***M. indica*** | ***T. angustirostris*** |
| 1975 | 86 | 1,702 | 12 | 159 | 2,013 | 7,670 | 2,864 | 13,533 | 3,961 | - |
| 1976 | 25 | 3,842 | 51 | 1,381 | 2,227 | 5,078 | 4,074 | 13,920 | 2,686 | - |
| 1977 | 13 | 3,642 | 16 | 684 | 3,239 | 5,803 | 2,734 | 15,061 | 3,316 | - |
| 1978 | 187 | 3,745 | 95 | 1,271 | 3,294 | 6,867 | 2,814 | 16,211 | 3,382 | - |
| 1979 | 9 | 2,864 | 47 | 273 | 2,212 | 3,574 | 1,426 | 18,043 | 2,952 | - |
| 1980 | 26 | 2,517 | 58 | 523 | 658 | 1,281 | 2,265 | 18,450 | 2,093 | - |
| 1981 | 2 | 2,922 | 198 | 351 | 776 | 1,325 | 2,594 | 19,623 | 2,513 | - |
| 1982 | 3 | 4,466 | 107 | 917 | 1,043 | 430 | 1,914 | 19,473 | 2,501 | - |
| 1983 | 1 | 4,369 | 143 | 357 | 2,172 | 4,771 | 1,486 | 17,967 | 2,307 | - |
| 1984 | 18 | 3,926 | 172 | 7,316 | 902 | 2,531 | 1,530 | 21,226 | 1,942 | - |
| 1985 | 23 | 4,884 | 124 | 1,574 | 1,152 | 706 | 1,793 | 17,610 | 1,624 | - |
| 1986 | 56 | 3,468 | 199 | 1,590 | 1,497 | 1,167 | 2,031 | 19,814 | 1,815 | 5 |
| 1987 | 20 | 3,628 | 366 | 1,206 | 2,366 | 2,527 | 2,629 | 25,028 | 2,231 | 15 |
| 1988 | 58 | 4,663 | 399 | 1,225 | 1,963 | 3,017 | 2,631 | 24,116 | 2,946 | 13 |
| 1989 | 18 | 4,977 | 219 | 2,522 | 2,535 | 661 | 3,094 | 21,583 | 1,812 | - |
| 1990 | 114 | 4,538 | 118 | 2,034 | 404 | 893 | 4,766 | 21,233 | 1,869 | - |
| 1991 | 6 | 3,024 | 195 | 2,652 | 921 | 225 | 6,973 | 23,734 | 2,339 | 3 |
| 1992 | 9 | 2,434 | 128 | 4,104 | 456 | 1,121 | 7,981 | 23,350 | 2,337 | 1 |
| 1993 | 34 | 2,895 | 166 | 2,889 | 634 | 4,100 | 8,276 | 26,157 | 2,168 | 1 |
| 1994 | 32 | 3,868 | 151 | 2,026 | 452 | 475 | 6,169 | 29,958 | 2,665 | 163 |
| 1995 | 30 | 4,918 | 2,586 | 1,177 | 675 | 1,083 | 6,265 | 31,279 | 2,110 | 174 |
| 1996 | 51 | 5,417 | 2,646 | 592 | 3,987 | 1,169 | 6,178 | 24,257 | 1,691 | 153 |
| 1997 | 253 | 5,248 | 2,856 | 1,069 | 4,241 | 1,598 | 9,612 | 21,374 | 1,578 | 141 |
| 1998 | 238 | 9,126 | 2,852 | 1,596 | 5,421 | 18,277 | 10,451 | 24,438 | 2,189 | 200 |
| 1999 | 4,043 | 8,569 | 3,197 | 6,918 | 4,471 | 6,529 | 12,322 | 21,363 | 2,481 | 1,272 |

**Table 2. Cont.**

| | Reconstructed retained bycatch (t) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | *T. orientalis* | *T. obesus* | *T. albacares* | *T. alalunga* | *K. pelamis* | Thunnini | *X. gladius* | *M. nigricans* | *M. indica* | *T. angustirostris* |
| 2000 | 137 | 8,611 | 4,028 | 2,479 | 4,627 | 3,770 | 13,584 | 19,536 | 1,835 | 1,325 |
| 2001 | 184 | 7,008 | 4,320 | 977 | 6,273 | 2,810 | 11,737 | 21,992 | 2,035 | 304 |
| 2002 | 79 | 7,390 | 3,795 | 3,334 | 3,711 | 3,768 | 12,699 | 21,394 | 2,336 | 1,164 |
| 2003 | 102 | 5,840 | 4,068 | 740 | 4,484 | 1,098 | 12,974 | 30,778 | 2,629 | 1,119 |
| 2004 | 24 | 9,066 | 3,534 | 7,459 | 4,808 | 2,304 | 12,081 | 28,131 | 2,816 | 1,024 |
| 2005 | 209 | 8,665 | 3,505 | 1,021 | 1,339 | 1,110 | 9,408 | 26,704 | 3,624 | 999 |
| 2006 | - | 11,462 | 3,606 | 568 | 1,757 | 389 | 8,780 | 23,180 | 3,126 | 1,111 |
| 2007 | 46 | 9,059 | 3,894 | 5,963 | 1,289 | 3,234 | 9,326 | 20,816 | 2,313 | 1,136 |
| 2008 | 18 | 10,892 | 3,866 | 1,044 | 882 | 1,926 | 10,110 | 21,186 | 2,570 | 997 |
| 2009 | 436 | 9,329 | 4,081 | 2,335 | 1,430 | 2,296 | 10,380 | 20,382 | 2,596 | 1,946 |
| 2010 | 2 | 8,655 | 4,582 | 510 | 1,471 | 1,301 | 10,021 | 21,860 | 2,807 | 2,112 |

| | Reconstructed retained bycatch (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | *T. audax* | *I. platypterus* | Istiophoridae | *E. lineatus* | Carangidae | Coryphaenidae | *Sarda* spp | Osteichthyes | Elasmobranchii |
| 1950 | - | 11 | - | - | - | 226 | 3,275 | 11 | 622 |
| 1951 | - | 12 | - | - | - | 238 | 4,988 | 12 | 676 |
| 1952 | 162 | 14 | - | - | - | 255 | 5,956 | 14 | 735 |
| 1953 | 182 | 14 | - | - | - | 268 | 2,983 | 14 | 795 |
| 1954 | 54 | 14 | - | - | - | 282 | 5,814 | 14 | 882 |
| 1955 | 46 | 14 | - | - | - | 297 | 8,922 | 14 | 980 |
| 1956 | 120 | 11 | - | - | - | 307 | 5,612 | 11 | 1,042 |
| 1957 | 166 | 8 | - | - | - | 318 | 3,662 | 8 | 1,111 |
| 1958 | 885 | 15 | 4 | - | - | 333 | 2,069 | 18 | 1,330 |
| 1959 | 825 | 25 | 10 | - | 30 | 405 | 4,789 | 30 | 1,393 |

**Table 2. Cont.**

| | Reconstructed retained bycatch (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | *T. audax* | *I. platypterus* | Istiophoridae | *E. lineatus* | Carangidae | Coryphaenidae | *Sarda* spp | Osteichthyes | Elasmobranchii |
| 1960 | 1,045 | 30 | 15 | - | - | 370 | 5,574 | 36 | 1,499 |
| 1961 | 2,530 | 18 | 8 | - | 163 | 389 | 8,235 | 73 | 1,609 |
| 1962 | 19,271 | 27 | 15 | - | 140 | 413 | 7,684 | 60 | 1,741 |
| 1963 | 20,050 | 64 | 39 | - | 240 | 434 | 7,154 | 83 | 1,877 |
| 1964 | 31,352 | 81 | 50 | 5 | 226 | 459 | 15,251 | 106 | 1,874 |
| 1965 | 29,049 | 217 | 142 | 16 | 155 | 486 | 16,928 | 289 | 2,035 |
| 1966 | 23,024 | 408 | 267 | 9 | 406 | 516 | 20,082 | 558 | 2,211 |
| 1967 | 25,636 | 438 | 309 | - | 115 | 545 | 20,928 | 583 | 2,400 |
| 1968 | 29,498 | 327 | 224 | - | 53 | 574 | 14,325 | 509 | 2,606 |
| 1969 | 21,245 | 516 | 346 | - | - | 610 | 14,562 | 688 | 2,843 |
| 1970 | 21,340 | 531 | 363 | - | 10 | 741 | 13,663 | 707 | 3,249 |
| 1971 | 22,394 | 519 | 338 | 6 | 13 | 848 | 15,991 | 716 | 3,344 |
| 1972 | 15,348 | 556 | 356 | 617 | 53 | 873 | 16,684 | 760 | 5,336 |
| 1973 | 15,459 | 806 | 521 | 1,674 | 75 | 1,053 | 16,419 | 1,225 | 6,071 |
| 1974 | 15,031 | 453 | 288 | 3,793 | 224 | 1,344 | 9,770 | 843 | 6,423 |
| 1975 | 17,060 | 21,478 | - | 511 | 206 | 1,650 | 21,185 | 112 | 6,330 |
| 1976 | 14,904 | 11,526 | - | 1,547 | 582 | 2,147 | 9,311 | 323 | 6,361 |
| 1977 | 11,232 | 6,591 | 15 | 1,458 | 1,266 | 2,558 | 18,831 | 474 | 7,007 |
| 1978 | 12,401 | 5,393 | 3 | 2,170 | 397 | 2,065 | 12,393 | 204 | 7,154 |
| 1979 | 12,660 | 5,100 | 6 | 1,364 | 158 | 2,203 | 9,202 | 538 | 9,330 |
| 1980 | 14,311 | 2,159 | - | 3,680 | 333 | 2,212 | 14,498 | 348 | 5,777 |
| 1981 | 14,687 | 2,414 | 9 | 1,911 | 328 | 2,315 | 16,834 | 1,135 | 8,584 |
| 1982 | 12,628 | 5,220 | 3 | 1,338 | 337 | 2,470 | 15,178 | 802 | 9,472 |
| 1983 | 10,774 | 2,722 | 2 | 1,235 | 3,193 | 4,688 | 24,730 | 354 | 9,576 |
| 1984 | 10,661 | 2,028 | - | 665 | 616 | 1,444 | 23,163 | 464 | 7,277 |

**Table 2. Cont.**

| | **Reconstructed retained bycatch (t)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | ***T. audax*** | ***I. platypterus*** | **Istiophoridae** | ***E. lineatus*** | **Carangidae** | **Coryphaenidae** | ***Sarda* spp** | **Osteichthyes** | **Elasmobranchii** |
| 1985 | 10,266 | 1,848 | 1 | 297 | 517 | 1,549 | 21,149 | 156 | 8,026 |
| 1986 | 13,935 | 1,030 | 1 | 586 | 423 | 3,866 | 10,021 | 164 | 7,809 |
| 1987 | 15,709 | 1,234 | 1,483 | 571 | 2,168 | 6,090 | 16,704 | 2,410 | 9,179 |
| 1988 | 15,830 | 1,626 | 1,877 | 1,268 | 2,259 | 3,243 | 22,648 | 2,407 | 8,694 |
| 1989 | 12,438 | 396 | 331 | 801 | 423 | 3,497 | 23,017 | 1,836 | 9,928 |
| 1990 | 10,704 | 179 | 495 | 788 | 481 | 3,611 | 33,292 | 1,238 | 10,165 |
| 1991 | 10,186 | 940 | 173 | 447 | 285 | 3,037 | 15,038 | 1,643 | 10,337 |
| 1992 | 10,064 | 3,756 | 4,175 | 107 | 224 | 2,310 | 18,213 | 1,342 | 12,973 |
| 1993 | 15,648 | 4,892 | 5,920 | 134 | 57 | 2,566 | 12,741 | 1,410 | 11,203 |
| 1994 | 11,631 | 3,619 | 4,693 | 228 | 62 | 6,311 | 21,508 | 2,130 | 17,969 |
| 1995 | 11,990 | 2,037 | 2,124 | 203 | 63 | 5,106 | 18,925 | 1,494 | 13,252 |
| 1996 | 10,176 | 1,356 | 1,845 | 718 | 213 | 3,269 | 12,202 | 1,959 | 15,442 |
| 1997 | 10,792 | 3,602 | 4,149 | 110 | 102 | 13,151 | 13,631 | 3,861 | 13,946 |
| 1998 | 12,403 | 2,961 | 2,965 | 527 | 113 | 15,100 | 24,769 | 7,624 | 17,902 |
| 1999 | 10,163 | 1,729 | 1,991 | 170 | 140 | 11,099 | 14,660 | 4,412 | 21,512 |
| 2000 | 7,705 | 2,014 | 1,842 | 295 | 213 | 9,034 | 15,320 | 5,364 | 24,762 |
| 2001 | 8,316 | 2,630 | 2,184 | 2,269 | 182 | 23,303 | 13,000 | 6,484 | 28,838 |
| 2002 | 8,396 | 2,820 | 4,445 | 3,886 | 189 | 18,111 | 14,447 | 9,717 | 28,993 |
| 2003 | 8,761 | 2,069 | 3,411 | 2,320 | 193 | 9,959 | 14,742 | 16,726 | 33,364 |
| 2004 | 8,280 | 2,349 | 5,140 | 3,796 | 208 | 13,450 | 15,624 | 2,976 | 31,397 |
| 2005 | 7,349 | 1,754 | 3,265 | 1,539 | 252 | 17,228 | 19,174 | 2,378 | 44,031 |
| 2006 | 7,068 | 2,882 | 3,000 | 2,194 | 413 | 21,711 | 22,495 | 3,432 | 40,798 |
| 2007 | 5,976 | 1,971 | 415 | 2,360 | 369 | 16,685 | 36,630 | 5,139 | 51,174 |
| 2008 | 6,169 | 1,401 | 704 | 3,630 | 280 | 15,388 | 31,265 | 2,796 | 53,351 |
| 2009 | 4,933 | 1,207 | 2,457 | 4,480 | 256 | 61,698 | 36,130 | 4,770 | 41,131 |
| 2010 | 4,968 | 1,164 | 857 | 3,765 | 264 | 55,250 | 27,241 | 5,449 | 50,640 |

**Table 3. Estimated discarded bycatch by species: 1950I 2010.**

| | Discarded bycatch (t) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | *C. hippurus* | *Alopias* spp. | *Isurus* spp. | Carangidae | Osteichthyes | *P. glauca* | Selachimorpha | *A. solandri* | Scombridae | *X. gladius* | Istiophoridae | *C. falciformis* | *C. longimanus* |
| 1950 | 600 | 300 | 1,100 | - | 5,800 | 9,400 | - | 400 | 1,100 | 1,200 | 400 | 1,600 | 600 |
| 1951 | 500 | 200 | 800 | - | 4,100 | 6,500 | - | 300 | 800 | 800 | 300 | 1,100 | 500 |
| 1952 | 800 | 300 | 1,500 | - | 7,100 | 13,200 | - | 500 | 1,500 | 1,700 | 500 | 2,300 | 800 |
| 1953 | 900 | 300 | 1,600 | - | 7,200 | 14,200 | - | 600 | 1,600 | 1,900 | 600 | 2,500 | 900 |
| 1954 | 800 | 300 | 1,500 | - | 7,600 | 13,600 | - | 500 | 1,500 | 1,800 | 500 | 2,300 | 800 |
| 1955 | 1,000 | 300 | 1,600 | - | 10,700 | 14,500 | - | 600 | 1,600 | 1,900 | 600 | 2,600 | 1,000 |
| 1956 | 900 | 300 | 1,800 | - | 11,800 | 15,900 | - | 600 | 1,800 | 2,100 | 600 | 2,800 | 900 |
| 1957 | 1,500 | 500 | 2,600 | - | 15,300 | 24,100 | - | 1,000 | 2,600 | 3,300 | 1,000 | 4,300 | 1,500 |
| 1958 | 1,700 | 500 | 3,100 | - | 17,000 | 28,300 | - | 1,200 | 3,100 | 3,800 | 1,200 | 5,000 | 1,700 |
| 1959 | 1,600 | 600 | 3,200 | - | 13,000 | 27,000 | - | 1,000 | 3,300 | 3,600 | 1,000 | 4,600 | 1,500 |
| 1960 | 2,300 | 600 | 3,600 | 100 | 16,000 | 32,800 | 100 | 1,600 | 3,800 | 4,500 | 1,600 | 5,700 | 2,100 |
| 1961 | 3,000 | 800 | 4,600 | 100 | 19,800 | 40,800 | 200 | 1,800 | 4,900 | 5,500 | 1,800 | 7,200 | 2,700 |
| 1962 | 3,300 | 900 | 5,300 | 200 | 23,500 | 48,500 | 200 | 2,200 | 5,500 | 6,600 | 2,200 | 8,500 | 3,100 |
| 1963 | 3,800 | 1,000 | 6,000 | 100 | 26,700 | 55,400 | 200 | 2,500 | 6,400 | 7,600 | 2,500 | 10,000 | 3,500 |
| 1964 | 3,100 | 800 | 4,700 | 200 | 22,300 | 44,700 | 200 | 2,000 | 5,100 | 6,000 | 2,000 | 7,800 | 2,800 |
| 1965 | 2,900 | 800 | 4,500 | 200 | 21,000 | 42,500 | 200 | 1,700 | 4,800 | 5,400 | 1,700 | 7,500 | 2,700 |
| 1966 | 3,400 | 800 | 5,300 | 200 | 24,600 | 49,700 | 200 | 2,100 | 5,600 | 6,400 | 2,100 | 8,800 | 3,200 |
| 1967 | 2,900 | 600 | 5,000 | 200 | 23,300 | 46,800 | 300 | 1,800 | 5,400 | 6,400 | 1,900 | 8,200 | 2,600 |
| 1968 | 3,100 | 800 | 5,000 | 200 | 23,000 | 45,800 | 200 | 1,800 | 5,400 | 5,900 | 1,800 | 7,900 | 2,800 |
| 1969 | 3,300 | 600 | 5,100 | 100 | 24,700 | 48,800 | 300 | 2,000 | 5,500 | 6,400 | 2,100 | 8,400 | 3,000 |
| 1970 | 3,700 | 800 | 5,100 | 100 | 25,400 | 48,400 | 300 | 2,100 | 5,600 | 6,300 | 2,200 | 8,300 | 3,300 |
| 1971 | 3,400 | 800 | 5,100 | 200 | 24,700 | 47,700 | 200 | 1,900 | 5,600 | 6,000 | 1,900 | 8,200 | 3,000 |
| 1972 | 3,700 | 1,000 | 5,600 | 100 | 26,300 | 52,700 | 200 | 2,100 | 6,000 | 6,900 | 2,200 | 9,000 | 3,400 |
| 1973 | 3,900 | 900 | 6,100 | 200 | 27,700 | 54,500 | 800 | 2,100 | 6,700 | 7,100 | 2,300 | 9,700 | 3,500 |
| 1974 | 3,300 | 800 | 5,100 | 200 | 23,100 | 46,000 | 900 | 1,800 | 5,700 | 6,200 | 2,000 | 8,000 | 2,900 |
| 1975 | 3,700 | 900 | 5,700 | 200 | 27,200 | 53,600 | 1,800 | 2,100 | 6,400 | 7,300 | 2,400 | 9,500 | 3,300 |
| 1976 | 4,300 | 1,200 | 6,800 | 300 | 31,500 | 63,000 | 1,700 | 2,600 | 7,500 | 8,200 | 2,900 | 11,100 | 3,800 |
| 1977 | 4,500 | 1,200 | 7,900 | 200 | 34,900 | 69,500 | 1,600 | 2,800 | 8,600 | 9,200 | 3,000 | 12,200 | 4,200 |
| 1978 | 4,600 | 1,200 | 7,400 | 200 | 34,800 | 67,400 | 2,400 | 2,800 | 8,200 | 8,900 | 3,100 | 11,900 | 4,100 |
| 1979 | 4,400 | 1,100 | 7,000 | 200 | 32,500 | 64,600 | 1,300 | 2,600 | 7,800 | 8,600 | 2,800 | 11,200 | 3,900 |

**Table 3. Cont.**

| | Discarded bycatch (t) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | *C. hippurus* | *Alopias* spp. | *Isurus* spp. | Carangidae | Osteichthyes | *P. glauca* | Selachimorpha | *A. solandri* | Scombridae | *X. gladius* | Istiophoridae | *C. falciformis* | *C. longimanus* |
| 1980 | 4,800 | 1,400 | 7,600 | 200 | 34,900 | 69,700 | 1,700 | 3,000 | 8,300 | 9,500 | 3,300 | 12,300 | 4,300 |
| 1981 | 4,300 | 900 | 6,500 | 300 | 31,000 | 59,500 | 3,300 | 2,300 | 7,800 | 7,900 | 2,700 | 10,700 | 3,400 |
| 1982 | 4,200 | 1,000 | 6,400 | 400 | 29,600 | 58,500 | 3,400 | 2,000 | 7,400 | 7,400 | 2,400 | 10,000 | 3,500 |
| 1983 | 4,500 | 900 | 6,200 | 200 | 28,600 | 56,400 | 3,000 | 2,100 | 7,500 | 7,400 | 2,500 | 9,600 | 3,500 |
| 1984 | 4,200 | 800 | 5,500 | 400 | 26,500 | 50,700 | 3,500 | 1,900 | 7,100 | 6,300 | 2,400 | 9,100 | 3,000 |
| 1985 | 4,600 | 1,000 | 6,100 | 500 | 30,400 | 57,500 | 3,700 | 2,100 | 7,700 | 7,500 | 2,500 | 10,300 | 3,400 |
| 1986 | 5,300 | 900 | 7,000 | 400 | 34,000 | 65,400 | 4,100 | 2,600 | 8,900 | 8,800 | 3,300 | 11,700 | 3,900 |
| 1987 | 6,200 | 1,300 | 7,700 | 400 | 36,100 | 72,100 | 3,600 | 2,600 | 9,600 | 9,200 | 3,100 | 12,300 | 4,700 |
| 1988 | 6,000 | 1,300 | 7,300 | 700 | 36,600 | 69,100 | 5,500 | 2,500 | 9,400 | 9,000 | 3,300 | 11,900 | 4,400 |
| 1989 | 5,500 | 1,000 | 6,200 | 600 | 32,200 | 59,200 | 6,300 | 2,200 | 8,800 | 7,400 | 3,200 | 10,300 | 3,600 |
| 1990 | 6,300 | 1,200 | 7,400 | 800 | 37,400 | 71,200 | 5,100 | 2,900 | 10,000 | 9,200 | 3,700 | 12,200 | 4,200 |
| 1991 | 6,000 | 1,000 | 7,200 | 1,100 | 36,800 | 68,300 | 4,300 | 2,700 | 9,800 | 8,800 | 3,400 | 11,300 | 3,900 |
| 1992 | 6,500 | 1,200 | 7,800 | 900 | 39,200 | 73,800 | 3,500 | 2,700 | 10,500 | 9,100 | 3,300 | 12,700 | 4,100 |
| 1993 | 6,200 | 1,000 | 7,500 | 700 | 37,500 | 72,100 | 1,900 | 2,800 | 9,800 | 9,300 | 3,200 | 12,200 | 4,100 |
| 1994 | 6,700 | 1,000 | 8,000 | 900 | 40,100 | 77,300 | 2,500 | 2,900 | 10,800 | 9,500 | 3,400 | 13,200 | 4,400 |
| 1995 | 6,000 | 900 | 6,400 | 700 | 35,200 | 67,100 | 2,400 | 2,500 | 9,200 | 8,500 | 3,000 | 11,300 | 3,700 |
| 1996 | 5,300 | 1,000 | 5,900 | 900 | 32,600 | 61,000 | 2,200 | 2,100 | 8,500 | 7,300 | 2,600 | 10,300 | 3,200 |
| 1997 | 6,200 | 1,000 | 6,900 | 1,400 | 37,800 | 71,400 | 2,300 | 2,300 | 9,900 | 8,700 | 2,700 | 12,100 | 3,800 |
| 1998 | 6,800 | 900 | 7,500 | 1,500 | 40,900 | 75,600 | 2,800 | 2,300 | 11,000 | 9,300 | 3,000 | 12,600 | 3,900 |
| 1999 | 5,900 | 700 | 6,200 | 1,300 | 36,600 | 65,100 | 2,700 | 1,900 | 9,500 | 7,800 | 2,500 | 10,600 | 3,100 |
| 2000 | 6,700 | 1,000 | 6,600 | 1,300 | 39,000 | 71,100 | 3,800 | 2,200 | 10,000 | 8,500 | 2,900 | 11,900 | 3,800 |
| 2001 | 7,600 | 1,200 | 8,400 | 1,500 | 45,900 | 86,100 | 4,000 | 2,400 | 12,000 | 10,300 | 3,100 | 14,700 | 4,500 |
| 2002 | 8,000 | 700 | 9,100 | 1,600 | 48,600 | 91,000 | 4,000 | 3,100 | 13,100 | 11,100 | 3,900 | 15,300 | 4,500 |
| 2003 | 8,300 | 800 | 8,900 | 1,600 | 48,500 | 89,300 | 4,300 | 2,800 | 13,000 | 11,400 | 3,700 | 14,500 | 4,700 |
| 2004 | 7,600 | 800 | 8,200 | 1,200 | 45,800 | 84,000 | 4,900 | 2,900 | 12,300 | 10,300 | 3,700 | 13,700 | 4,000 |
| 2005 | 7,700 | 700 | 7,400 | 1,600 | 42,700 | 76,100 | 5,100 | 2,200 | 11,900 | 9,100 | 3,100 | 12,700 | 3,800 |
| 2006 | 7,600 | 700 | 6,900 | 1,400 | 40,900 | 73,900 | 5,200 | 2,300 | 11,100 | 8,800 | 3,200 | 12,100 | 4,000 |
| 2007 | 7,400 | 400 | 6,600 | 1,500 | 40,100 | 72,200 | 5,200 | 2,200 | 11,100 | 8,800 | 3,000 | 12,000 | 3,600 |
| 2008 | 7,700 | 600 | 6,800 | 1,600 | 39,900 | 70,900 | 5,300 | 2,100 | 11,800 | 8,300 | 3,000 | 11,500 | 3,400 |
| 2009 | 7,900 | 700 | 7,500 | 1,600 | 43,000 | 76,000 | 5,700 | 2,500 | 12,500 | 9,000 | 3,600 | 12,300 | 3,500 |
| 2010 | 7,600 | 700 | 7,600 | 1,600 | 42,100 | 77,200 | 5,000 | 2,400 | 11,800 | 8,900 | 3,200 | 12,000 | 3,900 |

**Table 4. Estimated discards of target species in the Pacific Ocean: 1950-2010.**

| Year | *K. pelamis* | *T. maccoyii* | *T. alalunga* | *T. orientalis* | *T. albacares* | *T. obesus* | *X. gladius* | Elasmobranchii |
|---|---|---|---|---|---|---|---|---|
| 1950 | 1,330 | - | 1,339 | - | 2,462 | 1,459 | - | - |
| 1951 | 2,066 | - | 913 | - | 1,817 | 1,047 | - | - |
| 1952 | 1,845 | 2 | 2,031 | 275 | 2,759 | 1,969 | - | - |
| 1953 | 1,921 | 5 | 2,048 | 243 | 3,004 | 1,854 | - | - |
| 1954 | 2,613 | 5 | 2,192 | 275 | 2,889 | 1,432 | 9 | - |
| 1955 | 1,894 | 3 | 1,829 | 427 | 3,003 | 2,131 | 5 | - |
| 1956 | 2,004 | 8 | 1,671 | 578 | 3,525 | 2,479 | 7 | - |
| 1957 | 1,978 | 8 | 2,198 | 471 | 5,063 | 3,614 | 18 | - |
| 1958 | 2,896 | 17 | 2,689 | 240 | 5,218 | 4,527 | 51 | - |
| 1959 | 5,200 | 18 | 2,569 | 294 | 4,988 | 4,208 | 54 | - |
| 1960 | 3,084 | 21 | 2,951 | 378 | 6,908 | 4,897 | 70 | - |
| 1961 | 6,985 | 15 | 2,978 | 381 | 7,301 | 7,204 | 92 | - |
| 1962 | 8,565 | 13 | 3,721 | 381 | 6,930 | 6,494 | 1,136 | - |
| 1963 | 10,218 | 23 | 3,487 | 387 | 7,082 | 8,732 | 1,165 | - |
| 1964 | 8,636 | 24 | 2,859 | 314 | 6,956 | 6,186 | 917 | - |
| 1965 | 8,412 | 274 | 2,800 | 342 | 6,630 | 4,724 | 1,009 | - |
| 1966 | 8,260 | 288 | 4,655 | 265 | 7,546 | 5,354 | 1,210 | - |
| 1967 | 13,411 | 205 | 5,512 | 222 | 5,397 | 5,649 | 1,249 | - |
| 1968 | 8,505 | 212 | 4,533 | 255 | 7,193 | 5,276 | 1,207 | - |
| 1969 | 8,481 | 216 | 3,845 | 136 | 8,166 | 6,829 | 1,556 | - |
| 1970 | 9,471 | 179 | 4,943 | 110 | 8,863 | 5,627 | 1,212 | - |
| 1971 | 14,095 | 294 | 5,051 | 131 | 8,033 | 5,712 | 1,061 | 1 |
| 1972 | 6,338 | 315 | 5,183 | 125 | 10,307 | 7,217 | 1,048 | - |
| 1973 | 8,262 | 180 | 6,032 | 119 | 10,780 | 7,678 | 1,128 | 1 |
| 1974 | 11,818 | 202 | 4,518 | 205 | 10,221 | 6,753 | 1,021 | 1 |
| 1975 | 15,223 | 171 | 3,366 | 168 | 11,041 | 8,652 | 1,081 | 1 |
| 1976 | 16,837 | 183 | 4,911 | 110 | 12,813 | 11,089 | 1,304 | 1 |
| 1977 | 13,754 | 125 | 5,244 | 191 | 13,515 | 12,262 | 1,369 | - |
| 1978 | 22,672 | 108 | 5,357 | 328 | 13,901 | 11,073 | 1,379 | 4 |
| 1979 | 20,074 | 152 | 4,012 | 404 | 14,492 | 10,202 | 1,354 | 13 |
| 1980 | 21,890 | 235 | 4,515 | 319 | 15,276 | 11,185 | 1,213 | 8 |
| 1981 | 22,710 | 258 | 5,309 | 598 | 13,360 | 8,917 | 1,259 | 12 |
| 1982 | 25,873 | 120 | 5,169 | 465 | 12,044 | 8,868 | 1,131 | 8 |
| 1983 | 32,930 | 68 | 4,183 | 348 | 12,734 | 9,369 | 1,314 | 7 |
| 1984 | 34,941 | 48 | 3,958 | 158 | 12,610 | 8,995 | 1,242 | 10 |
| 1985 | 27,908 | 39 | 4,588 | 165 | 14,907 | 10,753 | 1,506 | 5 |
| 1986 | 35,307 | 37 | 4,571 | 220 | 15,421 | 13,531 | 1,509 | 20 |
| 1987 | 36,843 | 37 | 4,096 | 237 | 16,592 | 14,362 | 1,701 | 10 |
| 1988 | 43,892 | 24 | 5,012 | 115 | 17,847 | 12,055 | 1,745 | 10 |
| 1989 | 44,835 | 41 | 4,324 | 165 | 17,400 | 11,635 | 1,559 | 10 |
| 1990 | 49,434 | 58 | 3,907 | 106 | 19,466 | 15,062 | 1,465 | 41 |
| 1991 | 63,091 | 71 | 3,837 | 258 | 18,096 | 14,158 | 1,785 | 48 |
| 1992 | 60,853 | 73 | 5,389 | 203 | 17,990 | 14,050 | 2,211 | 33 |
| 1993 | 57,022 | 86 | 5,628 | 176 | 16,196 | 12,256 | 1,899 | 28 |
| 1994 | 62,445 | 79 | 6,059 | 258 | 17,825 | 14,032 | 1,720 | 36 |
| 1995 | 81,503 | 114 | 3,719 | 689 | 15,983 | 6,700 | 1,538 | 31 |
| 1996 | 67,474 | 67 | 3,839 | 401 | 16,680 | 7,563 | 1,733 | 43 |
| 1997 | 102,536 | 80 | 9,526 | 816 | 20,696 | 10,666 | 2,014 | 48 |
| 1998 | 115,155 | 105 | 11,559 | 333 | 24,154 | 10,969 | 2,007 | 68 |
| 1999 | 104,331 | 93 | 1,480 | 896 | 19,213 | 9,582 | 1,717 | 22 |
| 2000 | 79,556 | 71 | 412 | 1,089 | 22,778 | 11,274 | 1,801 | 5 |
| 2001 | 88,674 | 103 | 5,706 | 398 | 19,495 | 6,059 | 2,379 | 5 |
| 2002 | 65,175 | 114 | 5,944 | 187 | 14,761 | 3,431 | 2,537 | 5 |
| 2003 | 72,314 | 94 | 1,660 | 176 | 13,791 | 4,263 | 2,678 | 18 |
| 2004 | 75,046 | 61 | 3,453 | 288 | 19,260 | 7,508 | 2,667 | 8 |
| 2005 | 91,579 | 43 | 2,197 | 505 | 17,360 | 6,626 | 2,089 | 11 |
| 2006 | 72,132 | 14 | 1,347 | 281 | 9,943 | 4,616 | 2,447 | 11 |
| 2007 | 63,516 | 16 | 1,491 | 286 | 10,330 | 4,044 | 2,660 | 19 |
| 2008 | 46,310 | 17 | 2,187 | 273 | 8,774 | 2,286 | 2,511 | 24 |
| 2009 | 53,963 | 23 | 532 | 340 | 12,377 | 4,674 | 2,456 | 17 |
| 2010 | 36,778 | 21 | 413 | 113 | 7,999 | 2,223 | 2,603 | 11 |

## Table 5. Retained bycatch by gear type: 1950-2010.

| Year | Longline | Pole-and-lin | Purse Seine | Gillnet | Handline | Harpoon | Hooks and li | Ringnet | Small-scale h | Troll | Unknown |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1950 | 112 | 994 | - | - | 594 | - | - | - | 117 | - | 3,567 |
| 1951 | 97 | 1,707 | 37 | - | 630 | - | - | - | 124 | - | 4,665 |
| 1952 | 477 | 2,978 | 369 | - | 668 | - | - | - | 133 | - | 5,633 |
| 1953 | 466 | 3,197 | 283 | - | 707 | - | - | - | 141 | - | 2,782 |
| 1954 | 970 | 3,109 | 455 | - | 751 | - | - | - | 150 | - | 5,279 |
| 1955 | 2,270 | 5,063 | 396 | - | 797 | - | - | - | 160 | - | 8,447 |
| 1956 | 3,289 | 5,496 | 424 | - | 844 | - | - | - | 170 | - | 5,160 |
| 1957 | 4,612 | 6,233 | 589 | - | 895 | - | - | - | 181 | - | 3,254 |
| 1958 | 8,026 | 5,643 | 663 | - | 947 | - | - | - | 192 | - | 1,201 |
| 1959 | 6,941 | 3,326 | 719 | - | 1,005 | - | - | - | 206 | - | 3,943 |
| 1960 | 7,111 | 2,266 | 2,615 | - | 1,065 | - | - | - | 218 | - | 3,722 |
| 1961 | 11,952 | 3,461 | 4,217 | - | 1,128 | - | - | - | 233 | - | 5,114 |
| 1962 | 44,520 | 3,142 | 3,971 | - | 1,196 | - | - | - | 249 | - | 3,995 |
| 1963 | 47,931 | 3,311 | 4,928 |  | 1,269 | - | - | - | 264 | - | 4,349 |
| 1964 | 48,278 | 2,990 | 7,858 | 7 | 1,344 | - | - | - | 281 | - | 10,593 |
| 1965 | 44,384 | 3,071 | 4,706 | 2 | 1,425 | - | - | - | 300 | - | 16,147 |
| 1966 | 38,539 | 4,128 | 5,173 | 3 | 1,512 | - | - | - | 320 | - | 16,829 |
| 1967 | 40,204 | 6,057 | 10,862 | 11 | 1,602 | - | - | - | 341 | - | 12,862 |
| 1968 | 44,393 | 4,324 | 8,933 | 39 | 1,698 | - | - | - | 363 | - | 8,072 |
| 1969 | 36,213 | 5,340 | 3,718 | 7 | 1,800 | 8 | - | - | 387 | - | 13,505 |
| 1970 | 42,615 | 5,736 | 5,466 | 13 | 2,200 | - | - | 24 | 447 | - | 25,082 |
| 1971 | 38,070 | 5,109 | 11,301 | 13 | 2,464 | - | - | 26 | 494 | - | 19,677 |
| 1972 | 32,968 | 4,689 | 11,085 | 318 | 2,559 | - | - | 28 | 521 | - | 15,564 |
| 1973 | 32,332 | 4,950 | 11,915 | 4,408 | 3,061 | 1 | - | 32 | 614 | - | 22,275 |
| 1974 | 29,107 | 4,950 | 9,757 | 4,847 | 3,558 | 3 | - | 36 | 707 | - | 15,410 |
| 1975 | 46,846 | 4,386 | 18,878 | 10,457 | 3,631 | - | - | 38 | 730 | - | 15,566 |
| 1976 | 37,970 | 7,481 | 9,150 | 8,133 | 3,059 | - | - | 36 | 625 | - | 13,531 |
| 1977 | 29,889 | 7,178 | 16,136 | 8,127 | 4,335 | 5 | - | 40 | 941 | - | 17,289 |
| 1978 | 31,455 | 7,512 | 9,986 | 9,746 | 2,617 | 5 | - | 42 | 669 | - | 18,014 |
| 1979 | 35,151 | 6,076 | 5,810 | 4,425 | 3,354 | 25 | - | 46 | 719 | - | 16,355 |
| 1980 | 30,537 | 6,355 | 12,870 | 6,479 | 3,067 | 12 | - | 38 | 663 | 14 | 11,154 |
| 1981 | 34,709 | 6,153 | 11,661 | 7,771 | 3,383 | 49 | - | 42 | 812 | 23 | 13,918 |
| 1982 | 37,261 | 7,335 | 7,981 | 5,380 | 3,127 | 49 | - | 28 | 639 | 90 | 16,412 |
| 1983 | 30,986 | 7,488 | 19,030 | 4,420 | 3,399 | 7 | - | 38 | 706 | 86 | 24,687 |
| 1984 | 30,423 | 7,703 | 20,442 | 4,424 | 4,097 | 5 | - | 64 | 689 | 130 | 17,904 |
| 1985 | 26,031 | 7,305 | 12,522 | 4,959 | 4,681 | 1 | - | 102 | 782 | 121 | 16,795 |
| 1986 | 30,613 | 6,854 | 7,206 | 5,975 | 4,826 | 1 | - | 116 | 861 | 110 | 12,915 |
| 1987 | 47,965 | 6,271 | 16,489 | 3,954 | 3,824 | 60 | - | 74 | 721 | 87 | 16,119 |
| 1988 | 46,057 | 8,132 | 21,954 | 4,880 | 4,456 | 2 | - | 66 | 743 | 150 | 14,443 |
| 1989 | 36,258 | 8,319 | 22,411 | 5,028 | 4,693 | 1 | - | 74 | 823 | 152 | 12,329 |
| 1990 | 32,038 | 6,718 | 33,716 | 4,078 | 6,375 | 1 | - | 116 | 989 | 159 | 12,732 |
| 1991 | 40,114 | 5,267 | 15,346 | 2,837 | 7,755 | 1 | - | 98 | 1,135 | 136 | 9,469 |
| 1992 | 50,942 | 4,586 | 20,193 | 2,571 | 4,756 | 3 | - | 108 | 538 | 184 | 11,204 |
| 1993 | 63,072 | 5,417 | 13,599 | 1,417 | 4,560 | 1 | - | 104 | 594 | 209 | 12,918 |
| 1994 | 61,963 | 6,023 | 22,263 | 2,175 | 7,143 | 1 | - | 50 | 1,078 | 188 | 13,226 |
| 1995 | 53,164 | 6,830 | 18,641 | 1,792 | 8,011 | 2 | - | 58 | 1,248 | 3,219 | 12,526 |
| 1996 | 46,885 | 6,383 | 12,595 | 1,409 | 8,573 | 1 |  | 58 | 1,249 | 4,139 | 12,029 |
| 1997 | 64,969 | 6,360 | 14,010 | 1,465 | 4,473 | 9 | 566 | 60 | 1,306 | 4,295 | 13,801 |
| 1998 | 71,654 | 10,569 | 24,862 | 1,783 | 5,142 | 1 | - | 66 | 1,441 | 4,295 | 39,339 |
| 1999 | 72,137 | 10,605 | 19,816 | 2,076 | 5,055 | - | - | 66 | 1,466 | 4,430 | 21,390 |
| 2000 | 69,926 | 10,426 | 16,910 | 3,105 | 1,849 | - | 1,665 | 68 | 1,497 | 4,592 | 16,443 |
| 2001 | 82,032 | 8,339 | 15,945 | 3,316 | 1,630 | - | 11,584 | 64 | 1,391 | 4,908 | 15,637 |
| 2002 | 86,361 | 8,511 | 22,902 | 3,939 | 1,794 | - | 2,369 | 70 | 1,400 | 4,570 | 18,758 |
| 2003 | 103,626 | 7,260 | 16,616 | 3,569 | 2,619 | - | 3,609 | 88 | 1,401 | 3,871 | 12,718 |
| 2004 | 87,279 | 10,404 | 26,668 | 4,208 | 2,592 | 1 | 950 | 92 | 1,400 | 3,547 | 17,326 |
| 2005 | 87,367 | 9,552 | 22,342 | 4,401 | 3,082 | 1 | 381 | 94 | 1,400 | 3,266 | 21,668 |
| 2006 | 79,071 | 12,395 | 25,679 | 4,208 | 3,087 | 2 | 42 | 104 | 1,400 | 3,215 | 28,769 |
| 2007 | 82,189 | 10,294 | 46,413 | 4,145 | 3,361 | - | 32 | 120 | 1,400 | 3,526 | 26,315 |
| 2008 | 80,097 | 11,959 | 36,183 | 4,115 | 4,947 | 1 | - | 120 | 1,400 | 3,687 | 25,966 |
| 2009 | 70,924 | 10,598 | 44,863 | 3,931 | 3,946 | 1 | - | 120 | 1,400 | 3,738 | 72,752 |
| 2010 | 79,629 | 9,737 | 32,309 | 3,728 | 3,989 | - | - | 120 | 1,400 | 4,463 | 67,544 |

**Table 6. Discarded bycatch by gear type: 1950-2010.**

| Year | Longline | Purse Seine | Gillnet | Handline | Hook and Line | Unknown |
|---|---|---|---|---|---|---|
| 1950 | 21,200 | - | - | - | - | 1,300 |
| 1951 | 14,900 | - | - | - | - | 1,000 |
| 1952 | 29,400 | - | - | - | - | 800 |
| 1953 | 31,800 | - | - | - | - | 500 |
| 1954 | 30,000 | - | - | - | - | 1,200 |
| 1955 | 32,800 | - | - | - | - | 3,600 |
| 1956 | 35,000 | 200 | - | - | - | 4,300 |
| 1957 | 53,800 | 100 | - | - | - | 3,800 |
| 1958 | 63,100 | 100 | - | - | - | 3,400 |
| 1959 | 59,900 | 400 | - | - | - | 100 |
| 1960 | 73,900 | 800 | - | - | - | 100 |
| 1961 | 91,800 | 1,200 | - | - | - | 200 |
| 1962 | 108,700 | 1,200 | - | - | - | 100 |
| 1963 | 124,100 | 1,200 | - | - | 200 | 200 |
| 1964 | 99,500 | 1,500 | - | - | 200 | 500 |
| 1965 | 93,900 | 1,200 | - | - | 200 | 600 |
| 1966 | 110,300 | 1,200 | - | - | 200 | 700 |
| 1967 | 102,700 | 1,700 | - | - | 200 | 800 |
| 1968 | 101,200 | 1,400 | - | - | 200 | 900 |
| 1969 | 107,400 | 1,500 | - | - | 200 | 1,200 |
| 1970 | 107,900 | 1,800 | - | - | 200 | 1,700 |
| 1971 | 105,600 | 1,800 | - | - | 200 | 1,100 |
| 1972 | 117,100 | 1,500 | - | - | 200 | 400 |
| 1973 | 121,600 | 1,900 | 800 | 200 | 200 | 800 |
| 1974 | 102,300 | 2,000 | 800 | 200 | 200 | 500 |
| 1975 | 119,200 | 2,000 | 2,100 | 200 | 200 | 400 |
| 1976 | 139,900 | 2,600 | 1,800 | 200 | 200 | 200 |
| 1977 | 154,800 | 2,000 | 1,700 | 200 | 600 | 500 |
| 1978 | 150,600 | 2,600 | 2,900 | - | 400 | 500 |
| 1979 | 143,000 | 2,600 | 1,300 | 200 | 400 | 500 |
| 1980 | 156,000 | 2,600 | 1,800 | 200 | 200 | 200 |
| 1981 | 131,900 | 3,700 | 4,000 | 200 | 400 | 400 |
| 1982 | 128,200 | 3,500 | 4,100 | 200 | 200 | - |
| 1983 | 124,600 | 4,600 | 2,800 | 200 | 200 | - |
| 1984 | 111,600 | 5,600 | 3,800 | 200 | 200 | - |
| 1985 | 127,000 | 5,500 | 4,200 | 200 | 400 | - |
| 1986 | 144,800 | 6,500 | 4,400 | 200 | 400 | - |
| 1987 | 158,100 | 6,800 | 3,600 | - | 400 | - |
| 1988 | 152,400 | 8,300 | 5,700 | 200 | 400 | - |
| 1989 | 129,900 | 8,800 | 7,200 | 200 | 400 | - |
| 1990 | 156,000 | 10,100 | 4,900 | 200 | 400 | - |
| 1991 | 149,300 | 11,300 | 3,200 | 400 | 400 | - |
| 1992 | 161,200 | 11,400 | 2,300 | 200 | 200 | - |
| 1993 | 157,500 | 9,900 | 500 | 200 | 200 | - |
| 1994 | 167,900 | 11,200 | 600 | 400 | 600 | - |
| 1995 | 144,400 | 11,000 | 500 | 400 | 600 | - |
| 1996 | 130,600 | 10,800 | 500 | 400 | 600 | - |
| 1997 | 152,200 | 12,600 | 500 | 400 | 800 | - |
| 1998 | 160,800 | 15,600 | 500 | 400 | 800 | - |
| 1999 | 137,300 | 15,100 | 500 | 400 | 600 | - |
| 2000 | 151,200 | 14,600 | 2,200 | 200 | 600 | - |
| 2001 | 183,300 | 15,300 | 2,300 | 200 | 600 | - |
| 2002 | 193,600 | 17,100 | 2,500 | 200 | 600 | - |
| 2003 | 190,700 | 17,800 | 2,500 | 200 | 600 | - |
| 2004 | 178,500 | 16,900 | 3,200 | 200 | 600 | - |
| 2005 | 160,900 | 19,000 | 3,200 | 200 | 800 | - |
| 2006 | 156,200 | 17,700 | 3,200 | 200 | 800 | - |
| 2007 | 151,300 | 18,400 | 3,200 | 400 | 800 | - |
| 2008 | 148,100 | 20,500 | 3,100 | 400 | 800 | - |
| 2009 | 160,500 | 21,200 | 3,100 | 400 | 600 | - |
| 2010 | 161,800 | 18,600 | 2,800 | 200 | 600 | - |

## Table 7. Discarded target species in the Pacific Ocean: 1950-2010.

| Year | Longline | Pole-and-lin | Purse Seine | Gillnet | Handline | Ringnet | Small-scale h | Troll | Unknown |
|---|---|---|---|---|---|---|---|---|---|
| 1950 | 3,826 | 1,496 | 878 | - | 12 | - | 59 | - | 319 |
| 1951 | 2,647 | 2,082 | 775 | - | 13 | - | 62 | - | 264 |
| 1952 | 5,190 | 1,822 | 1,261 | - | 13 | - | 66 | 245 | 284 |
| 1953 | 5,644 | 1,687 | 1,246 | - | 14 | - | 70 | 172 | 242 |
| 1954 | 5,388 | 2,033 | 1,379 | - | 15 | - | 75 | 139 | 386 |
| 1955 | 5,738 | 1,502 | 972 | - | 16 | - | 80 | 148 | 836 |
| 1956 | 6,101 | 1,596 | 1,259 | - | 17 | - | 85 | 206 | 1,008 |
| 1957 | 9,464 | 1,544 | 1,077 | - | 18 | - | 91 | 236 | 920 |
| 1958 | 10,996 | 1,840 | 1,650 | - | 19 | - | 96 | 164 | 873 |
| 1959 | 10,453 | 2,406 | 3,925 | - | 20 | - | 103 | 217 | 207 |
| 1960 | 12,679 | 1,274 | 3,785 | - | 21 | - | 110 | 220 | 220 |
| 1961 | 15,504 | 1,781 | 7,123 | - | 23 | - | 117 | 153 | 255 |
| 1962 | 16,497 | 1,878 | 8,255 | - | 24 | - | 124 | 215 | 247 |
| 1963 | 19,001 | 1,263 | 10,125 | - | 26 | - | 132 | 276 | 271 |
| 1964 | 14,757 | 1,626 | 8,785 | 2 | 27 | - | 141 | 212 | 342 |
| 1965 | 13,527 | 1,631 | 8,361 | 2 | 29 | - | 150 | 185 | 306 |
| 1966 | 16,961 | 2,414 | 7,506 | 1 | 30 | - | 160 | 169 | 337 |
| 1967 | 15,902 | 2,014 | 12,880 | 1 | 32 | - | 171 | 211 | 434 |
| 1968 | 15,381 | 2,007 | 8,863 | - | 34 | - | 182 | 220 | 494 |
| 1969 | 17,136 | 3,729 | 7,390 | - | 36 | - | 194 | 210 | 534 |
| 1970 | 16,700 | 4,266 | 8,339 | 1 | 38 | 48 | 223 | 223 | 567 |
| 1971 | 16,323 | 4,138 | 12,888 | 2 | 43 | 52 | 248 | 220 | 464 |
| 1972 | 18,804 | 2,614 | 7,951 | 6 | 45 | 56 | 260 | 247 | 550 |
| 1973 | 19,802 | 3,473 | 9,609 | 24 | 53 | 63 | 306 | 183 | 667 |
| 1974 | 16,523 | 3,950 | 12,831 | 26 | 62 | 72 | 353 | 228 | 694 |
| 1975 | 18,474 | 3,025 | 16,812 | 30 | 63 | 76 | 365 | 205 | 653 |
| 1976 | 22,944 | 3,993 | 18,961 | 95 | 53 | 72 | 312 | 167 | 651 |
| 1977 | 26,458 | 3,575 | 14,772 | 120 | 76 | 81 | 470 | 128 | 780 |
| 1978 | 25,585 | 4,185 | 23,198 | 301 | 46 | 86 | 334 | 228 | 859 |
| 1979 | 24,008 | 3,560 | 21,562 | 178 | 58 | 93 | 360 | 85 | 799 |
| 1980 | 26,240 | 4,032 | 23,010 | 198 | 54 | 77 | 331 | 84 | 615 |
| 1981 | 21,952 | 3,524 | 24,964 | 641 | 61 | 86 | 406 | 159 | 630 |
| 1982 | 21,196 | 3,142 | 27,303 | 838 | 58 | 55 | 319 | 67 | 700 |
| 1983 | 21,103 | 3,435 | 34,550 | 565 | 60 | 75 | 353 | 106 | 706 |
| 1984 | 18,868 | 4,267 | 36,721 | 819 | 79 | 127 | 345 | 133 | 603 |
| 1985 | 22,108 | 2,934 | 32,484 | 894 | 89 | 205 | 392 | 105 | 660 |
| 1986 | 24,984 | 3,714 | 39,494 | 898 | 92 | 233 | 431 | 81 | 689 |
| 1987 | 26,220 | 3,041 | 42,533 | 767 | 75 | 148 | 360 | 58 | 676 |
| 1988 | 25,308 | 3,297 | 49,400 | 1,259 | 87 | 130 | 372 | 112 | 735 |
| 1989 | 22,071 | 3,214 | 51,523 | 1,641 | 90 | 148 | 412 | 120 | 750 |
| 1990 | 27,138 | 2,508 | 56,831 | 1,091 | 122 | 232 | 494 | 123 | 1,000 |
| 1991 | 25,542 | 3,189 | 69,900 | 756 | 146 | 195 | 568 | 127 | 921 |
| 1992 | 27,200 | 2,870 | 68,625 | 512 | 98 | 214 | 269 | 134 | 880 |
| 1993 | 25,481 | 3,146 | 63,097 | 149 | 92 | 208 | 297 | 93 | 728 |
| 1994 | 27,602 | 2,750 | 70,243 | 113 | 141 | 100 | 539 | 214 | 752 |
| 1995 | 13,704 | 3,005 | 91,544 | 105 | 158 | 114 | 624 | 332 | 691 |
| 1996 | 11,977 | 2,537 | 81,254 | 91 | 171 | 114 | 626 | 265 | 765 |
| 1997 | 15,385 | 2,782 | 126,339 | 109 | 153 | 119 | 654 | 248 | 593 |
| 1998 | 21,627 | 3,137 | 137,369 | 126 | 180 | 132 | 722 | 305 | 752 |
| 1999 | 9,768 | 3,354 | 122,029 | 99 | 187 | 133 | 732 | 244 | 788 |
| 2000 | 5,165 | 2,953 | 106,154 | 445 | 99 | 136 | 749 | 387 | 898 |
| 2001 | 10,260 | 2,420 | 107,713 | 504 | 94 | 127 | 696 | 285 | 720 |
| 2002 | 10,660 | 2,508 | 76,444 | 519 | 107 | 140 | 701 | 268 | 807 |
| 2003 | 8,869 | 2,575 | 80,907 | 526 | 141 | 178 | 700 | 364 | 734 |
| 2004 | 11,688 | 2,480 | 91,290 | 670 | 147 | 183 | 700 | 433 | 700 |
| 2005 | 8,369 | 2,635 | 106,570 | 685 | 148 | 187 | 700 | 280 | 836 |
| 2006 | 5,513 | 2,487 | 79,814 | 683 | 162 | 206 | 700 | 271 | 955 |
| 2007 | 5,581 | 2,787 | 70,675 | 721 | 185 | 240 | 700 | 266 | 1,207 |
| 2008 | 4,240 | 2,625 | 52,131 | 711 | 172 | 265 | 700 | 270 | 1,268 |
| 2009 | 7,769 | 2,596 | 60,494 | 702 | 136 | 375 | 700 | 247 | 1,363 |
| 2010 | 4,671 | 2,654 | 39,515 | 623 | 154 | 320 | 700 | 253 | 1,271 |

**Table 8. Catch time series of Pacific tunas used for the reference case analysis in their most recent stock assessments. These data were manually extracted from the original stock assessments using GraphClick.**

| Year | Pacific bluefin | Southern bluefin | N-Albacore | S-Albacore | W-Bigeye | E-Bigeye | E-Yellowfin | W-Yellowfin | Skipjack |
|---|---|---|---|---|---|---|---|---|---|
| 1952 | - | 829 | - | 130 | 33,396 | - | - | 23,058 | - |
| 1953 | 20,045 | 4,399 | - | 769 | 32,177 | - | - | 32,162 | - |
| 1954 | 28,543 | 2,871 | - | 9,798 | 21,073 | - | - | 28,550 | - |
| 1955 | 30,600 | 2,286 | - | 8,624 | 33,790 | - | - | 27,380 | - |
| 1956 | 39,683 | 10,567 | - | 7,631 | 36,845 | - | - | 29,260 | - |
| 1957 | 35,839 | 24,172 | - | 9,422 | 49,444 | - | - | 50,523 | - |
| 1958 | 29,306 | 14,784 | - | 19,007 | 68,749 | - | - | 59,021 | - |
| 1959 | 20,626 | 64,378 | - | 18,111 | 60,374 | - | - | 59,578 | - |
| 1960 | 26,248 | 79,371 | - | 22,190 | 63,429 | - | - | 72,858 | - |
| 1961 | 30,730 | 81,750 | - | 24,320 | 57,251 | - | - | 75,913 | - |
| 1962 | 33,040 | 45,757 | - | 27,014 | 55,260 | - | - | 75,301 | - |
| 1963 | 35,265 | 66,321 | - | 27,014 | 63,205 | - | - | 68,125 | - |
| 1964 | 26,814 | 49,867 | - | 18,663 | 45,309 | - | - | 55,457 | - |
| 1965 | 26,119 | 47,567 | - | 22,583 | 42,238 | - | - | 59,118 | - |
| 1966 | 31,048 | 47,656 | 67,491 | 37,877 | 45,344 | - | - | 85,212 | - |
| 1967 | 20,765 | 65,643 | 81,579 | 38,321 | 47,624 | - | - | 50,161 | - |
| 1968 | 21,483 | 58,394 | 69,811 | 29,548 | 37,222 | - | - | 55,604 | - |
| 1969 | 16,265 | 58,528 | 74,615 | 25,620 | 45,410 | - | - | 60,483 | - |
| 1970 | 11,967 | 48,156 | 67,855 | 33,415 | 42,372 | - | - | 92,638 | - |
| 1971 | 16,401 | 45,148 | 89,967 | 36,981 | 42,766 | - | - | 98,032 | - |
| 1972 | 20,886 | 51,925 | 106,500 | 35,552 | 57,474 | - | - | 109,000 | 217,000 |
| 1973 | 19,616 | 41,205 | 106,700 | 37,870 | 48,721 | - | - | 131,000 | 305,000 |
| 1974 | 20,390 | 46,777 | 115,000 | 31,529 | 51,998 | - | - | 133,400 | 328,000 |
| 1975 | 20,918 | 32,982 | 96,839 | 20,254 | 63,858 | 48,454 | 204,048 | 137,600 | 266,000 |
| 1976 | 19,456 | 42,509 | 124,600 | 25,803 | 68,164 | 69,523 | 234,740 | 144,900 | 330,000 |
| 1977 | 18,924 | 42,178 | 62,138 | 33,703 | 74,480 | 81,910 | 201,181 | 181,400 | 374,000 |
| 1978 | 26,801 | 35,908 | 98,213 | 34,237 | 61,146 | 84,503 | 177,760 | 175,300 | 408,000 |
| 1979 | 31,551 | 38,673 | 71,141 | 26,277 | 74,480 | 76,510 | 187,287 | 207,500 | 374,000 |
| 1980 | 23,398 | 45,054 | 74,492 | 30,504 | 71,376 | 84,823 | 159,414 | 225,100 | 416,000 |
| 1981 | 34,539 | 45,104 | 70,646 | 31,663 | 62,193 | 68,346 | 178,465 | 219,100 | 403,000 |
| 1982 | 29,333 | 42,788 | 73,030 | 27,067 | 72,438 | 62,201 | 131,274 | 220,900 | 459,000 |
| 1983 | 20,658 | 42,881 | 55,479 | 27,067 | 76,934 | 69,024 | 104,693 | 259,800 | 641,000 |
| 1984 | 11,938 | 37,090 | 72,158 | 24,638 | 82,666 | 60,301 | 154,011 | 265,200 | 724,000 |
| 1985 | 15,894 | 33,325 | 56,067 | 27,616 | 90,013 | 74,735 | 221,845 | 274,400 | 584,000 |
| 1986 | 19,061 | 28,319 | 45,723 | 30,377 | 79,026 | 111,248 | 286,366 | 255,100 | 709,000 |
| 1987 | 15,907 | 25,575 | 48,962 | 28,301 | 101,800 | 107,482 | 287,307 | 277,000 | 650,000 |
| 1988 | 9,400 | 23,145 | 45,219 | 43,703 | 97,920 | 76,702 | 296,108 | 319,000 | 795,000 |
| 1989 | 10,781 | 17,843 | 43,785 | 50,497 | 99,980 | 70,873 | 299,867 | 323,300 | 776,000 |
| 1990 | 8,805 | 13,870 | 53,170 | 32,168 | 121,500 | 124,999 | 299,957 | 360,800 | 863,000 |
| 1991 | 15,625 | 13,691 | 37,348 | 33,952 | 105,500 | 131,780 | 269,001 | 392,300 | 1,071,000 |
| 1992 | 13,734 | 14,217 | 54,381 | 38,270 | 120,900 | 107,273 | 252,993 | 377,300 | 988,000 |
| 1993 | 11,065 | 14,342 | 53,665 | 35,342 | 105,100 | 98,342 | 257,857 | 324,600 | 918,000 |
| 1994 | 17,590 | 13,155 | 73,342 | 43,144 | 128,300 | 125,753 | 255,446 | 373,400 | 1,012,000 |
| 1995 | 29,010 | 13,932 | 68,175 | 37,523 | 114,500 | 117,565 | 250,802 | 400,800 | 1,048,000 |
| 1996 | 23,802 | 16,646 | 87,439 | 35,920 | 115,700 | 121,572 | 273,446 | 345,600 | 1,035,000 |
| 1997 | 24,494 | 16,076 | 105,700 | 41,433 | 176,900 | 123,442 | 282,072 | 428,400 | 976,000 |
| 1998 | 16,204 | 17,777 | 98,366 | 53,185 | 158,000 | 111,957 | 285,191 | 493,200 | 1,330,000 |
| 1999 | 28,672 | 19,529 | 123,800 | 39,220 | 144,600 | 95,206 | 307,788 | 442,600 | 1,205,000 |
| 2000 | 33,391 | 15,475 | 84,664 | 41,629 | 151,200 | 151,936 | 294,700 | 468,700 | 1,221,000 |
| 2001 | 18,469 | 16,031 | 89,730 | 59,766 | 136,800 | 141,663 | 432,486 | 448,200 | 1,121,000 |
| 2002 | 18,469 | 15,258 | 104,600 | 74,608 | 154,000 | 168,669 | 445,282 | 493,400 | 1,321,000 |
| 2003 | 17,777 | 14,077 | 92,617 | 62,485 | 119,600 | 130,585 | 426,077 | 535,000 | 1,281,000 |
| 2004 | 24,894 | 13,505 | 90,437 | 66,421 | 178,500 | 123,942 | 302,054 | 454,100 | 1,405,000 |
| 2005 | 28,508 | 16,151 | 63,627 | 67,225 | 148,900 | 110,139 | 285,997 | 577,700 | 1,480,000 |
| 2006 | 25,496 | 11,741 | 66,644 | 64,428 | 155,900 | 123,957 | 181,160 | 515,100 | 1,558,000 |
| 2007 | 21,067 | 10,583 | 91,788 | 53,814 | 134,500 | 100,649 | 182,723 | 530,900 | 1,661,000 |
| 2008 | 23,773 | 11,396 | 68,702 | 63,691 | 134,000 | 106,410 | 197,023 | 647,400 | 1,618,000 |
| 2009 | 19,555 | 10,946 | 76,683 | 93,902 | 142,000 | 107,616 | 248,692 | 506,400 | 1,782,000 |
| 2010 | 17,439 | 9,723 | - | 90,576 | 116,900 | 98,131 | 228,349 | - | 1,611,000 |
| 2011 | - | - | - | 55,160 | - | 76,839 | 206,635 | - | - |

**Table 9. Catch time series of Pacific sharks and billfishes used for the reference case analysis in their most recent stock assessments. These data were manually extracted from the original stock assessments using GraphClick.**

| Year | Blue shark | Silky shark | Swordfish | Blue marlin | Striped marlin |
|---|---|---|---|---|---|
| 1950 | - | - | - | 161 | - |
| 1951 | - | - | 11,714 | 234 | - |
| 1952 | - | - | 11,714 | 8,375 | 5,142 |
| 1953 | - | - | 12,463 | 9,351 | 3,447 |
| 1954 | - | - | 13,613 | 7,406 | 4,299 |
| 1955 | - | - | 14,179 | 8,377 | 4,299 |
| 1956 | - | - | 15,469 | 7,659 | 5,891 |
| 1957 | - | - | 15,313 | 11,766 | 5,891 |
| 1958 | - | - | 19,777 | 12,541 | 7,450 |
| 1959 | - | - | 18,747 | 12,321 | 7,634 |
| 1960 | - | - | 22,067 | 10,873 | 5,896 |
| 1961 | - | - | 21,563 | 16,711 | 5,896 |
| 1962 | - | - | 12,723 | 18,754 | 6,346 |
| 1963 | - | - | 11,604 | 20,037 | 5,816 |
| 1964 | - | - | 9,230 | 16,967 | 8,519 |
| 1965 | - | - | 11,359 | 13,910 | 7,230 |
| 1966 | - | - | 12,419 | 13,714 | 4,805 |
| 1967 | - | - | 12,673 | 12,380 | 6,549 |
| 1968 | - | - | 12,458 | 13,079 | 5,942 |
| 1969 | - | - | 12,273 | 13,283 | 7,072 |
| 1970 | - | - | 11,084 | 14,811 | 8,397 |
| 1971 | 36,445 | - | 9,156 | 9,187 | 7,682 |
| 1972 | 33,928 | - | 8,754 | 10,836 | 5,217 |
| 1973 | 37,675 | - | 9,909 | 12,257 | 8,554 |
| 1974 | 35,039 | - | 9,716 | 11,560 | 7,777 |
| 1975 | 39,922 | - | 12,293 | 10,719 | 10,174 |
| 1976 | 54,275 | - | 13,768 | 11,716 | 6,821 |
| 1977 | 66,308 | - | 13,272 | 12,315 | 7,709 |
| 1978 | 62,153 | - | 14,210 | 14,512 | 10,395 |
| 1979 | 68,925 | - | 11,997 | 15,196 | 7,695 |
| 1980 | 74,489 | - | 11,033 | 15,801 | 8,518 |
| 1981 | 87,103 | - | 12,971 | 16,602 | 7,519 |
| 1982 | 70,944 | - | 11,976 | 17,458 | 5,761 |
| 1983 | 68,098 | - | 12,791 | 16,815 | 5,562 |
| 1984 | 63,196 | - | 13,600 | 19,320 | 7,338 |
| 1985 | 60,866 | - | 16,014 | 15,350 | 7,937 |
| 1986 | 56,711 | - | 14,781 | 17,830 | 10,776 |
| 1987 | 50,909 | - | 15,501 | 24,509 | 9,081 |
| 1988 | 55,883 | - | 14,075 | 20,877 | 9,537 |
| 1989 | 62,204 | - | 13,349 | 18,179 | 7,118 |
| 1990 | 48,623 | - | 15,752 | 16,184 | 6,266 |
| 1991 | 49,053 | - | 14,339 | 17,388 | 6,431 |
| 1992 | 41,362 | - | 19,871 | 20,163 | 6,148 |
| 1993 | 38,775 | - | 20,339 | 21,880 | 7,090 |
| 1994 | 32,963 | 4,194 | 16,275 | 22,104 | 6,304 |
| 1995 | 40,443 | 4,601 | 14,637 | 23,226 | 6,523 |
| 1996 | 36,508 | 4,386 | 13,983 | 15,089 | 5,016 |
| 1997 | 40,922 | 4,386 | 17,076 | 17,207 | 4,565 |
| 1998 | 41,632 | 5,398 | 18,223 | 17,854 | 6,153 |
| 1999 | 40,453 | 5,510 | 15,723 | 16,479 | 4,498 |
| 2000 | 48,680 | 5,368 | 18,652 | 20,086 | 4,397 |
| 2001 | 37,257 | 4,979 | 15,363 | 22,759 | 3,842 |
| 2002 | 37,257 | 4,856 | 14,710 | 22,737 | 4,263 |
| 2003 | 37,257 | 3,619 | 14,510 | 25,362 | 3,611 |
| 2004 | 42,268 | 3,991 | 13,104 | 22,189 | 3,600 |
| 2005 | 44,756 | 4,398 | 12,921 | 23,916 | 3,234 |
| 2006 | 42,149 | 4,897 | 11,728 | 20,962 | 3,670 |
| 2007 | 41,177 | 5,795 | - | 18,541 | 2,593 |
| 2008 | 38,791 | 6,195 | - | 17,650 | 2,558 |
| 2009 | 39,850 | 5,948 | - | 18,049 | - |
| 2010 | 40,559 | - | - | 19,328 | - |
| 2011 | 33,897 | - | - | 16,807 | - |